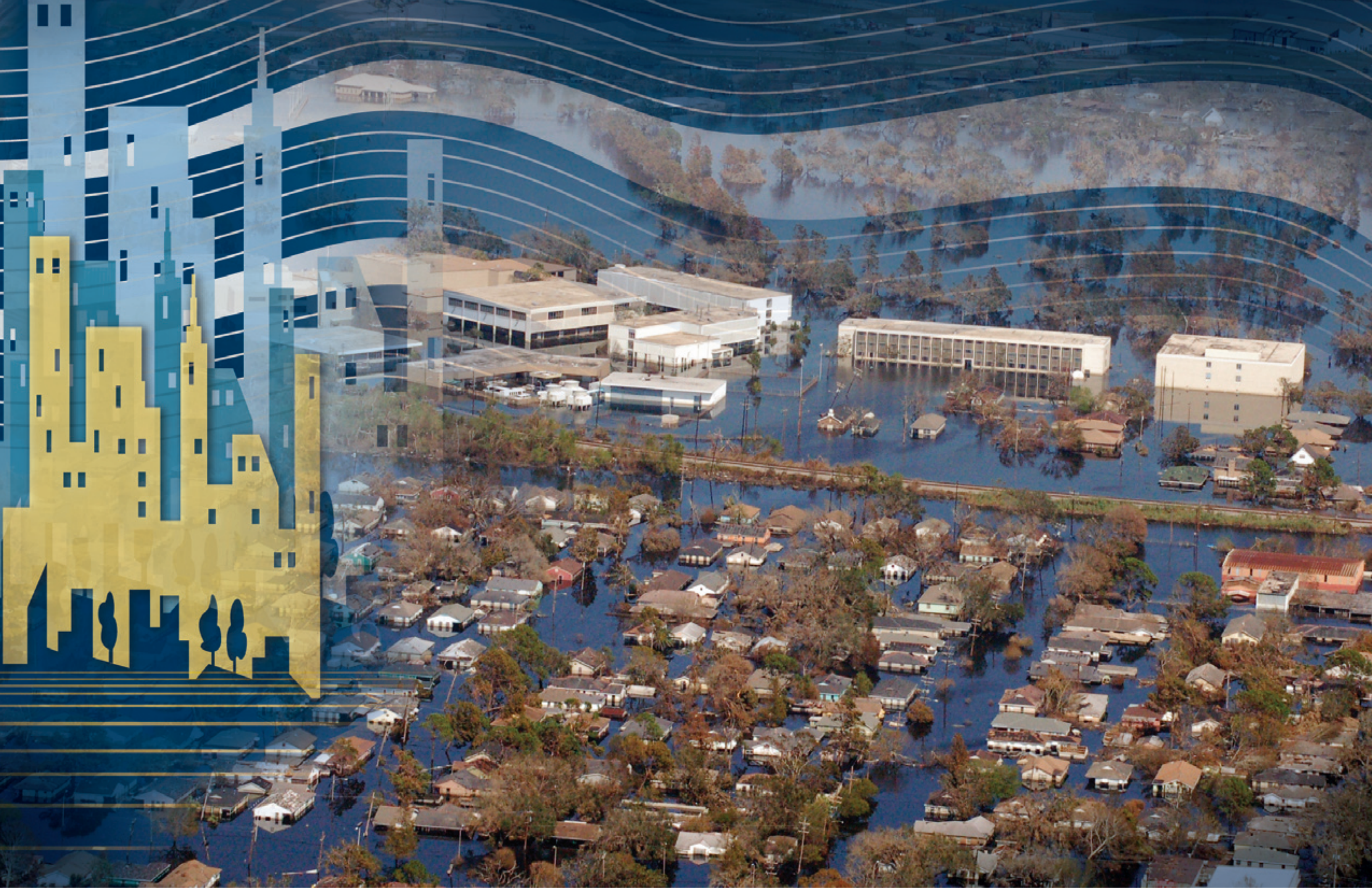

Risk Management Series

Design Guide

for Improving Critical Facility Safety from Flooding and High Winds

FEMA 543 / January 2007

FEMA

FEMA 543 / *January 2007*

RISK MANAGEMENT SERIES

Design Guide *for* Improving Critical Facility Safety from Flooding and High Winds

PROVIDING PROTECTION TO PEOPLE AND BUILDINGS

FEMA

BACKGROUND

On August 29, 2005, Hurricane Katrina caused extensive damage to the coast along the Gulf of Mexico, resulting in an unprecedented relief, recovery, and reconstruction effort. This reconstruction presents a unique opportunity to rebuild the communities and public infrastructure using the latest hazard mitigation techniques proven to be more protective of lives and property.

Critical facilities comprise all public and private facilities deemed by a community to be essential for the delivery of vital services, protection of special populations, and the provision of other services of importance for that community. This manual concentrates on a smaller group of facilities that are crucial for protecting the health and safety of the population: health care, educational, and emergency response facilities.

The *Design Guide for Improving Critical Facility Safety from Flooding and High Winds* (FEMA 543) was developed with the support of the Federal Emergency Management Agency (FEMA) Region IV in the aftermath of Hurricane Katrina. This manual recommends incorporating hazard mitigation measures into all stages and at all levels of critical facility planning and design, for both new construction and the reconstruction and rehabilitation of existing facilities. It provides building professionals and decisionmakers with information and guidelines for implementing a variety of mitigation measures to reduce the vulnerability to damage and disruption of operations during severe flooding and high-wind events. The underlying theme of this manual is that by building more robust critical facilities that will remain operational during and after a major disaster, people's lives and the community's vitality can be better preserved and protected.

This manual is a part of FEMA's Risk Management Series, which provides guidelines for mitigating against multiple hazards. The series emphasizes mitigation best practices for specific building uses, such as schools, hospitals, higher education buildings, multi-family dwellings, commercial buildings, and light industrial facilities.

OBJECTIVES

The poor performance of many critical facilities in the affected areas was not unique to Hurricane Katrina. It was observed in numerous hurricanes dating back more than three decades. Several reasons may explain this kind of performance. In many cases the damaged facilities were quite old and were constructed well before the introduction of modern codes and standards. Some of the older facilities were damaged because building components had deteriorated as a result of inadequate maintenance. Many facilities occupy unsuitable buildings that were never intended for this type of use. Some newer facilities suffered damage as a result of deficiencies in design and construction or the application of inappropriate design criteria and standards.

The primary objective of this manual is to assist the building design community and local officials and decisionmakers in adopting and implementing sound mitigation measures that will decrease the vulnerability of critical facilities to major disasters.

The goals of this manual are to:

- Present and recommend the use of building design features and building materials and methods that can improve the performance of critical facilities in hazard-prone areas during and after flooding and high-wind events.

- Introduce and provide guidelines for implementing flooding and high-wind mitigation best practices into the process of design, construction, and operation and maintenance of critical facilities.

SCOPE

To aid in the reconstruction of the Gulf Coast in the wake of Hurricane Katrina, this manual presents an overview of the principal planning and design considerations for improving the performance of critical facilities during, and in the aftermath of, flooding and high-wind events. It provides design guidance and practical recommendations for protecting critical facilities and their occupants against these natural hazards. The focus is on the design for new construction, but this manual also addresses rehabilitation of existing critical facilities. It presents incremental approaches that can be implemented over time to decrease the vulnerability of buildings, but emphasizes the importance of incorporating the requirements for mitigation against flooding and high winds into the planning and design of critical facilities from the very beginning of the process.

The material and recommendations contained in this manual are applicable to many facilities, but address primarily the following critical facilities:

- Schools
- Health Care Facilities
- Fire Stations
- Police Stations
- Emergency Operation Centers (EOCs)

The information presented in this manual provides a comprehensive survey of the methods and processes necessary to protect critical facilities from natural hazards, but is necessarily limited. It is not expected that the reader will be able to use this information directly to develop plans and specifications. It is intended as an introduction to a broader understanding of the fundamental approaches to risk mitigation planning and design. This will help building officials and professionals move on to the implementation phase that involves consultants, procurement personnel, and project administrators, with a better grasp of the task in front of them—improving the safety and welfare of their communities.

TARGET AUDIENCE

This manual describes various mitigation measures that have been successful in the past and could be implemented quickly, especially in areas recovering from a disaster. The intended audience comprises the people who own, operate, design, build, and maintain critical facilities in hazard-prone areas. This includes planning, building design, and construction professionals working for private organizations, State and local government officials working in the building sector, and relevant technical and management personnel involved with the operation of critical facilities.

TRAINING

In tandem with the publication of this manual, FEMA has developed a companion training course targeted to building design professionals and facility managers interested in improving the functionality of critical facilities in natural disasters. For transfer of its content, FEMA will promote a series of workshops directed at these professionals and others involved in planning, design, construction, rehabilitation, and management of critical facilities in areas exposed to flooding and high winds.

The training course emphasizes the best practices in mitigating against flooding and winds hazards. It is organized around a series of exercises, starting with vulnerability analysis, and progressing through assessment of risks, assessment of building systems performance (especially the effects of physical damage on the facility's functionality), and the selection of appropriate mitigation measures to be incorporated into the design of critical facilities.

The expansive scope of reconstruction activities in the aftermath of Hurricane Katrina requires that this course be initially offered and delivered only to affected communities in the Gulf States. However, the relevance and usefulness of this course extends far beyond the hurricane-prone regions, to areas exposed to other wind hazards, as well as areas subject to all types of coastal and riverine flooding.

ORGANIZATION AND CONTENTS

This manual is divided into four main chapters.

Chapter 1 presents an overview of the principal design considerations to help owners, managers, and designers when determining the location, building characteristics, and hazard resistance of critical facilities. It outlines the basic principles and design tools for improving the safety of critical facilities exposed to flooding and high winds. It also provides guidelines for facility managers and building professionals on how to coordinate the process of planning and design of critical facilities.

Chapter 2 discusses the nature of flood forces and their effects on buildings. It outlines the procedures for risk assessment, and describes current mitigation methods for reducing the effects of flooding. It underlines the need to avoid high-risk areas for the construction of new critical facilities, and encourages the application of mitigation measures when critical facilities must remain in high-risk areas. This chapter provides extensive review of the requirements of the National Flood Insurance Program (NFIP), model building codes and other standards, as well as new FEMA policy updates resulting from the experiences of Hurricanes Katrina and Rita.

Chapter 3 discusses the effects of wind forces on the structural and nonstructural building components of critical facilities. By reviewing numerous examples of wind-induced damage to these facilities, it points out the best practices pertaining to new construction and rehabilitation of existing facilities. It concentrates on building components most critical for protecting the uninterrupted operation of critical facilities and provides detailed guidelines for improving their design and construction in hurricane- and tornado-prone areas.

Chapter 4 discusses the performance of hospital, schools, and emergency response facilities (i.e., EOCs, and police and fire rescue stations) during Hurricane Katrina. This chapter emphasizes the lessons learned about the adverse effects on the functionality of critical facilities arising from damage to buildings and contents, especially the ways that various types of physical damage disrupted their operations.

Appendix A contains a list of acronyms and Appendix B contains a glossary of terms that appear in this manual. Appendix C contains an overview of the FEMA grant programs available for funding construction or rehabilitation of critical facilities.

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This manual will be revised periodically and FEMA welcomes comments and suggestions for improvements in future editions. Please send your comments and suggestions via e-mail to: RiskManagementSeriesPubs@dhs.gov

CHAPTER 3– MAKING CRITICAL FACILITIES SAFE FROM HIGH WIND........3-1

APPENDICES

CRITICAL FACILITY DESIGN CONSIDERATIONS 1

1.1 INTRODUCTION

This chapter introduces the role of hazard mitigation in the planning, design, and construction of critical facilities. It describes the way building design determines how well a critical facility is protected against natural hazard risks, specifically the risks associated with flooding and high winds. Critical facilities, and the functions they perform, are the most significant components of the system that protects the health, safety, and well-being of communities at risk.

The devastating effects of recent hurricanes, especially Hurricane Katrina, underscored the vulnerability of coastal areas of the United States, the fastest growing regions of the country. The population pressure and the aggressive coastal development in areas subject to hurricanes and coastal storms created the conditions that require careful consideration of the effects of natural hazards on the sustainability of this development. One of the most important determinants of the sustainability of coastal communities is the reliability of their physical and social infrastructure. The communities that cannot rely on their own critical infrastructure are extremely vulnerable to disasters. This is why the design of critical facilities to improve their resistance to damage, and their ability to function without interruption during and in the aftermath of hazard events, deserves special attention.

To ensure safe and uninterrupted operation of critical facilities, which is vital in the post-disaster period, facility owners must incorporate a comprehensive approach to identify hazards and avoid them when feasible. In cases when exposure to hazards is unavoidable, it is recommended that they build new facilities, or rehabilitate the existing ones to resist the forces and conditions associated with these hazards.

1.1.1 CRITICAL FACILITIES

In general usage, the term "critical facilities" is used to describe all manmade structures or other improvements that, because of their function, size, service area, or uniqueness, have the potential to cause serious bodily harm, extensive property damage, or disruption of vital socioeconomic activities if they are destroyed, damaged, or if their functionality is impaired.

Critical facilities commonly include all public and private facilities that a community considers essential for the delivery of vital services and for the protection of the community. They usually include emergency response facilities (fire stations, police stations, rescue squads, and emergency operation centers [EOCs]), custodial facilities (jails and other detention centers, long-term care facilities, hospitals, and other health care facilities), schools, emergency shelters, utilities (water supply, wastewater treatment facilities, and power), communications facilities, and any other assets determined by the community to be of critical importance for the protection of the health and safety of the population. The adverse effects of damaged critical facilities can extend far beyond direct physical damage. Disruption of health care, fire, and police services can impair search and rescue, emergency medical care, and even access to damaged areas.

The number and nature of critical facilities in a community can differ greatly from one jurisdiction to another, and usually comprise both public and private facilities. In this sense, each community needs to determine the relative importance of the publicly and privately owned facilities that deliver vital services, provide important functions, and protect special populations.

Minimum requirements for the design of new critical facilities and for improvements to existing facilities are found in the model building codes and the design and construction standards. ASCE 7, *Minimum Design Loads for Buildings and Other Structures,* is the best known standard. Published by the American Society of Civil Engineers (ASCE), it classifies buildings and other structures into four categories based on occupancy. Most critical facilities fall into Category III or Category IV, described below:

Category I includes buildings and other structures whose failure would represent a low hazard to human life, such as agricultural buildings and storage facilities.

Category II includes all buildings not specifically included in other categories.

Category III includes buildings and other structures that represent a substantial hazard to human life in the event of failure. They include buildings with higher concentrations of occupants (i.e., where more than 300 people congregate in one area). These are typically educational facilities with capacities greater than 250 for elementary and secondary facilities, 500 for colleges and adult education facilities, or 150 for daycare facilities.

Category IV includes essential facilities such as hospitals, fire and police stations, rescue and other emergency service facilities, power stations, water supply facilities, aviation facilities, and other buildings critical for the national and civil defense.

This manual concentrates on a number of critical or, as they are sometimes called, essential facilities, that deal with health and safety in emergencies, and include health care facilities, police and fire stations, EOCs, and schools. These facilities are chosen because of their vitally important role in protecting the health and safety of the community. Although limited in scope to several specific types of facilities, the information and recommendations in this manual are valuable and applicable to other types of critical facilities located in areas prone to flooding and exposed to high winds.

1.1.2 HURRICANE KATRINA

Although not the strongest storm to hit the coast of the United States, Hurricane Katrina caused the greatest disaster in the nation's history. The hurricane made its first landfall on August 25, 2005, on the southeast coast of Florida as a Category 1 hurricane.

It then crossed Florida into the Gulf of Mexico, where it gained strength to a Category 5 hurricane. Before making its second landfall near Buras in southeast Louisiana, Katrina weakened to a Category 3 hurricane. Moving across southeast Louisiana, Katrina continued northward, pushing storm surge into coastal areas of Alabama, Mississippi, and Louisiana. After crossing over Lake Borgne, it finally made a third landfall as a Category 3 hurricane near Pearlington, Mississippi, at the Louisiana/Mississippi border (see Figures 1-1 and 1-2). The hurricane caused extensive devastation along the gulf coast, with southeast Louisiana and the coast of Mississippi bearing the brunt of the catastrophic damage.

Wind damage was widespread and severe in many areas; however, the greatest damage was caused by Hurricane Katrina's storm surge flooding. Although the storm weakened from a powerful Category 5 to a Category 3 hurricane just before making landfall in Louisiana and Mississippi, the storm surge appears to have maintained a level associated with a Category 5 hurricane. The surge built by the stronger winds over open water could not dissipate as quickly as the wind speeds decreased, and the shallow depth of the off-shore shelf and the shape of the shoreline contributed to the high surge elevations. The Mississippi coastline experienced the highest storm surge on record. The storm surge also contributed to failures of a number of levees, notably the levee system that protects the City of New Orleans from Lake Borgne and Lake Pontchartrain. An estimated 80 percent of the city subsequently flooded.

The disaster was further compounded by the poor performance of critical facilities during and after the storm. Critical facilities typically did not perform any better than ordinary commercial buildings, but the extent of the damage to these facilities and the subsequent disruption of their operations caused much greater hardship. Facilities such as hurricane evacuation shelters, police and fire stations, hospitals, and EOCs were severely damaged and many were completely destroyed. Some facilities experienced a loss of function when critical support equipment, such as vehicles and communication equipment, were damaged or destroyed. While most of the damage to critical facilities was caused by the storm surge, wind damage also was widespread and substantial. In several instances, critical facilities were destroyed completely or damaged so severely that all the occupants had to be evacuated

Figure 1-1: Hurricane Katrina's path through Louisiana and Mississippi

(BASED ON HURRICANE STORM TRACK DATA FROM THE NATIONAL HURRICANE CENTER)

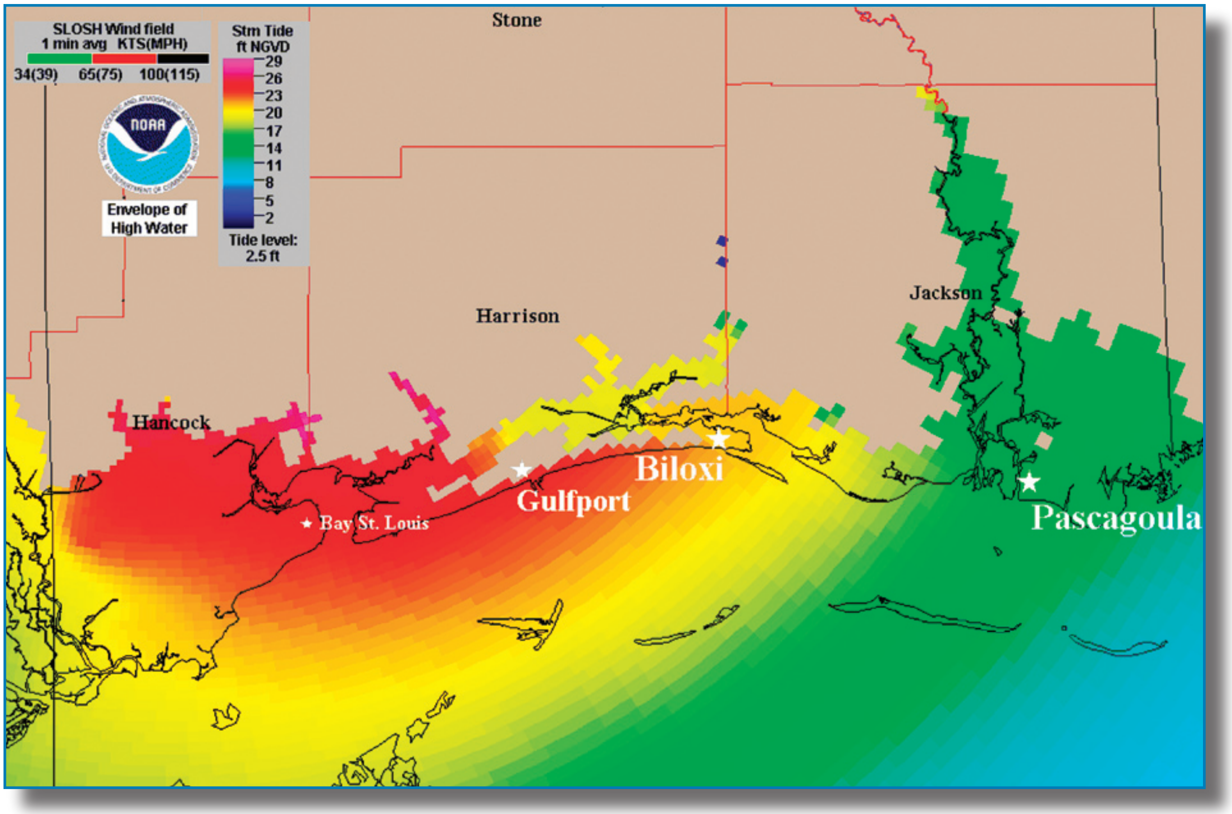


Figure 1-2: Mississippi coast SLOSH NOAA data

SOURCE: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA)

after the hurricane had moved inland. The loss of so many critical facilities placed a severe strain on the emergency operations and recovery efforts.

The estimated death toll of Hurricane Katrina exceeded 1,800. More than 85 percent of casualties were recorded in Louisiana and about 13 percent of victims lost their lives in Mississippi. Other deaths attributed both directly and indirectly to Katrina were reported in Florida, Alabama, Georgia, Kentucky, and Ohio. Hurricane Katrina ranks as the third deadliest hurricane in the United States, surpassed only by the Texas Hurricane at Galveston in 1900, where at least 6,000 and possibly as many as 10,000 lives were lost, and the Florida Hurricane at Lake Okeechobee in 1928, which claimed 2,500 lives. Estimated total economic losses from Katrina are in excess of $150 billion, and insured losses are $40 billion, making Katrina the most expensive natural disaster in the nation’s history.

1.2 HAZARD MITIGATION

1.2.1 HAZARD MITIGATION FOR CRITICAL FACILITIES

Mitigation can reduce the enormous cost of disasters to property owners, communities, and the government. Since the late 1980s, hazard mitigation has become well known in many parts of the country for initiatives in land use planning, adoption of building codes, elevation of homes, floodplain buyouts, and retrofitting buildings to resist damage in flooding, high winds, or seismic events. Incorporating mitigation measures in the planning and design of buildings is recommended because these measures reduce injuries and damage resulting from building failures during hazard events. Incorporating mitigation measures in the design of critical facilities, however, is crucial for minimizing the disruption of their operations and protecting the uninterrupted provision of critical services.

"Mitigation" is defined as any sustained action taken to reduce or eliminate long-term risk to life and property from hazard events. The goal is to save lives and reduce property damage in ways that are cost-effective and environmentally sound.

The first Federal program to support State and local mitigation programs was established by the Stafford Act in 1988. Growing support and recognition of the need to improve disaster resistance led to passage of the Disaster Mitigation Act of 2000, which amended the Stafford Act. This statute reinforces the importance of comprehensive, multi-hazard mitigation planning, and emphasizes planning for disasters before they occur. As part of the

Since 1977, Federal agencies have been charged by Executive Order 11988 to provide leadership "to reduce the risk of flood loss, to minimize the impact of floods on human safety, health and welfare, and to restore and preserve the natural and beneficial values served by floodplains in carrying out their responsibilities for (1) acquiring, managing, and disposing of Federal lands and facilities; (2) providing federally undertaken, financed, or assisted construction and improvements; and (3) conducting Federal activities and programs affecting land use, including but not limited to water and related land resources planning, regulating, and licensing activities."

planning process, States and communities are encouraged to identify existing critical facilities and to evaluate their vulnerability to natural hazards. To qualify for certain Federal mitigation grant programs, projects to rehabilitate critical facilities must be consistent with State and local mitigation plans. Appendix C provides an overview of conditions and requirements for obtaining funding assistance from major mitigation funding programs administered by the Federal Emergency Management Agency (FEMA).

There is no single procedure mandated for the planning, site selection, and design of critical facilities, because none can be assumed to be universally applicable. The decision to build a critical facility depends on many factors and requires a rigorous and comprehensive analysis of all the conditions that may affect the operation of a facility. This manual primarily addresses the design of new facilities and measures to improve the disaster resistance of existing facilities exposed to flooding and high winds, based on the assumption that all other alternatives to minimize or avoid such risks have been thoroughly evaluated and rejected as infeasible or impractical. It is outside the scope of this manual to try to depict in detail this evaluation process in its full range and complexity. Communities, as well as the owners and operators of critical facilities, must evaluate all alternatives, assess all risks, and consider all short-term and long-term effects of proposed projects, whenever construction or rehabilitation of these facilities is considered. Careful analysis of alternatives and the potential adverse effects of exposing critical facilities to natural hazards is also intended to help identify the most appropriate hazard-resistant measures when avoidance is not practical.

1.2.2 SITE SELECTION

Site selection is a particularly significant step when planning new critical facilities or when planning substantial improvements to existing facilities in hazard-prone areas. The earliest steps in the planning process should be to identify hazards and assess the risks for the facility at the proposed site. In addition, alternative solutions should be considered in order to avoid site-specific hazards like floods. After decisions about the building location have been made, hazard mitigation involves acquiring a full understanding of the prevalent hazards and considering all appropriate hazard-resistance measures to ensure the uninterrupted operation of critical facilities.

All work on critical facilities must meet the minimum requirements of building codes and related regulations. However, the importance of uninterrupted operation of critical facilities frequently makes it necessary to go beyond the code requirements to provide acceptable levels of protection for the facility's functionality during, and in the immediate aftermath of, a hazard event.

Typically, the selection of a site for a critical facility is based on specific functions of a facility and the characteristics of its service area. In cases where critical facilities may be exposed to flooding and wind hazards, it is recommended that the final site decision be made only after all alternative sites have been evaluated for hazard exposure and the resulting effects of the hazard exposure on the design, construction, and operation of a facility.

Considering that critical facilities should avoid hazard-prone areas, site selection may sometimes be a difficult and prolonged process. This is especially true in situations when the facility service requirements cannot be easily reconciled with requirements to minimize the exposure to hazards. Sometimes a facility, like a fire station for example, cannot fulfill its rapid response function if it is located outside the hazard zone, far from the area the facility is intended to serve. Additionally, site selection is not always controlled by the community. Many local jurisdictions report that the high cost and the scarcity of available land can severely limit the consideration of alternative locations. The consequences of accepting a flood-prone site include not only the potential physical damage, but also the loss of services provided by the critical facility. This loss of service can adversely affect the community as a whole, both in the immediate post-event period and during its long-term recovery. Section 2.5.1 contains a discussion and a number of questions that can help guide determinations about whether the risks associated with building a critical facility in a floodplain are acceptable.

If the site selection process determines that no other practical and feasible alternatives are available and that a facility must be located in a hazard-prone area, the highest level of protection should be a design priority.

1.2.3 FACILITY DESIGN

The nature of services provided by critical facilities requires that designers and decisionmakers define a design objective of achieving building performance levels beyond the minimum requirements prescribed by the building code. While compliance with the building code may satisfy the requirements to protect the facility's occupants, it may be insufficient to ensure the continued operation of the facility. When designing or rehabilitating a critical facility located in an area subject to high-wind or flooding risks, this manual recommends a set of guidelines intended to minimize the interruption in operation of critical facilities, both during and in the aftermath of hazard events.

❍ Conduct an in-house assessment of the facility needs, with the assistance of decisionmakers and consultants. Public committees may contribute advice and guidance throughout the programming and design process. For large programs, committees may acquire specialists at different stages as necessary.

❍ Determine the size and scope of the proposed program. In a smaller area, an architect may be employed to assist the decisionmakers with this task, possibly later becoming the design architect.

❍ Assess the needs of the facility to determine the availability of suitable sites (and lease/purchase as necessary).

❍ Develop occupant specifications, seeking advice from facility managers and both in-house and consulting professionals.

❍ Assess financial needs.

❍ Identify financial resources, including alternative sources of funding (e.g., Federal and State programs, local taxes, bond issues, and utility fees).

❍ Ensure funding (e.g., bond issue, establishment of utility districts, etc.).

❍ Appoint a building program management staff (appointed officials or a committee).

❍ Determine the design and construction process (i.e., conventional design and bid, design/build, or construction management).

❍ Select and hire architects and other special design consultants or design/build team members. The timing of this phase varies depending on the number of variables.

❍ Develop building programs, including building size, room size, equipment, and environmental requirements. This may be done in-house, or architects and independent program consultants may assist.

❍ Appoint a local representative to the staff and a public stakeholders committee for the design phase.

❍ Develop designs with cost estimates. Hold public meetings, with the architects in attendance, and encourage public input into the design. Implement local area progress reviews.

❍ Complete the design and solicit a local review of the contract documents.

❍ Submit construction documents to the local jurisdiction and any permitting agencies for review and approval.

❍ Submit documents to the building department.

❍ Select the contractor (if bidding is used), or finalize design/build or construction management contracts.

❍ Undertake critical facility construction.

❍ Administer the construction contract.

❍ Monitor the construction progress and conduct inspections, as required.

❍ Complete contracted tasks.

- Conduct inspections and provide proof of the architect's acceptance.
- Inspect the critical facility and obtain concurrence/acceptance by the owner.
- Commission the facility and occupy it.

The sequence of the above steps may vary, depending on the complexity of the program; some steps may be implemented simultaneously. Figure 1-3 shows a flow chart of this typical process. Also shown (in the five boxes to the right) are specific activities related to designing for multiple hazards and how these activities fit into the construction process.

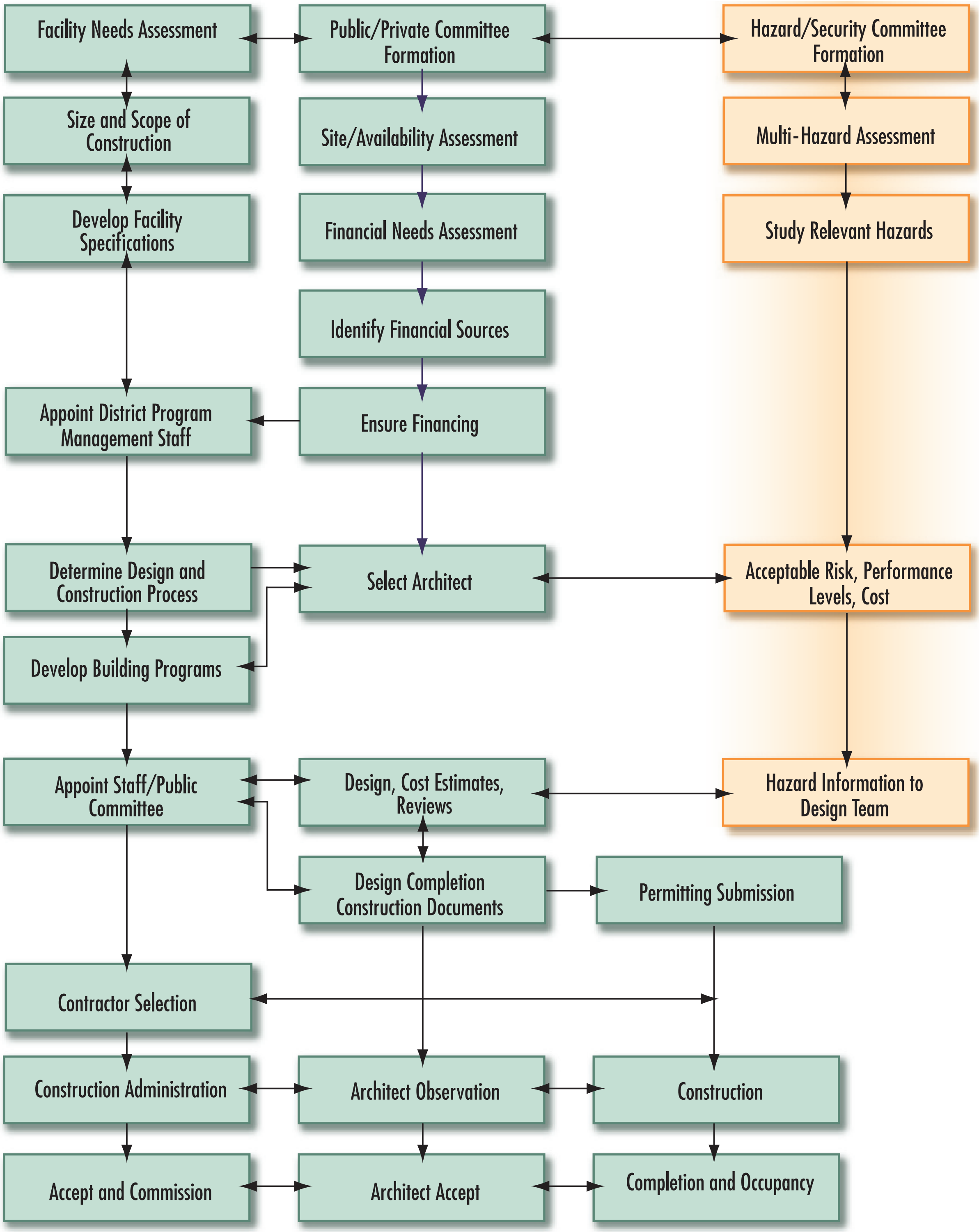


Figure 1-3: Process flow chart for decisionmakers

1.3 PERFORMANCE-BASED DESIGN

1.3.1 BACKGROUND

The model building codes define the minimum design requirements to ensure occupants' safety in critical facilities. Recent natural disasters have forced recognition that damage can occur even when buildings are compliant with the building code. The fact that a large number of critical facilities in communities affected by Hurricane Katrina were shut down (frequently as a result of minor building or equipment damage) suggests that satisfying the minimum code criteria may not be sufficient to ensure continued availability of critical services. Communities depend on the uninterrupted operation of critical facilities, especially during and immediately following natural disasters. In order to meet that need, critical facilities should be designed and constructed according to criteria that result in continued and uninterrupted provision of critical services.

Performance-based codes define acceptable or tolerable levels of risk for a variety of health, safety, and public welfare issues. Currently available are the *International Code Council Performance Code for Buildings and Facilities* by the International Code Council (ICC, 2006), *101 Life Safety Code* (NFPA, 2006a), and the *NFPA 5000 Building Construction and Safety Code* (NFPA, 2006b) by the National Fire Protection Association (NFPA). The ICC performance code addresses all types of building issues, while the provisions of the *101 Life Safety Code,* "Performance-Based Option," address only issues related to "life safety systems." The *NFPA 5000 Building Construction and Safety Code* sets forth both performance and prescriptive options that apply to all traditional building code issues.

Building performance indicates how well a structure supports the defined needs of its users. The term "performance," as it relates to critical facilities exposed to natural hazards, usually refers to a building's condition after a disaster, i.e., it signifies a level of damage or a load. Acceptable performance indicates acceptable levels of damage or a building condition ,that allows uninterrupted facility operation. Consequently, performance-based design for critical facilities is the process or methodology used by design professionals to create buildings that protect a facility's functionality and the continued availability of services. This approach represents a major change in perception that gives performance-based design considerations a greater importance in the decisionmaking process for design and construction of critical facilities.

The performance-based design approach is not proposed as an immediate substitute for design to traditional codes. Rather, it is seen as an opportunity for enhancing and tailoring the design to match the objectives of the community.

FEMA recently funded the development of next-generation, performance-based seismic design guidelines for new and existing buildings. This process includes detailed modeling; simulation of building response to extreme loading; and estimation of potential casualties, loss of occupancy, and economic losses. The process allows the design of a building to be adjusted to balance the level of acceptable risks and the cost of achieving the required level of building performance. Currently the process focuses on seismic hazards, but it is general enough to be used with other hazards, as soon as the development of performance-based design criteria for wind and other extreme loads advances to the point that they can be incorporated into standardized models.

1.3.2 PRESCRIPTIVE VS. PERFORMANCE-BASED DESIGN

Design and construction in the United States is generally regulated by building codes and standards. Building codes typically seek to ensure the health, safety, and well-being of people in buildings. Toward this purpose, the building codes and standards set minimum design and construction requirements to address structural strength, adequate means of egress for facilities, sanitary equipment, light and ventilation, and fire safety. Building regulations may also promote other objectives, such as energy efficiency, serviceability, quality or value, and accessibility for persons with disabilities. These prescriptive standards are easy to understand and follow, and easy to monitor. This is their great strength.

Historically, building codes were based on a prescriptive approach that limited the available solutions for compliance, which did not encourage creativity and innovation. Prescriptive or specification-based design emphasized the “input,” or the materials and methods required. In contrast, the focus of performance-based design is the “output,” or the expectations and requirements of the users of a building.

Performance-based design requirements define goals and objectives to be achieved and describe methods that can be used to demonstrate whether buildings meet these goals and objectives. This approach provides a systematic method for assessing the performance capabilities of a building, system, or component, which can then be used to verify the equivalent performance of alternatives, deliver standard performance at a reduced cost, or confirm the higher performance needed for critical facilities.

1.3.3 THE PROCESS OF PERFORMANCE-BASED DESIGN OF CRITICAL FACILITIES

The performance-based design process explicitly evaluates how building systems are likely to perform under a variety of conditions associated with potential hazard events. The process takes into consideration the uncertainties inherent in quantifying potential risks and assessing the actual responses of building systems and the potential effects of the performance of these systems on the functionality of critical facilities. Identifying the performance capability of a facility is an integral part of the design process and guides the many design decisions that must be made. Figure 1-4 presents the key steps in this iterative performance-based design process.

Performance-based design starts with selecting design criteria articulated through one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring different levels of damage and the consequential losses that occur as a result of this damage. Losses can be associated with structural or nonstructural damage, and can be expressed in the form of casualties, direct economic costs, and loss of service costs. Loss of service costs may be the most important loss component to consider for critical facilities. Acceptable risks are typically expressed as acceptable losses for specific levels of hazard intensity and frequency. They take into consideration all the potential hazards that could affect the building and the probability of their occurrence during a specified time period. The overall analysis must consider not only the intensity and frequency of occurrence of hazard events, but also the effectiveness and reliability of the building systems to survive the event without significant interruption in the operation of a facility.

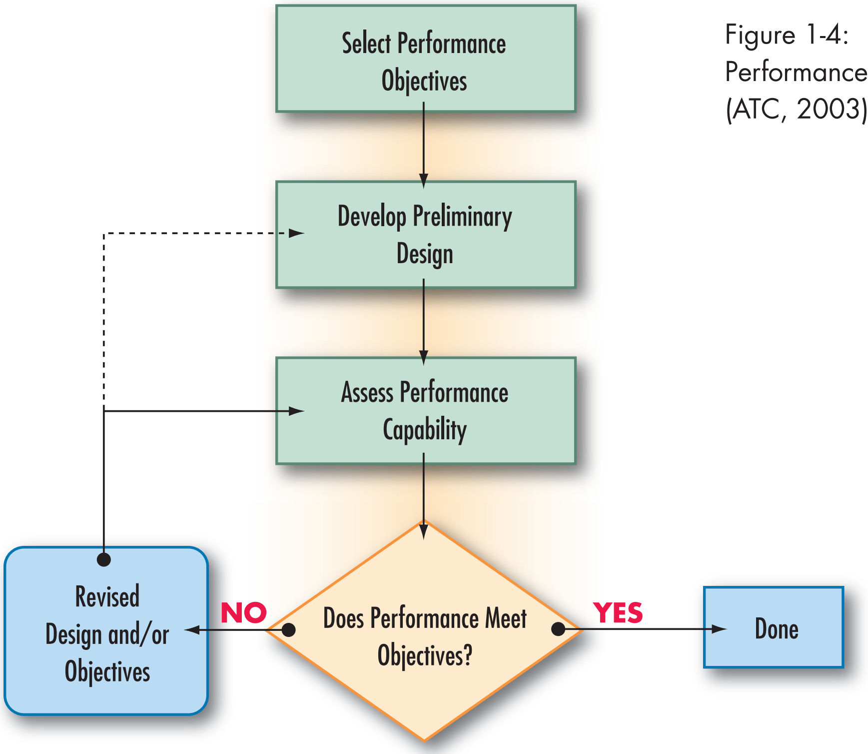


Figure 1-4:
Performance-based design flow diagram (ATC, 2003)

1.3.4 ACCEPTABLE RISK AND PERFORMANCE LEVELS

Performance-based design requires a quantitative measure of risk. It also establishes the basis for evaluating acceptable losses and selecting appropriate designs. While specific performance objectives can vary for each project, the notion of acceptable performance generally follows a trend corresponding to:

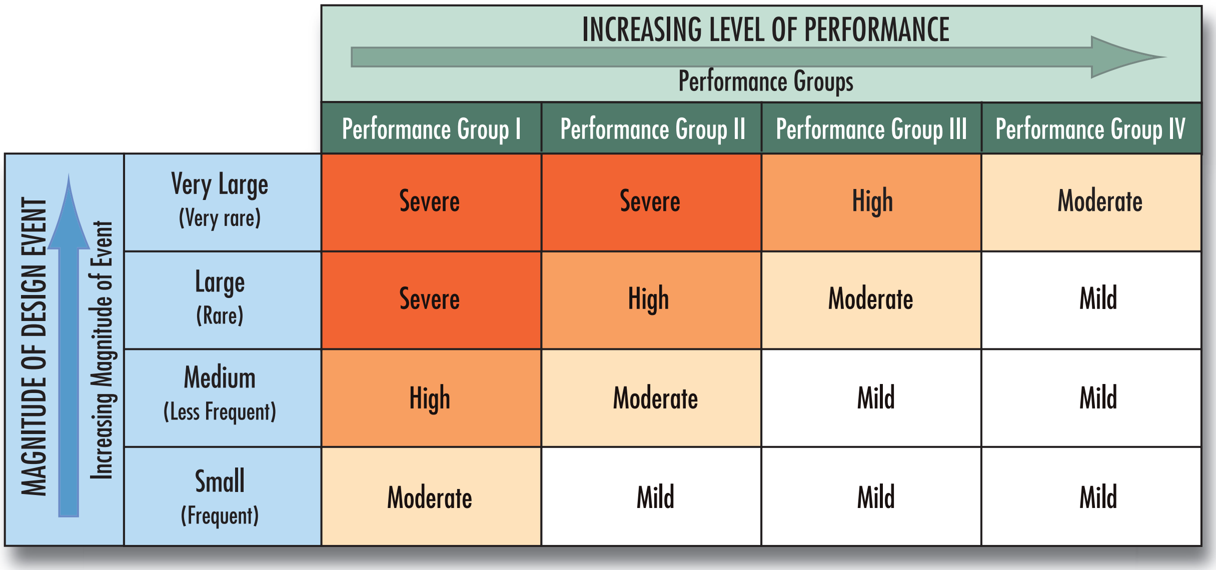
- Little or no damage for small, frequently occurring events
- Moderate damage for medium-sized, less frequent events
- Significant damage for very large, very rare events

Performance objectives should be higher and the corresponding acceptable levels of damage lower for critical facilities and other important buildings than for non-critical facilities. This trend is illustrated in Figure 1-5, taken from the ICC Performance Code for Buildings and Facilities (ICC, 2006). This document defines acceptable performance for facilities in one of four performance groups (I, II, III, and IV), using four damage levels (mild, moderate, high, and severe), and given four hazard levels (small, medium, large, and very large). The relative return periods (length of time between occurrences) commonly associated with the hazard levels for each type of hazard event (seismic, flood, and wind) are indicated in Figure 1-6.

Since losses can be associated with structural damage, nonstructural damage, or both, performance objectives must be expressed in terms of the potential performance of both structural and nonstructural systems. The *ICC Performance Code for Buildings and Facilities* has formalized the following four design performance levels, each of which addresses structural damage, nonstructural systems, occupant hazards, overall extent of damage, and release of hazardous materials. These definitions are general to all hazards and are related to tolerable limits of impact to the building, its contents, and its occupants.

Mild Impact: At the mild impact level, the building has no structural damage and is safe to occupy. The nonstructural systems needed for normal building or facility use and emergency operations are fully operational. The number of injured occupants is minimal, and the nature of the injuries minor. The overall extent of the damage is minimal. Minimal amounts of hazardous materials may be released into the environment.

Moderate Impact: At the moderate impact level, structural damage is repairable and some delay in re-occupancy can be expected. The nonstructural systems needed for normal building or facility use and emergency operations are fully operational, although some cleanup and repair may be needed. Injuries to occupants may be locally significant, but generally moderate in numbers and in nature. There is a low likelihood of a single life loss and very low likelihood of multiple life loss. The extent of the damage can be locally significant, but is moderate overall. Some hazardous materials may be released into the environment, but the risk to the community is minimal.



INCREASING LEVEL OF PERFORMANCE

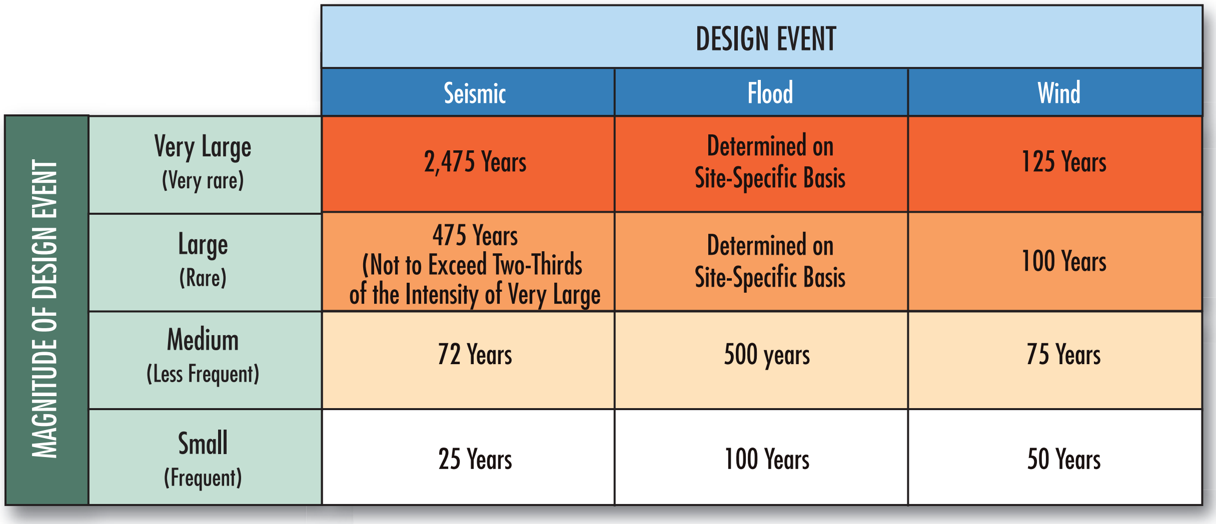
Performance Groups

MAGNITUDE OF DESIGN EVENT

Increasing Magnitude of Event

	Performance Group I	Performance Group II	Performance Group III	Performance Group IV
Very Large (Very rare)	Severe	Severe	High	Moderate
Large (Rare)	Severe	High	Moderate	Mild
Medium (Less Frequent)	High	Moderate	Mild	Mild
Small (Frequent)	Moderate	Mild	Mild	Mild

Figure 1-5: Maximum level of damage to be tolerated (Table 303.3, ICC, 2006b)
Note: Performance Group I: Buildings that represent a low hazard to human life in the event of failure. Performance Group II: All buildings except those in Groups I, III, and IV. Performance Group III: Buildings with a substantial hazard to human life in the event of failure. Group IV: Buildings designed as essential facilities, including emergency operations centers and designated disaster shelters.



DESIGN EVENT

MAGNITUDE OF DESIGN EVENT

	Seismic	Flood	Wind
Very Large (Very rare)	2,475 Years	Determined on Site-Specific Basis	125 Years
Large (Rare)	475 Years (Not to Exceed Two-Thirds of the Intensity of Very Large	Determined on Site-Specific Basis	100 Years
Medium (Less Frequent)	72 Years	500 years	75 Years
Small (Frequent)	25 Years	100 Years	50 Years

Figure 1-6: Relative magnitude and return period for seismic, flood, and wind events (ICC, 2006b)

High Impact: At the high impact level, there is significant damage to structural elements, but no falling debris. Significant delays in reoccupancy can be expected. The nonstructural systems needed for normal building use are significantly damaged and inoperable. Emergency systems may be damaged, but remain operational. Injuries to occupants may be locally significant with a high risk to life, but are generally moderate in numbers and nature. There is a moderate likelihood of a single life loss, with a low probability of multiple life loss. The extent of damage can be generally significant and at some locations total. Hazardous materials are released into the environment, with localized relocation required in the immediate vicinity.

Severe Impact: At the severe impact level, there is substantial structural damage. Repair may not be technically possible. The building is not safe for re-occupancy due to the potential for collapse. The nonstructural systems for normal use and emergency systems may be nonfunctional. Injuries to occupants may be high in number and significant in nature. Significant risk to life may exist. There is a high likelihood of single life loss and a moderate likelihood of multiple life loss. Overall damage is substantial. Significant amounts of hazardous materials may be released into the environment, with relocation needed beyond the immediate vicinity.

Once the preliminary design has been developed, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events. Using fragility relationships (vulnerability functions defining the relationship between load and damage) developed through testing or calculation, building responses are equated to damage states expressed as levels of performance. If the simulated performance meets or exceeds the performance objectives, the design is completed. If not, the design must be revised in an iterative process until the performance objectives are met. In some cases it will not be possible to meet the stated objective at a reasonable cost, in which case the team of decisionmakers may elect to relax some of the original performance objectives.

Continued and uninterrupted operation is the most important performance requirement of any critical facility, regardless of the level of structural and nonstructural building damage. In other words, the acceptable performance of a critical facility is achieved as long as the structural and nonstructural damage to the building does not disrupt or impair the continued operation of that facility. In recent hurricanes, however, undamaged structures were frequently rendered inoperable as a result of nonstructural damage resulting in unacceptable performance (FEMA, 2006).

In terms of affecting the ability of a facility to function, the failure of nonstructural systems (roofing; exterior envelope; heating, ventillating, and air conditioning [HVAC]; emergency systems) can be as significant as the failure of structural components. Performance-based design provides a framework for considering the potential hazards that can affect a facility or site, and for explicitly evaluating the performance capability of the facility and its components.

Consideration must also be given to the likely possibility that at least a portion of the distribution systems for critical infrastructure services (e.g., electrical power, communications, potable water, and sanitary sewer) could be interrupted. The impact of such an interruption in service should be assessed for the facility, along with an estimate of the time it would take until service could be restored or supplemented. For protecting the continued operation of critical facilities, the most reliable approach is to provide alternative onsite sources for critical infrastructure needs in the form of: (1) emergency power generation capabilities; (2) local wireless communications; (3) potable water supplies; and (4) temporary onsite storage for sanitary waste.

While the practice of performance-based design is currently more advanced in the field of seismic design than the fields of flood and high-wind design, the theory of performance-based design is completely transferable to all hazards. The practice of performance-based design will prompt designers and owners of buildings in flood- or high-wind-prone regions to begin thinking in terms of a few basic objectives:

- Can the real probabilities and frequencies of high-wind and flood events during the useful life of the building be defined with an acceptable degree of accuracy?

- Can the extent and kinds of damage that can be tolerated be defined?

❍ Are there ways in which an acceptable level of performance can be achieved?

❍ Are there alternative levels of performance that can be achieved, and how much do they cost over the lifetime/ ownership of the building compared to the benefits of reduced damage and improved performance?

❍ How do these levels compare to the performance levels of designs using the minimum requirements of the applicable building code?

1.3.5 PERFORMANCE-BASED FLOOD DESIGN

The performance levels and objectives for flood hazards, first outlined in FEMA 424 (2004), have been expanded and generalized for performance-based flood design of critical facilities as follows:

Level 1 (Operational): The facility sustains no structural or nonstructural damage, emergency operations are fully functional, and the building can be immediately operational. The site is not affected by erosion, but may have minor debris and sediment deposits.

Level 2 (Moderate Impact): The facility is affected by flooding above the lowest floor, but damage is minimal due to low depths and short duration of flooding. Cleanup, drying, and minor repairs are required, especially of surface materials and affected equipment, but the building can be back in service in a short period of time.

Level 3 (High Impact): The facility may sustain structural or nonstructural damage that requires repair or partial reconstruction, but the threat to life is minimal and occupant injuries should be few and minor. Water damage to the interior of the facility requires cleanup, drying, and repairs, and can prohibit occupancy of all or a portion of the facility for several weeks to several months.

Level 4 (Severe Impact): The facility is severely damaged and likely requires demolition or extensive structural repair. Threats to occupants are substantial, and warning plans should prompt evacuation prior to the onset of this level of flooding. Level 4 is applicable to facilities affected by all types of flooding, including those that result from failure of dams, levees, or floodwalls.

Planning and design to achieve an appropriate level of flood protection for critical facilities should include avoidance of flood hazard areas and adding a factor of safety (freeboard) to the anticipated flood elevation. Performance evaluation of a facility affected by flooding needs to include consideration of the building response to the following load conditions (fragility functions must be developed to relate calculated response to actual damage states):

- ❍ Lateral hydrostatic forces
- ❍ Vertical (buoyant) hydrostatic forces
- ❍ Hydrodynamic forces
- ❍ Surge forces
- ❍ Impact forces of flood-borne debris
- ❍ Breaking wave forces
- ❍ Localized scour

1.3.6 PERFORMANCE-BASED HIGH-WIND DESIGN

The performance objectives for wind hazards, outlined in FEMA 424, have been expanded and generalized for performance-based flood design of critical facilities as follows:

Level 1 (Operational): The facility is essentially undamaged and can be immediately operational.

Level 2 (Moderate Impact): The facility is damaged and needs some repairs, but can remain occupied and be functional after minor repairs to nonstructural components are complete.

Level 3 (High Impact): The facility may be structurally damaged but the threat to life is minimal and occupant injuries should be few and minor. However, damage to nonstructural components (e.g., roofing, building envelope, exterior-mounted equipment) is great, and the cost to repair the damage is significant. If rain accompanies the windstorm, or if rain occurs prior to execution of emergency repairs, water damage to the interior of the facility can prohibit occupancy of all or a portion of the facility for several weeks to several months.

Level 4 (Severe Impact): The facility is severely damaged and will probably need to be demolished. Significant collapse may have occurred, and there is a great likelihood of occupant casualties unless the facility has a specially designed occupant shelter. Level 4 is applicable to facilities struck by strong or violent hurricanes or tornadoes. For other types of windstorms, Level 4 should not be reached.

The challenge with respect to performance-based high-wind design is assessing the wind resistance of the building envelope and exterior-mounted equipment, and the corresponding damage susceptibility. This is challenging because of several factors:

- Analytical tools (i.e., calculations) are currently not available for many envelope systems and components, and there is a lack of realistic long-term wind resistance data.

- Because of the complexity of their wind load response, many envelope systems and components require laboratory testing, rather than analytical evaluation, in order to determine their load-carrying capacity.

- It is likely that finite element analysis will eventually augment or replace laboratory testing, but substantial research is necessary before finite element analysis becomes available for the broad range of existing building envelope systems.

- Before performance-based design for high winds can become a reality, a solid research base on the response of buildings and components to the effects of high winds must be established.

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2.1 GENERAL DESIGN CONSIDERATIONS

This chapter introduces the physical nature and mechanics of floods and explains how flood probabilities are determined and how flood hazard areas are identified. It describes the types of flood damage that can result when critical facilities are located in flood hazard areas or are affected by flooding. A series of requirements and best practices are introduced that facility owners, planners, and designers should consider for reducing the risks from flooding to new critical facilities and to existing facilities already located in areas prone to flooding.

This chapter demonstrates why avoidance of flood hazard areas is the most effective way to minimize the life-safety risk to the occupants and general public who rely on these facilities, as well as to minimize the potential for damage to buildings and other elements of critical facilities. When an existing facility is exposed to flooding, or if a new facility is proposed for a flood hazard area, steps need to be taken to minimize the risks. A well-planned, designed, constructed, and maintained critical facility should be able to withstand damage and remain functional after a flooding event, even one of low probability.

2.1.1 NATURE AND CHARACTERISTICS OF FLOODING

Flooding is the most common natural hazard in the United States, affecting more than 20,000 local jurisdictions and representing more than 70 percent of Presidential disaster declarations. Several evaluations have estimated that 7 to 10 percent of the Nation's land area is subject to flooding. Some communities have very little flood risk; others lie entirely within a floodplain.

Flooding is a natural process that may occur in a variety of forms: long-duration flooding along rivers that drain large watersheds; flash floods that send a devastating wall of water down a mountain canyon; and coastal flooding that accompanies high tides and onshore winds, hurricanes, and nor'easters. When the natural process does not affect human activity, flooding is not a problem. In fact, many species of plants and animals that live adjacent to bodies of water are adapted to a regimen of periodic flooding.

Flooding is only considered a problem when human development is located in flood-prone areas. Such development exposes people to potentially life threatening situations and makes property vulnerable to serious damage or destruction. It also can disrupt the natural surface flow, redirecting water onto lands not normally subject to flooding.

Flooding along waterways normally occurs as a result of excessive rainfall or snowmelt that creates water flows exceeding the capacity of channels. Flooding along shorelines is usually a result of coastal storms that generate storm surges or waves above normal tidal fluctuations. Factors that can affect the frequency and severity of flooding and the resulting damage include:

❍ Channel obstructions caused by fallen trees, accumulated debris, and ice jams

❍ Channel obstructions caused by road and rail crossings where the bridge or culvert openings are insufficient to convey floodwaters

❍ Erosion of shorelines and stream banks, often with episodic collapse of large areas of land

❍ Deposition of sediment that settles out of floodwaters or is carried inland by wave action

❍ Increased upland development of impervious surfaces and manmade drainage improvements that increase runoff volumes

- Land subsidence, which increases flood depths

- Failure of dams (resulting from seismic activity, lack of maintenance, flows that exceed the design, or destructive acts), which may suddenly and unexpectedly release large volumes of water

- Failure of levees (associated with flows that exceed the design, weakening by seismic activity, lack of maintenance, or destructive acts), which may result in sudden flooding of areas behind levees

Each type of flooding has characteristics that represent important aspects of the hazard. These characteristics should be considered in the selection of critical facility sites, the design of new facilities, and the expansion or rehabilitation of existing flood-prone facilities.

Riverine flooding results from the accumulation of runoff from rainfall or snowmelt, such that the volume of flow exceeds the capacity of waterway channels and spreads out over the adjacent land. Riverine flooding flows downstream under the force of gravity. Its depth, duration, and velocity are functions of many factors, including watershed size and slope, degree of upstream development, soil types and nature of vegetation, topography, and characteristics of storms (or depth of snowpack and rate of melting). Figure 2-1 illustrates a cross-section of the generic riverine floodplain.

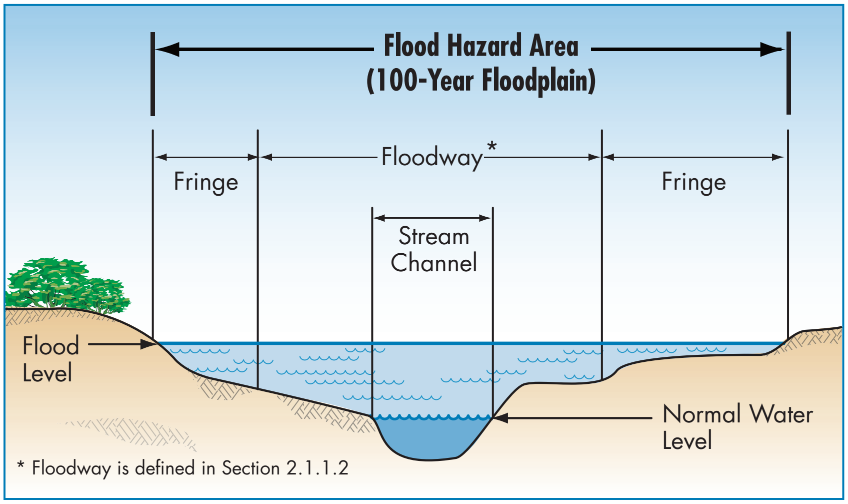

Figure 2-1:
The riverine floodplain

Coastal flooding is experienced along the Atlantic, Gulf, and Pacific coasts, and many larger lakes, including the Great Lakes. Coastal flooding is influenced by storm surges associated with tropical cyclonic weather systems (hurricanes, tropical storms, tropical depressions, typhoons), extratropical systems (nor'easters), and tsunamis (surge induced by seismic activity). Coastal flooding can also be characterized by wind-driven waves, which also affect reaches along the Great Lakes shorelines; winds blowing across the broad expanses of water generate waves that can rival those experienced along ocean shorelines. Some Great Lakes shorelines experience coastal erosion, in part because the erosion is associated with fluctuations in water levels. Figure 2-2 is a schematic of the generic coastal floodplain.

A number of factors associated with riverine and coastal flooding are important in the selection of sites for critical facilities, in site design, and in the architectural and engineering design of critical facilities.

Depth: The most obvious characteristic of any flood is the depth of the water. Depending on many factors, such as the shape of a river

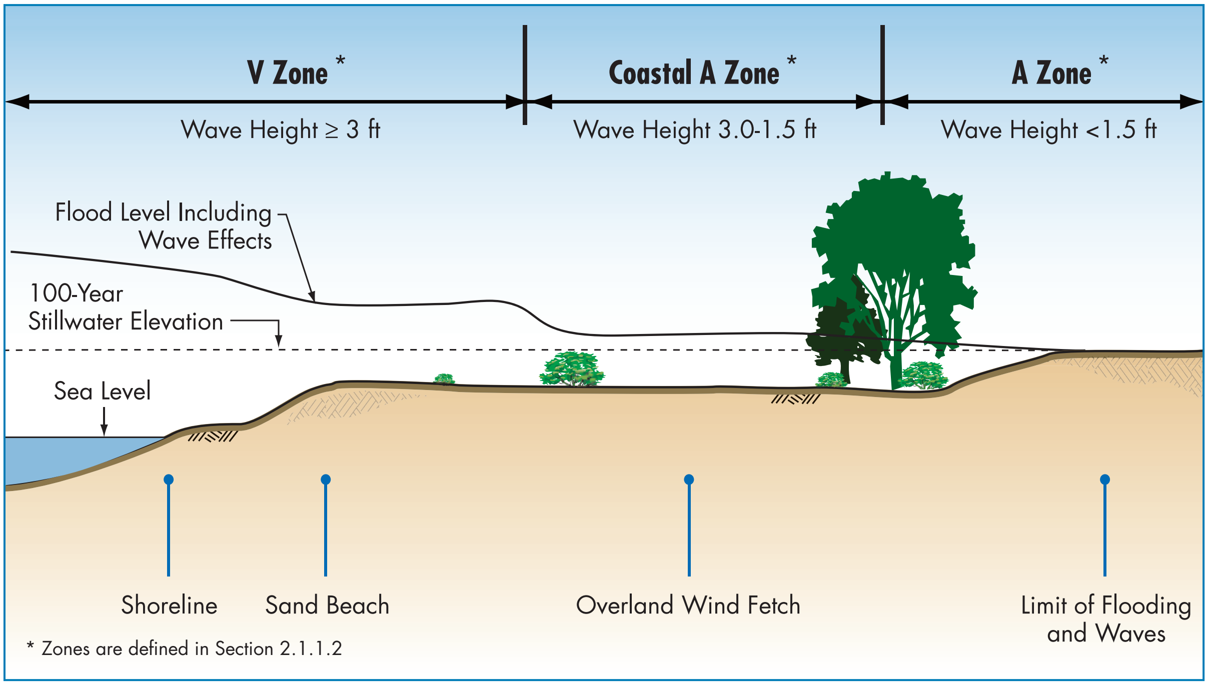

Figure 2-2: The floodplain along an open coast

valley or the presence of obstructing bridges, riverine flooding may rise just a few feet or tens of feet above normal levels. The depth of coastal flooding is influenced by such factors as the tidal cycle, the duration of the storm, the elevation of the land, and the presence of waves. Depth is a critical factor in building design, because the hydrostatic forces on a vertical surface (such as a foundation wall) are directly related to depth, and because costs associated with protecting buildings from flooding increase with depth. Under certain conditions, hurricanes can produce storm surge flooding that is 20 to 30 feet above mean sea level or, in extreme cases such as reported during Hurricane Katrina, as much as 35 feet above mean sea level.

Duration: Duration is the measure of how long the water remains above normal levels. The duration of riverine flooding is primarily a function of watershed size and the longitudinal slope of the valley (which influences how fast water drains away). Small watersheds are more likely to be "flashy," which refers to the rapidity with which floodwaters rise and fall. Areas adjacent to large rivers may be flooded for weeks or months. Most coastal flooding is influenced by the normal tidal cycle, as well as how fast coastal storms move through the region. Areas subject to coastal flooding can experience long duration flooding where drainage is poor or slow as a result of topography or the presence of flood control structures. For example, there may be depressions in the land that would hold water, or water may be trapped behind a floodwall or levee with inadequate drainage. More commonly, coastal flooding is of shorter duration, on the order of 12 to 24 hours, especially if storms move rapidly. Flooding along large lakes, including those behind dams, can be of very long duration because the large volume of water takes longer to drain. For building design, duration is important because it affects access, building usability, and saturation and stability of soils and building materials. Information about flood duration is sometimes available as part of a flood study, or could be developed by a qualified engineer.

Local drainage problems create ponding and local flooding that often is not directly associated with a body of water such as a creek or river. Although such flooding is relatively shallow and not characterized by high velocity flows, considerable damage may result. Areas with poor drainage frequently experience repetitive damage. Some local drainage problems are exacerbated by old or undersized drainage system infrastructure. Flooding caused by drainage problems typically occurs as sheetflow or along waterways with small drainage areas. This type of flooding is often not mapped or regulated.

Velocity: The velocity of floodwaters ranges from extremely high (associated with flash floods or storm surge) to very low or nearly stagnant (in backwater areas and expansive floodplains). Velocity is important in site planning because of the potential for erosion. In structural design, velocity is a factor in determining the hydrodynamic loads and impact loads. Even shallow, high-velocity water can threaten the lives of pedestrians and motorists. Accurate estimates of velocities are difficult to make, although velocity information may be found in some floodplain studies.

Wave action: Waves contribute to erosion and scour (see Figure 2-2), and also contribute significantly to design loads on buildings. The magnitude of wave forces can be 10 to more than 100 times greater than wind and other design loads, and thus may control many design parameters. Waves must be accounted for in site planning along coastal shorelines, in flood hazard areas that are inland of open coasts, and other areas where waves occur, including areas with sufficient fetch that winds can generate waves (such as lakes and expansive riverine floodplains). Waves on top of storm surges may be as much as 50 percent higher than the depth of the surge.

Impacts from debris and ice: Floating debris and ice contribute to the loads that must be accounted for in structure design. The methods and models used to predict and delineate flood hazard areas do not specifically incorporate debris loads. Thus, there are few sources to determine the potential effects of debris impact, other than past observations and judgment.

Erosion and scour: Erosion is the lowering of the ground surface as a result of a flood event, or the gradual recession of a shoreline as a result of long-term coastal processes. Scour refers to a localized lowering of the ground surface due to the interaction of currents and/or waves with structural elements, such as pilings. Soil characteristics influence an area's susceptibility to scour. Erosion and scour may affect the stability of foundations and filled areas, and may cause extensive site damage.

2.1.1.1 Probability of Occurrence or Frequency

The probability of occurrence, or frequency, is a statement of the likelihood that an event of a certain magnitude will occur in a given period of time. For many decades, floodplain management has been based on the flood that has a 1 percent chance of occurring in any given year, commonly called the "100-year flood." For certain critical actions and decisions, such as planning or constructing a critical facility, the basis of risk decisions should be the flood that has a 0.2 percent probability of occurring in any given year, commonly called the "500-year flood."

The assigned frequency of a flood (e.g., 100-year) is independent of the number of years between actual occurrences. Hurricane Camille hit the Mississippi coast in 1969 with storm surge flooding that far exceeded previous events, and Hurricane Katrina affected much the same area. Although just 36 years apart, both storms produced flood levels significantly higher than the 100-year flood.

The term "100-year flood" as an expression of probability or frequency is often misunderstood because it conveys the impression that a flood of that magnitude will occur only once every 100 years. Actually, the 1-percent-annual-chance flood has one chance in 100 of occurring in any given year. The fact that a 1-percent-annual-chance flood is experienced at a specific location does not alter the probability that a comparable flood could occur at the same location in the next year, or even multiple times in a single year. As the length of the period increases, so does the probability that a flood of a specific magnitude or greater will occur. For example, during a 30-year period (the usual lending period for a home mortgage), the probability that a 100-year flood will occur is 26 percent. And during a 70-year period (the potential useful life of many buildings), the probability increases to 50 percent. Similarly, the 500-year flood has a 0.2-percent probability of being equaled or exceeded in any given year, and during a 70-year period the probability of occurrence is 18 percent.

Regardless of the flood selected for design purposes (the "design flood"), the designer must determine specific characteristics associated with that flood. Determining a flood with a specific probability of occurrence is done in a multi-step process that typically involves using computer models that are in the public domain. If a sufficiently long record of flood information exists, the design flood may be determined by applying statistical tools to the data. Alternatively, water resource engineers sometimes apply computer models to simulate different rainfall events over watersheds, to predict how much water will run off and accumulate in channels. Other computer models are used to characterize the flow of water down the watershed and predict how high the floodwaters will rise.

Flood frequency analyses are performed using historical records, and the results are influenced by the length of the record. Such analyses do not account for recent changes to the land (upland development or subsidence) or future changes (additional development, greater subsidence, or climatic variations).

For coastal areas, both historical storms and simulated storm surge models can be used to predict the probability that floodwaters will rise to a certain level and be accompanied by waves of certain heights. Many coastal storms will produce storm surge flooding that, depending on local topography, may extend inland significantly farther than anticipated for the 1-percent-annual-chance flood. Statistically, such extreme storm surges occur less frequently than the 1-percent or 0.2-percent-annual-chance floods, but their consequences can be catastrophic.

Planners and designers should research the relationship between the flood levels for different frequency events and extreme events, especially in hurricane-prone communities. The difference in flood levels may be extreme in some situations, depending on local conditions and the source of flooding. In other areas the lower probability flood depths might not be much higher than the 1-percent-annual-chance flood.

The National Flood Insurance Program (NFIP) is a Federal program that encourages communities to regulate flood hazard areas and, in return, offers property owners insurance protection against losses from flooding (see Sections 2.1.3.1 and 2.1.3.2). The NFIP uses the 1-percent-annual-chance flood as the basis for flood hazard maps, for setting insurance rates, and for application of regulations in order to minimize future flood damage. The 1-percent-annual-chance flood is also used as the standard for examination of older buildings to determine the measures to apply in order to reduce future damage.

Satisfying the minimum requirements of the NFIP does not provide adequate protection for critical facilities that need to be functional even after low probability events. Nearly every year, a very low probability flood occurs somewhere in the United States, often with catastrophic consequences. Therefore, for planning and design of critical facilities, use of a lower probability flood (at least the 500-year) is strongly recommended. As noted in Section 2.1.3.3, the 500-year level of protection is required if Federal funds are involved in constructing facilities that are vital for emergency response and rapid recovery, including hospitals, EOCs, emergency shelters, and other buildings that support vital services. This reinforces the importance of protecting both the functionality and financial investment in a critical facility with stricter standards than those applied to other buildings.

The Saffir-Simpson Hurricane Scale categorizes hurricanes based on sustained wind speeds (see Section 3.1.1). Storm surge is not always correlated with the category because other factors influence surge elevations, notably forward speed of the storm, tide cycle, offshore bathymetry, and land topography.

2.1.1.2 Hazard Identification and Flood Data

Flood hazard maps identify areas of the landscape that are subject to flooding, usually flooding by the 1-percent-annual-chance flood. Maps prepared by the NFIP are the minimum basis of State and local floodplain regulatory programs. Some States and communities have prepared maps of a floodplain based on the assumption that the upper watershed area is fully developed according to existing zoning. Some communities base their regulations on a flood of record or a historically significant flood that exceeds the base flood shown on the NFIP maps.

The flood hazard maps used by the appropriate regulatory authority should be consulted during planning and site selection, site design, and architectural and engineering design (whether for the design of new buildings or rehabilitation of existing buildings). Regardless of the flood hazard data required for regulatory purposes, additional research should be conducted on past major floods and other factors that could lead to more severe flooding.

The NFIP produces Flood Insurance Rate Maps (FIRMs) for more than 20,000 communities nationwide. FIRMs are prepared for each local jurisdiction that has been determined to have some degree of flood risk. The current effective maps are typically available for viewing in community planning or permit offices.[1] It is important to use the most recent flood hazard map when determining site-specific flood hazard characteristics. Although many FIRMs are more than 15 years old, often one or more panels or portions of a map panel have been revised and republished. Communities must adopt revised maps to continue participating in the NFIP.

It is important to note that the number of revised and updated FIRMs is increasing rapidly. During the last few years FEMA, in partnership with many States and communities, has been implementing an initiative to modernize and update all maps that are determined to be out of date. The modernization process may involve an examination of flood experience in the period since the original flood studies were prepared, use of more detailed topography and base maps, re-computation of flood discharges and flood heights, and re-delineation of flood hazard area boundaries.

Some FIRMs do not show the 0.2-percent-annual-chance flood hazard area (500-year floodplain), and many FIRMs do not provide detailed information about predicted flood elevations along every body of water, especially smaller streams and tributaries. Determining the 500-year flood is especially difficult when records of past flood events are limited. When existing data are insufficient, additional statistical methods and engineering analyses are necessary to determine the flood-prone areas and the appropriate characteristics of flooding required for site layout and building design.

If a proposed facility site or existing facility is affected by flooding, a site-specific topographic survey is critical to delineate the land that is below the flood elevation used for planning purposes. If detailed flood elevation information is not available, a floodplain study may be required to identify the important flood characteristics and data required for sound design. Having flood hazard areas delineated on a map conveys a degree of precision that may be misleading. Flood maps have a number of limitations that should be taken into consideration, especially during site selection and design of critical facilities. Some of the well-known limitations are:

- Flood hazard areas are approximations based on probabilities; the flood elevations shown and the areas delineated should not be taken as absolutes, in part because they are based on numerical approximations of the real world.

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[1] Flood maps may also be viewed at FEMA's Map Store at http://www.fema.gov. For a fee, copies may be ordered online or by calling (800) 358-9616. The Flood Insurance Study (FIS) and engineering analyses used to determine the flood hazard area may be ordered through the FEMA Web site.

- FIRMs and Flood Insurance Studies (FISs) are prepared to meet the requirements of the NFIP. For the most part, floodplains along smaller streams and drainage areas (less than 1 square mile) are not shown.

- Especially for older maps, the topography used to delineate the flood boundary may have had contour intervals of 5, 10, or even 20 feet, which significantly affects the precision with which the boundary is determined. The actual elevation of the ground relative to the flood elevation is critical, as opposed to whether an area is shown as being in or out of the mapped flood hazard area.

In communities along the Gulf and Atlantic coasts, facility owners, planners, and designers should check with emergency management offices for maps that estimate storm surge flooding from hurricanes. Local planning or engineering offices may have post-disaster advisory flood maps and documentation of past storm surge events. The FIRMs and regulatory design flood elevations (DFEs) do not reflect low probability/high magnitude flooding that may result from a hurricane making landfall at a specific location.

- Maps are based on the data available at the time they were prepared, and therefore do not account for subsequent upland development (new development that increases rainfall-runoff tends to increase flooding).

- The scale of the maps may impede precise determinations (many older maps are 1 inch = 2,000 feet).

- Flooding characteristics may have been altered by development, sometimes by upland development that has increased runoff, and other times by local modifications that have altered the shape of the land surface of the floodplain (such as fills or levees).

- Local conditions are not reflected, especially conditions that change regularly, such as stream bank erosion and shoreline erosion.

- Areas exposed to very low probability flooding are not shown, such as flooding

Designers and property owners in coastal regions should be aware that current FIRMs may not fully account for natural and manmade changes to beaches, wetlands, and other coastal environments (e.g., the erosion of protective dunes during the base flood). Since the original FIRMs were published in the early 1980s, FEMA has made significant improvements in the models and methods used to identify coastal flood hazards. Before any action is considered, the Flood Insurance Study report should be checked to verify that all pertinent hazards have been addressed. A coastal engineer or similar professional should be consulted if there are any questions concerning the coastal flood data.

from extreme hurricane storm surges, extreme riverine flooding, dam failures, or overtopping or failure of levees.

The flood hazard maps prepared by the NFIP show different flood zones to delineate different floodplain characteristics (see Figures 2-3 and 2-4). The flood zones shown on the NFIP maps, and some other designations, are as described below.

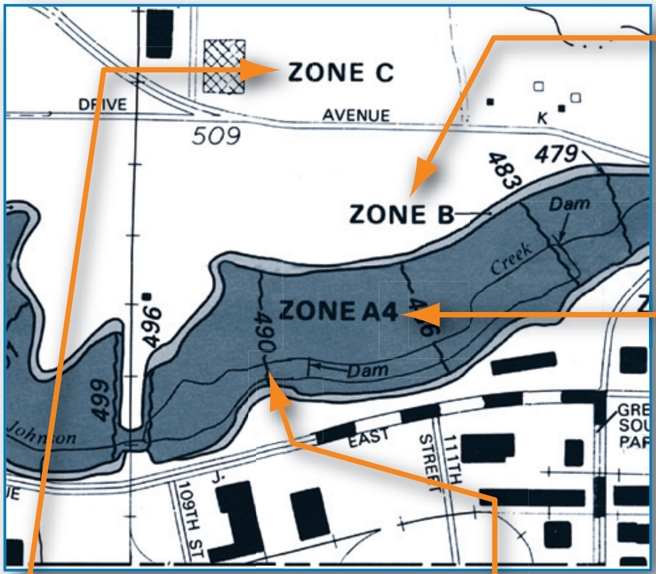
A Zones: (also called "unnumbered A Zones" or "approximate A Zones"). This designation is used for flood hazard areas where engineering analyses have not been performed to develop detailed flood elevations. Base flood elevations (BFEs) are not provided. Additional engineering analyses and site-specific assessments usually are required to determine the design flood elevation.

"Base flood elevation" is the elevation above a datum to which floodwaters are predicted to rise during the 1-percent-annual-chance flood (also called the "base flood" or the 100-year flood).

AE Zones or A1-A30 Zones: (also called "numbered A Zones"). These designations are used for flood hazard areas where engineering analyses have produced detailed flood elevations and boundaries for the base flood (1-percent-annual-chance flood). BFEs are provided. For riverine waterways with these zones, FISs include longitudinal profiles showing water surface elevations for different frequency flood events.

Floodways: The floodway includes the waterway channel and adjacent land areas that must be reserved in order to convey the discharge of the base flood without cumulatively increasing the water surface elevation above a designated height. Floodways are designated for most waterways that have AE Zones or numbered A Zones. FISs include data on floodway widths and mean floodway velocities.

AO and AH Zones: These zones include areas of shallow flooding and are generally shown where the flood depth averages from 1 to 3 feet, where a clearly defined channel does not exist, where the path of flooding is unpredictable, and where velocity flow may be evident. These zones are characterized by ponding or sheetflow. BFEs may be provided for AH Zones; flood depths may be specified in AO Zones.



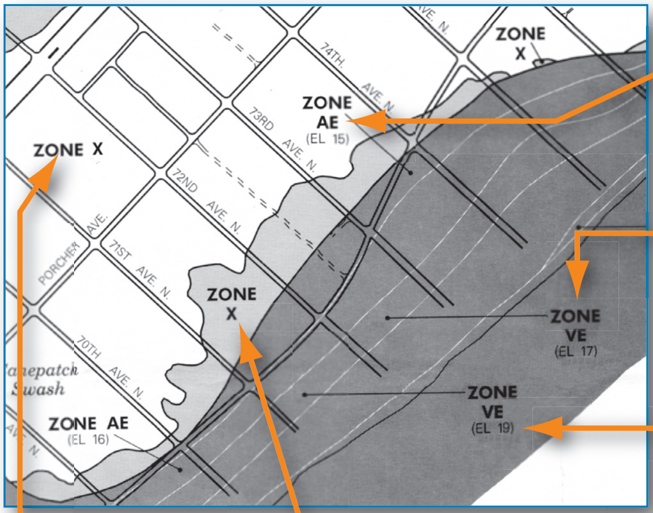
Zone B (or shaded Zone X) is subject to flooding by the 500-year flood (0.2 percent annual chance), and is a moderate risk area.

Zone A, A Zones A1-A30, and **Zone AE** are subject to flooding by the base of the 1percent annual chance (100-year) flood, and are considered high-risk areas.

Zone C (or Zone X) is all other areas, considered low-risk.

Base Flood Elevation (BFE), is the predicted water surface elevation of the base flood at specific locations (in feet above the datum).

Figure 2-3: Riverine flood hazard zones



Zone A, A Zones A1-A30, and **Zone AE** are subject to flooding by the base or 100-year flood (1percent annual chance), and waves less than 3 feet.

Zone V, V Zones V1-V30, and **Zone VE** are where waves are expected to be 3 feet or more.

Base Flood Elevation (BFE) is the predicted water surface elevation (in feet above datum).

Zone X
is all other areas.

Shaded Zone X
(or Zone B) is subject to flooding by the 500-year flood (0.2 percent annual chance).

Figure 2-4: Coastal flood hazard areas

Shaded X (or B) Zones: This zone shows areas of the 500-year flood (0.2-percent-annual-chance flood), or areas protected by flood control levees. This zone is not shown on many NFIP maps; its absence does not imply that flooding of this frequency will not occur.

Unshaded X (or C) Zones: These zones are all land areas not mapped as flood hazard areas that are outside of the floodplain and designated for the purposes of regulating development pursuant to the NFIP. These zones may still be subject to small stream flooding and flooding from local drainage problems.

V Zones (V, VE, and V1-V30): Also known as coastal high-hazard areas or special flood hazard areas subject to high-velocity wave action. V Zones are relatively narrow areas along open coastlines and some large lake shores that are subject to high-velocity wave action from storms or seismic sources. V Zones extend from offshore to the inland limit of a primary frontal dune, or to an inland limit where the height of breaking waves drops below 3 feet.

Coastal A Zone: This zone, which is not delineated on NFIP maps, is where the potential of breaking wave heights is between 1.5 feet and 3 feet during base flood conditions. Coastal A Zones are landward of the mapped V Zone, or landward of open coasts that do not have a V Zone because breaking waves are predicted to be less than 3 feet high. In these areas, the principal sources of flooding are tides, storm surges, seiches, or tsunamis, not riverine flooding.

Coastal A Zone: The current editions of the model building codes refer to ASCE 7 and ASCE 24, which are two design standards that include requirements for Coastal A Zones that account for the increased risk from the additional wave height (see Section 2.3.2).

Flood hazards and characteristics of flooding must be identified to evaluate appropriately the impact of site development, to calculate flood loads, to design floodproofing measures, and to identify and prioritize retrofit measures for existing critical facilities. Table 2-3 in Section 2.5 outlines a series of questions to facilitate this objective.

Many characteristics of flooding are not shown on the FIRMs but may be found in the FIS or the study or report prepared by the entity that produced the flood hazard map. Hurricane storm surge inundation maps based on the National Hurricane Center models have been prepared by the U.S. Army Corps of Engineers for most reaches of the Atlantic and Gulf coasts. The maps combine the results of many scenarios to show the maximum potential surge inundation associated with different categories of hurricanes. State and local emergency management offices use the maps for evacuation planning.

Hurricanes can produce storm surge flooding and waves that rise much higher than the BFE shown on the FIRMs.

2.1.1.3 Design Flood Elevation

The DFE establishes the minimum level of flood protection that must be provided. The DFE, as used in the model building codes, is defined as either the BFE determined by the NFIP and shown on FIRMs, or the elevation of a design flood designated by the community, whichever is higher. The DFE will always be at least as high as the BFE. Communities may use a design flood that is higher than the base flood for a number of reasons. For example, a design flood may be used to account for future upland development, to recognize a historic flood, or to incorporate a factor of safety, known as freeboard.

"Freeboard" is a factor of safety usually expressed in feet above a flood level. Freeboard compensates for the many unknown factors that could contribute to flood heights, such as wave action, constricting bridge openings, and the hydrological effect of urbanization of the watershed. A freeboard from 1 to 3 feet is often applied to critical facilities.

Facility owners, planners, and designers should check with the appropriate regulatory authority to determine the minimum flood elevation to be used in site planning and design. Although the NFIP minimum is the BFE, State or local regulations commonly cite the 0.2-percent-annual-chance flood (500-year flood) as the design requirement for critical facilities, or the regulations may call for added freeboard above the minimum flood elevation. Even if there is no specific requirement to use the 0.2-percent-annual-chance flood for siting and design purposes, it is strongly recommended that decisionmakers take into consideration the flood conditions associated with this lower probability event or from other floods of record.

2.1.1.4 Advisory Base Flood Elevation

The flood maps and flood hazard data described in Section 2.1.1.2 are the minimum information required to be used for regulatory purposes. The updating of FIRMs is a continuous process and it relies heavily on examination of storm event data and physical changes to the landscape. If significant flood events have occurred since the effective date of the FIRM, these events may change the statistical analyses, which would then prompt an update of the flood maps and produce revised elevations for the 1-percent-annual-chance flood. Critical facility owners, planners, and designers should contact community officials to determine whether there have been any significant flood events or other changes that may affect flood hazards since the effective date of the FIRM. The best available information should be used at all times.

FEMA works closely with communities to develop new flood hazard data or revise existing data during the standard flood study process. Updating flood hazard data includes the analysis of historical data. If a major flood event significantly alters the physical environment or if it is determined to be statistically significant, FEMA may decide to release Advisory BFEs (ABFEs) and Flood Recovery Maps (see Figure 2-5).

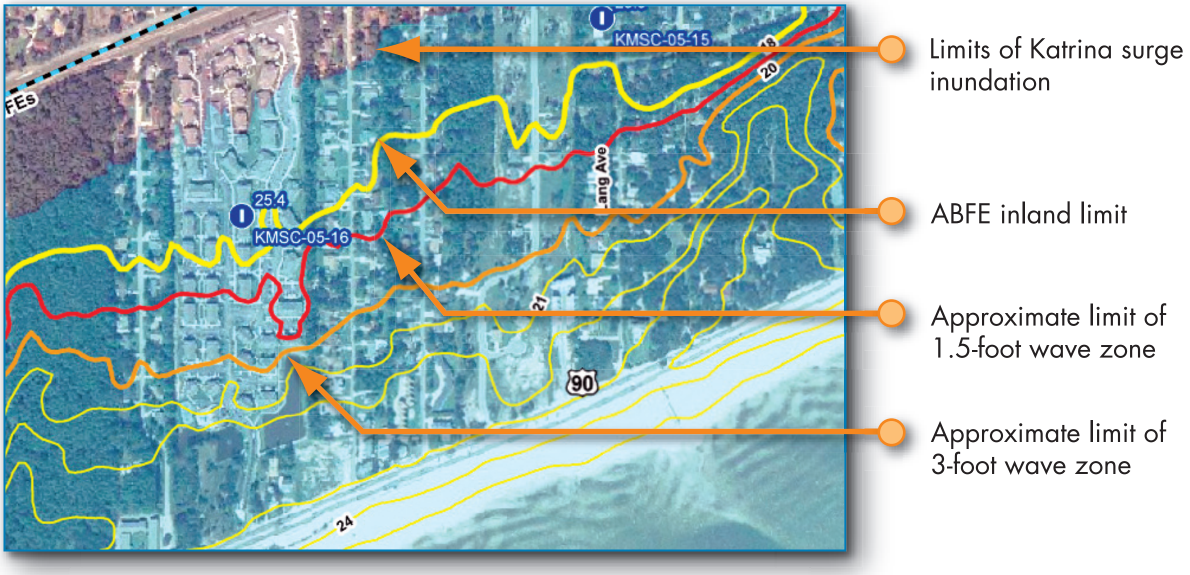


Figure 2-5: Example of a flood recovery map showing ABFEs and other flood hazard information.

After Hurricane Katrina, FEMA expedited development of Flood Recovery Maps and ABFEs for the Mississippi coast—the new maps were delivered just 3 months after the storm.

ABFEs represent the best estimate of the expected 1-percent-annual-chance flood elevations. They are provided as interim flood hazard information until more detailed flood hazard data become available. Flood Recovery Maps depict the ABFEs, and in general, reflect additional information such as inundation limits and surveyed high water marks (but not the 500-year flood hazard area). For coastal areas, the Flood Recovery Maps may also show the inland debris line and the limit of the 1.5-foot wave (Coastal A Zone).

When ABFEs and Flood Recovery Maps are produced and released, FEMA strongly encourages States and communities, as well as private property owners and critical facility owners, to use the information to make decisions about reconstruction until more definitive data become available. FEMA issues guidance to help the users apply the updated flood elevation information at specific locations.

After Flood Recovery Maps are released, FEMA begins the formal process of updating the FIRMs. The community and property owners are notified through public notices and meetings when the preliminary revised maps are available and a formal comment period is opened. The final maps are prepared after consideration of comments. Communities are required to adopt and use the revised FIRMs in order to continue their participation in the NFIP.

2.1.2 FLOOD LOADS

Floodwaters can impose a variety of loads on buildings and building elements. This section provides a brief overview of flood loads and factors that are important for calculating flood loads, including:

❍ Hydrostatic loads, including buoyancy, which increase as the depth of water increases

❍ Hydrodynamic loads, which result from moving water

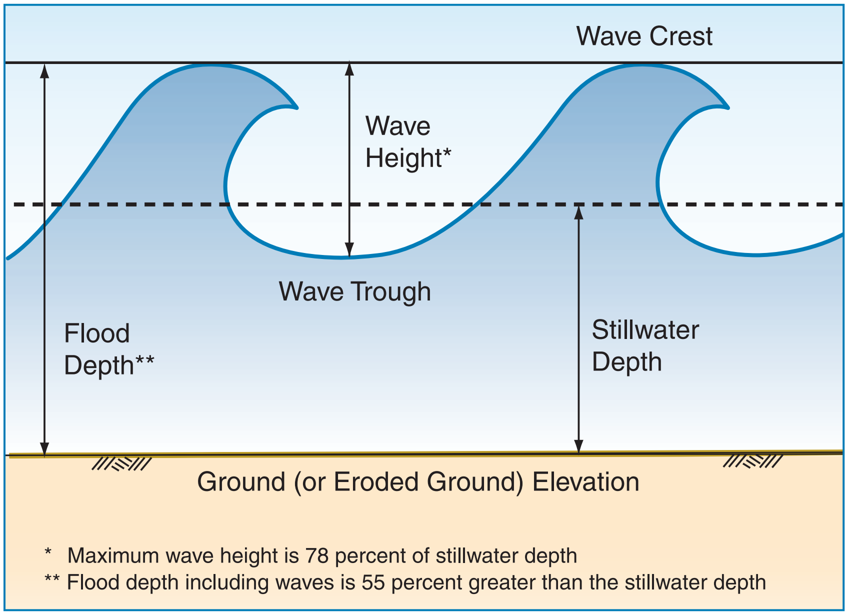
- Breaking wave loads, which are most likely to occur in coastal areas
- Impact loads resulting from floating debris striking a building or building element
- Long-term erosion and localized scour, which can increase the effects and magnitudes of other loads

2.1.2.1 Design Flood Depth

Water depth associated with the design flood is computed by determining the DFE (see Section 2.1.1.3 or 2.1.1.4) and subtracting the elevation of the ground at the building site. Since these elevation data usually are obtained from different sources, it is important to determine whether they are based on the same datum. If not, standard corrections must be applied.

Flood depth is the most important factor required to compute flood loads, because almost every other flood load calculation depends directly or indirectly on this factor. In riverine areas, the flood depth rarely accounts for waves. In coastal areas, the total flood depth is composed of a “stillwater” depth, plus the expected height of waves (see Figure 2-6).

Figure 2-6:
Definition sketch—wave height and stillwater depth



The following characteristics that may add to the flood depth should be taken into consideration.

Waves and storm-induced erosion are most common in coastal areas. However, wide rivers and lakes may experience wind-driven waves and erodible soils are found throughout the United States. For more information about waves and erosion, refer to FEMA 55, *Coastal Construction Manual*.

Small waves: In Coastal A Zones (see Section 2.3.2), the DFE shown on FEMA's maps does not include the wave height. Coastal A Zones are characterized by 1.5- to 3-foot high waves. The flood depth should be increased by 3 feet for sites close to the V Zone boundary or the shoreline. For sites farther inland, where the flood depth is at least 3 feet, it should be increased by 1.5 feet. Interpolation may be used to determine the amount that should be added to the flood depth to account for waves in the Coastal A Zone.

Erosion and scour: Flood depths in areas with erodible soils should consider the effects of erosion where floodwaters lower the ground surface or cause local scour around foundation elements. In these areas, the flood depth determined using the design flood elevation should be increased to account for changes in conditions during a flood event. Not only does lowering the ground surface effectively result in deeper water against the foundation, it may also remove supporting soil from the foundation, which must be accounted for in the foundation design.

2.1.2.2 Design Flood Velocity—Riverine

There are few sources of information that are readily available for estimating design flood velocities at specific locations along riverine bodies of water. If a riverine source has been studied using detailed hydraulic methods, some information may be available in summary form in published studies. Studies prepared for the NFIP (see Section 2.1.1.2) contain tables of data for waterways for which floodways were delineated. For specified cross-sections along the waterway, the Floodway Data Table includes a mean velocity expressed in feet per second. This value is the average of all velocities across the floodway. Generally, velocities in the flood fringe (landward of the floodway) will be lower than in the floodway.

For waterways without detailed studies, methods that are commonly used in civil engineering for estimating open channel flow velocities can be applied.

2.1.2.3 Design Flood Velocity—Coastal

Estimating design flood velocities in coastal flood hazard areas is subject to considerable uncertainty, and there is little reliable historical information or measurements from actual coastal flood events. In this context, velocity does not refer to the motion associated with breaking waves, but the speed of the mass movement of floodwater over an area.

The direction and velocity of floodwaters can vary significantly throughout a coastal flood event. Floodwaters can approach a site from one direction as a storm approaches, then shift to another direction (or through several directions) as the storm moves through the area. Floodwaters can inundate some low-lying coastal sites from both the front (e.g., ocean) and the back (e.g., bay, sound, or river). In a similar manner, at any given site, flow velocities can vary from close to zero to very high. For these reasons, when determining flood loads for building design, velocities should be estimated conservatively and it should be assumed that floodwaters can approach from the most critical direction and that flow velocities can be high.

Despite the uncertainties, there are methods to approximate coastal flood velocities. One common method is based on the stillwater depth (flood depth without waves). Designers should consider the topography, the distance from the source of flooding, and the proximity to other buildings and obstructions before selecting the flood velocity for design. Those factors can direct and confine floodwaters, with a resulting acceleration of velocities. This increase in velocities is described as the "expected upper bound." The "expected lower bound" velocities are experienced in areas where those factors are not expected to influence the direction and velocity of floodwaters.

Upper bound velocities caused by Hurricane Katrina along the Mississippi coast, where storm surge depths neared 35 feet deep, have been estimated at nearly 30 feet per second (20 miles per hour).

Figure 2-7 shows the general relationship between velocity and stillwater depth. For design purposes, actual flood velocities are assumed to lie between the upper and lower bounds. Conservative designs will take into account the upper bound velocities.

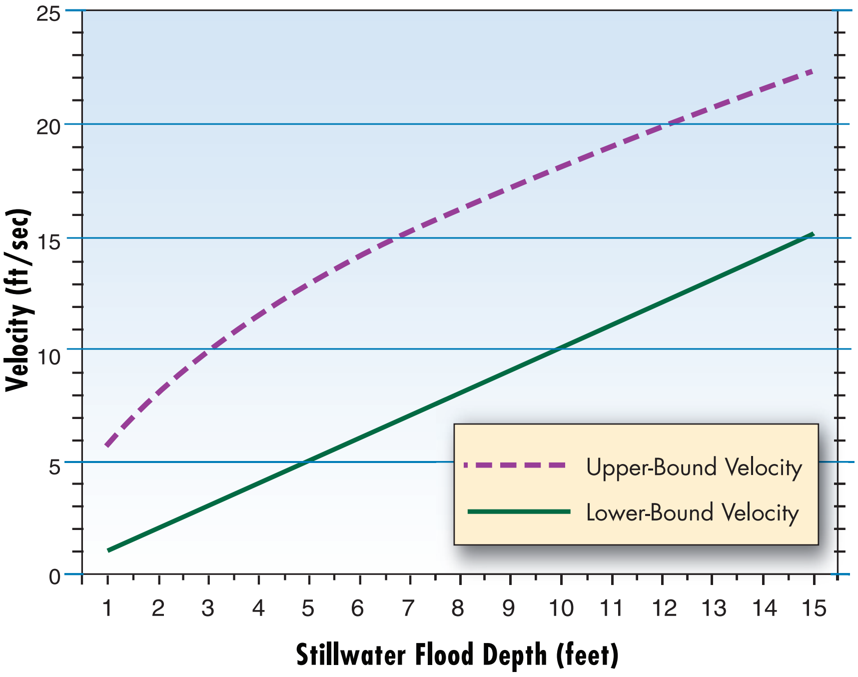


Figure 2-7:
Velocity as a function of stillwater flood depth

2.1.2.4 Hydrostatic Loads

Hydrostatic loads occur when water comes into contact with a building or building component, both above and below the ground level. They act as lateral pressure or vertical pressure (buoyancy). Hydrostatic loads on inclined or irregular surfaces may be resolved into lateral and vertical loads based on the surface geometry and the distribution of hydrostatic pressure.

Lateral hydrostatic loads are a direct function of water depth (see Figure 2-8). These loads can cause serious deflection or displacement of buildings or building components if there is a substantial difference in water levels on opposite sides of the component (or inside and outside of the building). Hydrostatic loads are balanced on foundation elements of elevated buildings, such as piers and columns, because the element is surrounded by water. If not oriented parallel to the flow of water, shearwalls may experience hydrostatic loads due to a difference of water depth on either side of the wall. To reduce excessive pressure from standing water, floodplain management requirements in A Zones call for openings in walls that enclose areas below the flood elevation (see description of continuous perimeter wall foundation in Section 2.3.1.2).

Buoyant forces resulting from the displacement of water are also of concern, especially for dry floodproofed buildings and aboveground and underground tanks. Buoyancy force is resisted by the dead load of the building or the weight of the tank. When determining buoyancy force, the weight of occupants or other live loads (such as the contents of a tank) should not be considered. If the building or tank does not weigh enough "empty," then additional stabilizing measures need to be taken to avoid flotation. This becomes a significant consideration for designs intended to dry floodproof a building. Buoyancy force is slightly larger in saltwater, because saltwater weighs slightly more than fresh water.

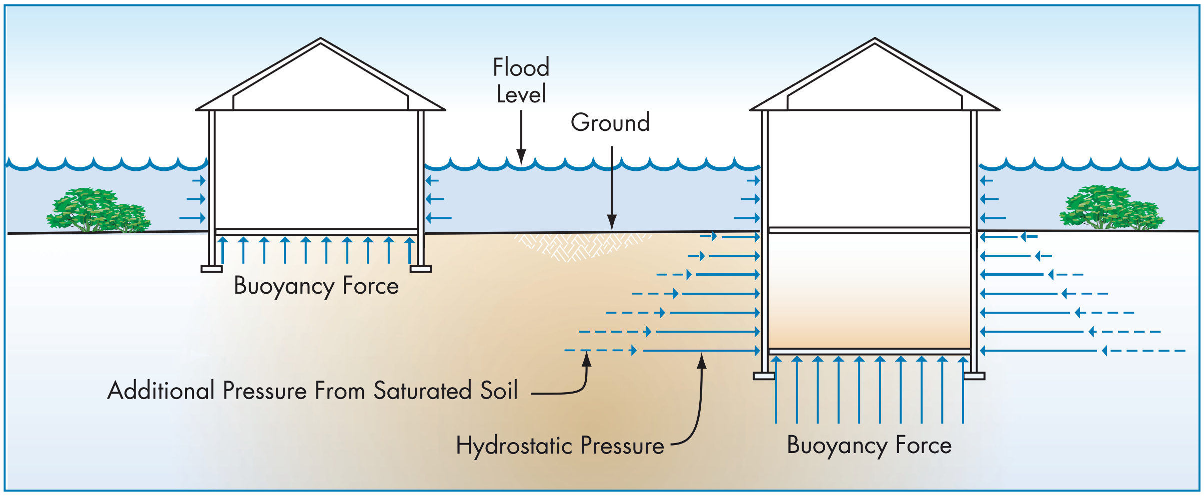


Figure 2-8: Hydrostatic loads on buildings

2.1.2.5 Hydrodynamic Loads

Water flowing around a building or a structural element that extends below the flood level imposes hydrodynamic loads. The loads, which are a function of flow velocity and structure geometry, include frontal impact on the upstream face, drag along the sides, and suction on the downstream side (see Figure 2-9). Ways to determine or estimate flood velocities are described in Section 2.1.2.2 and Section 2.1.2.3.

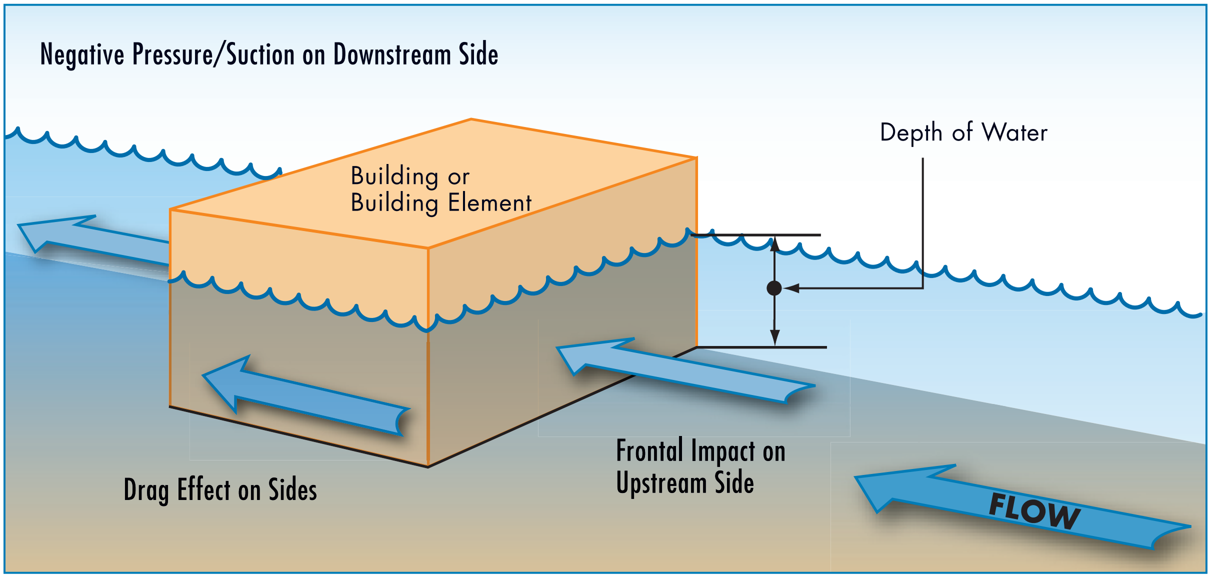


Figure 2-9: Hydrodynamic loads on a building or building element

The most common computation methods for hydrodynamic loads are outlined in the design standard *Minimum Design Loads for Buildings and Other Structures*, produced by the American Society of Civil Engineers' Structural Engineers Institute (ASCE/SEI, 2005). Those methods assume that the flood velocity is constant (i.e., steady state flow) and that the dynamic load imposed by floodwaters moving at less than 10 feet per second can be converted to an equivalent hydrostatic load. This conversion is accomplished by adding an equivalent surcharge depth to the depth of water on the upstream side. The equivalent surcharge depth is a function of the velocity. Loads imposed by floodwaters with velocities greater than 10 feet per second cannot be converted to equivalent hydrostatic loads. Instead, they must be determined according to the principles of fluid mechanics or hydraulic models.

Hydrodynamic loads become important when flow reaches moderate velocities of 5 feet per second. The components of hydrodynamic loads are laterally imposed, caused by the impact of the mass of water against the building, and drag forces along the wetted surfaces. Drag coefficients for common building elements, such as columns and piers, can be found in a number of sources. ASCE 7 recommends values for a variety of conditions.

Another component of hydrodynamic loads is wave loads. As described in ASCE 7, "design and construction of buildings and other structures subject to wave loads shall account for the following loads: waves breaking on any portion of the building or structure; uplift forces caused by shoaling waves beneath a building or structure, or portion thereof; wave runup striking any portion of the building or structure; wave-induced drag and inertia forces; and wave-induced scour at the base of a building or structure, or its foundation."

Wave forces striking buildings and building elements can be 10 to 100 or more times higher than wind forces and other forces. Forces of this magnitude can be substantial, even when acting over the relatively small surface area of the supporting structure of elevated buildings. Post-storm damage inspections show that breaking wave loads overwhelm virtually all wood-frame and unreinforced masonry walls below the wave crest elevation. Only engineered and massive structural elements are capable of withstanding breaking wave loads. The magnitude of wave forces is the rationale behind the floodplain management requirement for the bottom of the lowest horizontal structural member to be at or above the design flood elevation in environments where waves are predicted to be 3 feet or higher (V Zones). Because waves as low as 1.5 feet can impose considerable loads, there is a growing awareness of the value of accounting for waves in areas that are referred to as "Coastal A Zones."

Computation of wave loads depends on the determination of wave height. Equations for wave height are based on the assumption that waves are depth-limited (on the order of 75 to 80 percent of stillwater depth) and that waves propagating into shallow water break when the wave height reaches a certain proportion of the underlying stillwater depth. These assumptions are used by FEMA to determine coastal high hazard areas (V Zones) where breaking waves are predicted to be 3 feet or higher. At any given site, wave heights may be moderated by other factors. Designers should refer to ASCE 7 for detailed discussion and computation procedures.

Breaking wave loads on vertical walls or supporting structural members reach a maximum when the direction of wave approach is perpendicular to the wall. The duration of individual loads is brief, with peak pressures probably occurring within 0.1 to 0.3 seconds after the wave breaks. It is common to assume that the direction of approach will be perpendicular to the shoreline, in which case the orientation of the wall to the shoreline will influence the magnitude of the load placed on the wall. ASCE 7 provides a method for reducing breaking wave loads on vertical walls for waves that approach a building from a direction other than straight on. Structures should be designed for repetitive impact loads that occur during a storm. Some storms may last for just a few hours, as hurricanes move through the area, or for several days, as during some winter coastal storms (nor'easters) that affect the Mid-Atlantic and northeastern States.

2.1.2.6 Debris Impact Loads

Debris impact loads are imposed on a building or building elements by objects carried by moving water. Objects commonly carried by floodwaters include trees, dislodged tanks, and remnants of manmade structures such as docks and buildings (see Figure 2-10). Extreme impact loads result from less common sources, such as shipping containers, boats, and barges. The magnitude of these loads is very difficult to predict, yet some reasonable allowance should be made during the design process.

Impact loads are influenced by the location of the building in the potential debris stream. The potential for debris impacts is significant if a building is located immediately adjacent to, or downstream from, other buildings, among closely-spaced buildings, or downstream from large floatable objects. While these conditions may be observable in coastal areas, it is more difficult to estimate the potential for debris in riverine flood hazard areas. Any riverine waterway, whether a large river or smaller urban stream, can carry large quantities of debris, especially uprooted trees.

Figure 2-10:
The South Cameron Memorial Hospital, Cameron, LA, was damaged by debris carried by Hurricane Katrina's storm surge (2005).

SOURCE: LSU AGCENTER

The basic equation for estimating the magnitude of impact loads depends on several variables that must be selected by the designer. These variables include several coefficients, building or building element stiffness, debris weight, debris velocity, and duration of impact. The latter three variables, described in more detail in ASCE 7, are briefly described below.

Debris weight: Debris weight is one of the more difficult variables to estimate. Unless otherwise indicated by field conditions, ASCE 7 recommends using an average object weight of 1,000 pounds. This weight corresponds to a 30-foot long log only 1 foot in diameter, small in comparison to large trees that may be uprooted during a flood. In coastal areas, expected debris weights depend on the nature of the debris. In the Pacific Northwest, large trees and logs are common, with weights in excess of 4,000 pounds. In areas where piers and pilings are likely to become debris, 1,000 pounds is reasonable. In areas where most debris is likely to result from building damage (failed decks, steps, failed walls, propane tanks), the average debris weight may be less than 500 pounds.

Debris velocity: The velocity of the debris depends on the nature of the debris and the velocity of floodwaters. For the impact load computation, the velocity of the water-borne object is assumed to be the same as the flood velocity. Although this assumption is reasonable for smaller objects, it is conservative for large objects.

Debris impact duration: Duration of impact is the elapsed time during which the impact load acts on the building or building element. The duration of impact is influenced primarily by the natural frequency[2] of the building or element, which is a function of the building's stiffness. Stiffness is determined by the properties of the material, the number of supporting members (columns or piles), the height of the building above the ground, and the height at which the element is struck. Despite all the variables that may influence duration of impact, early assumptions suggested a 1-second duration. A review of results from several laboratory tests that measured impacts yielded much briefer periods, and ASCE 7 currently recommends a duration of 0.03 second.

2.1.2.7 Erosion and Localized Scour

Erosion generally refers to a lowering of the ground surface as a result of a flood event. Erosion may occur in riverine and coastal flood hazard areas. In coastal areas, erosion may affect the general ground surface and may cause a short-term or long-term recession of the shoreline. Erosion should be considered during load calculations, because it increases the local flood depth, which in turn influences load calculations. In areas subject to gradual erosion of the ground surface, additional foundation embedment depth can mitigate the effects. However, where waterways are prone to changing channels and where shoreline erosion is significant, engineered solutions are unlikely to be effective. Avoidance of sites in areas subject to active erosion is the safest and most cost-effective course of action.

Localized scour results from turbulence at the ground level around foundation elements. Scour occurs in both riverine and coastal flood hazard areas, especially in areas with erodible soils.

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[2] The frequency at which an object will vibrate freely when set in motion.

Determining potential scour is critical in the design of foundations to ensure that failure during and after flooding does not occur as a result of the loss in either bearing capacity or anchoring resistance around the posts, piles, piers, columns, footings, or walls (see Figure 2-11). Scour determinations require knowledge of the flood depth, flow conditions, soil characteristics, and foundation type.

At some locations, soil at or below the ground surface can be resistant to localized scour, and calculated scour depths based on unconsolidated surface soils below will be excessive. In instances where the designer believes the underlying soil at a site will be scour-resistant, the assistance of a geotechnical engineer or geologist should be sought.

Figure 2-11:
Local scour undermined this shallow foundation (also note that the building was not anchored to the foundation).

2.1.3 FLOODPLAIN MANAGEMENT REQUIREMENTS AND BUILDING CODES

The NFIP is the basis for the minimum requirements included in model building codes and standards for design and construction methods to resist flood damage. The original authorizing legislation for the NFIP is the National Flood Insurance Act of 1968 (42 U.S.C. 4001 et seq.). In that act, Congress expressly found that “a program of flood insurance can promote the public interest by encouraging sound land use by minimizing exposure of property to flood losses…”

The most convincing evidence of the effectiveness of the NFIP minimum requirements is found in flood insurance claim payment statistics. Buildings that pre-date the NFIP requirements are, by and large, not constructed to resist flood damage. Buildings that post-date the NFIP (i.e., those that were constructed after a community joined the program and began applying the minimum requirements) are designed to resist flood damage. The NFIP reports that aggregate loss data indicate that buildings that meet the minimum requirements experience 70 percent less damage than buildings that pre-date the NFIP. There is ample evidence that buildings designed to exceed the minimum requirements are even less likely to sustain damage.

2.1.3.1 Overview of the NFIP

The NFIP is based on the premise that the Federal government will make flood insurance available in communities that agree to recognize and incorporate flood hazards in land use and development decisions. In some States and communities this is achieved by guiding development to areas with a lower risk. When decisions result in development within flood hazard areas, application of the criteria set forth in Federal regulation 44 CFR §60.3 are intended to minimize exposure and flood-related damage. State and local governments are responsible for applying the provisions of the NFIP through the regulatory permitting processes. At the Federal level, the NFIP is managed by FEMA and has three main elements:

- Hazard identification and mapping, under which engineering studies are conducted and flood maps are prepared in partnership with States and communities. These maps delineate areas that are predicted to be subject to flooding under certain conditions.

- Floodplain management criteria for development, which establish the minimum requirements to be applied to development within mapped flood hazard areas. The intent is to recognize hazards in the entire land development process.

❍ Flood insurance, which provides some financial protection for property owners to cover flood-related damage to buildings and contents.

"Substantial damage" is damage of any origin sustained by a structure whereby the cost of restoring the structure to its condition before the damage would equal or exceed 50 percent of the market value of the structure before the damage occurred.

"Substantial improvement" is any repair, reconstruction, rehabilitation, addition, or improvement of a building, the cost of which exceeds 50 percent of the market value of the building before the improvement or repair is started (certain historic structures may be excluded).

Federal flood insurance is intended to shift some of the costs of flood disasters away from the taxpayer by providing property owners an alternative to disaster assistance and disaster loans. Disaster assistance provides limited funding for repair and cleanup, and is available only after the President signs a major disaster declaration for the area. NFIP flood insurance claims are paid any time damage from a qualifying flood event[3] occurs, regardless of whether a major disaster is declared. Community officials should be aware that public buildings may be subject to a mandated reduction in disaster assistance payments if the building is in a mapped flood hazard area and is not covered by flood insurance.

Another important objective of the NFIP is to break the cycle of flood damage. Many buildings have been flooded, repaired or rebuilt, and flooded again. Before the NFIP, in some parts of the country this cycle occurred every couple of years, with reconstruction taking place in the same flood-prone areas, using the same construction techniques that did not adequately resist flood damage. NFIP provisions guide development to lower risk areas by requiring compliance with performance measures to minimize exposure of new buildings and buildings that undergo major renovation or expansion (called "substantial improvement" or repair of "substantial damage"). This achieves the long-term objective of building disaster-resistant communities.

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[3] For the purpose of adjusting claims for flood damage, the NFIP defines a flood as "a general and temporary condition of partial or complete inundation of two or more acres of normally dry land area or of two or more properties (at least one of which is the policyholder's property) from: overflow of inland or tidal waters; unusual and rapid accumulation or runoff of surface waters from any source; mudflow; or collapse or subsidence of land along the shore of a lake or similar body of water as a result of erosion or undermining caused by waves or currents of water exceeding anticipated cyclical levels that result in a flood as defined above."

2.1.3.2 Summary of the NFIP Minimum Requirements

The performance requirements of the NFIP are set forth in Federal regulation 44 CFR Part 60. The requirements apply to all development, which the NFIP broadly defines to include buildings and structures, site work, roads and bridges, and other activities. Buildings must be designed and constructed to resist flood damage, which is primarily achieved through elevation (or floodproofing). Additional specific requirements apply to existing development, especially existing buildings. Existing buildings that are proposed for substantial improvement, including restoration following substantial damage, are subject to the regulations.

Although the NFIP regulations primarily focus on how to build structures, one of the long-term objectives of the program is to guide development to less hazardous locations. Preparing flood hazard maps and making the information available to the public is fundamental in satisfying that objective. With that information, people can make informed decisions about where to build, how to use site design to minimize exposure to flooding, and how to design buildings that will resist flood damage.

The NFIP's broad performance requirements for site work in flood hazard areas are as follows:

- Building sites shall be reasonably safe from flooding.
- Adequate site drainage shall be provided to reduce exposure to flooding.
- New and replacement sanitary sewage systems shall be designed to minimize or eliminate infiltration of floodwaters into the systems and discharges from the systems into floodwaters.
- Development in floodways shall be prohibited, unless engineering analyses show that there will be no increases in flood levels.

The NFIP's broad performance requirements for new buildings proposed for flood hazard areas (and substantial improvement of existing flood-prone buildings) are as follows:

- ❍ Buildings shall be designed and adequately anchored to prevent flotation, collapse, or lateral movement resulting from hydrodynamic and hydrostatic loads, including the effects of buoyancy.
- ❍ Building materials used below the design flood elevation shall be resistant to flood damage.
- ❍ Buildings shall be constructed to minimize flood damage (primarily by elevating to or above the base flood level, or by specially designed and certified floodproofing measures).
- ❍ Buildings shall be constructed with electrical, heating, ventilation, plumbing, and air conditioning equipment and other service facilities designed to prevent water from entering or accumulating within the components.

Owners, planners and designers should determine if there are any applicable State-specific requirements for floodplain development. Some States require that local jurisdictions apply standards that exceed the minimum requirements of the NFIP. In particular, some States require that critical facilities be located outside of the floodplain (including the 500-year floodplain) or they are to be designed and constructed to resist conditions associated with the 500-year flood. Some States have regulations that impose other higher standards, while some States have direct permitting authority over certain types of construction or certain types of applicants.

States often use governors' executive orders to influence State-constructed and State-funded critical facilities, requiring location outside of the 500-year floodplain where feasible, or protection to the 500-year flood level if avoiding the floodplain is not practical. In 2004, a review of State and local floodplain management programs determined that Alabama, Illinois, Michigan, New York, North Carolina, Ohio, and Virginia have requirements for critical facilities (ASFPM, 2004).

As participants in the NFIP, States are required to ensure that development that is not subject to local regulations, such as State construction, satisfies the same performance requirements. If critical facilities are exempt from local permits, this may be accomplished through a State permit, a governor's executive order, or other mechanisms that apply to entities not subject to local authorities.

2.1.3.3 Executive Order 11988 and Critical Facilities

When Federal funding is provided for the planning, design, and construction of new critical facilities, or for the repair of existing critical facilities located within the 500-year floodplain, the funding agency is required to address additional considerations. Executive Order 11988, Floodplain Management, requires Federal agencies to apply a decisionmaking process to avoid, to the extent possible, the long- and short-term adverse impacts associated with the occupancy and modification of floodplains, and to avoid the direct or indirect support of floodplain development whenever there is a practicable alternative. If there is no practicable alternative, the Federal agency must minimize any adverse impacts to life, property, and the natural and beneficial functions of floodplains.

The executive order establishes the base flood elevation as the minimum standard for all Federal agencies. Implementation guidance specifically addresses "critical actions," which are described as those actions for which even a slight chance of flooding would be too great. The construction or repair of critical facilities, such as fire stations, hospitals and clinics, EOCs, the storage of hazardous wastes, and the storage of critical records, are examples of critical actions.

After determining that a site is in a mapped flood hazard area, and after giving public notice, the Federal funding agency is required to identify and evaluate practicable alternatives to locating a critical facility in a 500-year floodplain. If the Federal agency has determined that the only practicable alternative is to proceed, then the impacts of the proposed action must be identified. If the identified impacts are harmful to people, property, and the natural and beneficial functions of the floodplain, the Federal

FEMA's eight-step decisionmaking process for complying with Executive Order 11988 must be applied before Federal disaster assistance is used to repair, rehabilitate, or reconstruct damaged existing critical facilities in the 500-year floodplain.

agency is required to minimize the adverse effects on the floodplain and the funded activity.

Having identified the impacts of the proposed action and the methods to minimize these impacts, the Federal agency is required to re-evaluate the proposed action. The re-evaluation must consider whether the action is still feasible, whether the action can be modified to relocate the facility or eliminate or reduce identified impacts, or if a “no action” alternative should be chosen. If the finding results in a determination that there is no practicable alternative to locating a critical facility in the floodplain, or otherwise affecting the floodplain, then a statement of findings and a public explanation must be provided.

2.1.3.4 Scope of Model Building Codes and Standards

The *International Building Code* (IBC, 2003) and the *Building Construction and Safety Code*™ (NFPA 5000, 2003) were the first model codes to include comprehensive provisions that address flood hazards. Both codes are consistent with the minimum provisions of the NFIP that pertain to the design and construction of buildings. The NFIP requirements that pertain to site development, floodways, coastal setback lines, erosion-prone areas, and other environmental constraints are found in other local ordinances. The codes require designers to identify and design for anticipated environmental loads and load combinations, including wind, seismic, snow, and flood loads, as well as the soil conditions.

The IBC and NFPA 5000 incorporate by reference a number of standards that are developed through a rigorous consensus process. The best known is *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-05). The model building codes require that applicable loads be accounted for in the design. The 1998 edition of ASCE 7 was the first version of the standard to include flood loads explicitly, including hydrostatic loads, hydrodynamic loads (velocity and waves), and debris impact loads.

The IBC and NFPA 5000 also incorporate by reference a standard that was first published by ASCE in 1998 and revised in 2005, *Flood Resistant Design and Construction* (ASCE/SEI 24-05).

Developed through a consensus process, ASCE 24 addresses specific topics pertinent to designing buildings in flood hazard areas, including floodways, coastal high hazard areas, and other high-risk flood hazard areas such as alluvial fans, flash flood areas, mudslide areas, erosion-prone areas, and high floodwater velocity areas.

Section 1.2 describes the four categories used by ASCE 7 to classify structures based on occupancy; different requirements apply based on a structure's category. The same categories are used in ASCE 24 and different flood-resistant requirements apply to the different categories. Table 2-1 summarizes the elevation requirements of ASCE 24 that exceed the NFIP minimum requirements for the critical facilities addressed by this manual (Category III or Category IV structures).

ASCE 7-05 outlines methods to determine design loads and load combinations in flood hazard areas, including hydrostatic loads, hydrodynamic loads, wave loads, and debris impact loads.

ASCE 24-05 addresses design requirements for structures in coastal high-hazard areas (V Zones).

Table 2-1: ASCE/SEI 24-05 provisions related to the elevation of critical facilities

		Category III	Category IV
Elevation of Lowest Floor or Bottom of Lowest Horizontal Structural	A Zone: elevation of lowest floor	BFE +1 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher
	V Zone and Coastal A Zone: where the lowest horizontal structural member is parallel to direction of wave approach	BFE +1 ft or DFE, whichever is higher	BFE +1 ft or DFE, whichever is higher
	V Zone and Coastal A Zone: where the lowest horizontal structural member is perpendicular to direction of wave approach	BFE +2 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher
Elevation Below which Flood-Damage-Resistant Materials Shall	A Zone	BFE +1 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher
	V Zone and Coastal A Zone: where the lowest horizontal structural member is parallel to direction of wave approach	BFE +2 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher
	V Zone and Coastal A Zone: where the lowest horizontal structural member is perpendicular to direction of wave approach	BFE +3 ft or DFE, whichever is higher	BFE +3 ft or DFE, whichever is higher
Minimum Elevation of Utilities and Equipment	A Zone	BFE +1 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher
	V Zone and Coastal A Zone: where the lowest horizontal structural member is parallel to direction of wave approach	BFE +2 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher
	V Zone and Coastal A Zone: where the lowest horizontal structural member is perpendicular to direction of wave approach	BFE +3 ft or DFE, whichever is higher	BFE +3 ft or DFE, whichever is higher
Dry Floodproofing	A Zone: elevation to which dry floodproofing extends	BFE +1 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher
	V Zone and Coastal A Zone: dry floodproofing not allowed	Not applicable	Not applicable

2.2 CRITICAL FACILITIES EXPOSED TO FLOODING

2.2.1 EVALUATING RISK AND AVOIDING FLOOD HAZARDS

Flood hazards are very site-specific. When a flood hazard map is prepared, lines drawn on the map appear to precisely define the hazard area. Land that is on one side of the line is “in” the mapped flood hazard area, while the other side of the line is “out.” Although the delineation may be an approximation, having hazard areas shown on a map facilitates avoiding such areas to the maximum extent practical. Where it is unavoidable, facility owners should carefully evaluate all of the benefits and all of the costs in order to determine long-term acceptable risks, and to develop appropriate plans for design and construction of new facilities.

Even in communities with expansive floodplains, it should be possible to avoid locating new critical facilities in floodways and coastal areas subject to significant waves (V Zones).

Section 2.2.2 describes the damage sustained by existing buildings exposed to flood hazards, including site damage, structural and nonstructural building damage, destruction or impairment of service equipment, and loss of contents. These types of damage, along with loss of function and community service, are avoided if critical facilities are located away from flood hazard areas. Damage is reduced when critical facilities that must be located in flood hazard areas are built to exceed the minimum requirements.

2.2.1.1 Benefits/Costs: Determining Acceptable Risk

Extreme hurricane storm surge flooding may be a very low-probability event, but the flood water depths and waves may be much more severe than the conditions of the base flood shown on the FIRMs. The potential impacts on a critical facility must be carefully considered in order to make an informed decision regarding acceptable risk and potential damage. If possible, it is always best to avoid locating critical facilities in areas subject to extreme storm surge flooding.

Many decisions that are made with respect to critical facilities are, in part, based on a determination of acceptable risk. Risk includes the potential losses associated with a hazard. Ideally, risk is defined in terms of expected probability and frequency of the hazard occurring, the people and property exposed, and the potential consequences. Choosing a site that is affected by flooding is a decision to accept some degree of risk. Although the flood-prone land may have a lower initial cost, the incremental costs of construction, plus the likely increased costs of maintenance, repair, and replacement, may be significant. Another cost of locating a critical facility in a flood-prone area is related to access problems if roads and driveways are impassable. Although the building may be elevated and protected, if access is restricted periodically, then the use of the facility is affected.

The building owner and the design team can influence the degree of risk (e.g., the frequency with which flooding may affect the site). They control it through the selection of the site design and the building design measures. Fundamentally, this process is a balancing of the benefits of an acceptable level of disaster resistance with the costs of achieving that degree of protection. With respect to mitigation of future hazard events:

❍ Benefits are characterized and measured as future damages avoided if the mitigation measures (including avoiding flood hazard areas) are implemented.

❍ Costs are the costs associated with implementing measures to eliminate or reduce exposure to hazards.

Section 2.2.2 describes damage and losses that are incurred by buildings exposed to flooding. Direct damage includes damage to physical property, including the site, the building, building materials, utilities, and building contents. Indirect damage that is not listed includes health hazards, loss of functionality, emergency response, evacuation, and expenses associated with occupying another building during repairs.

Sometimes developers are required to set aside land to meet adequate facilities requirements, or land may be donated to support community or non-profit facilities, such as fire stations. If the donated land is affected by flood hazards, it may be difficult to avoid floodplain impacts entirely. Careful consideration should be made whether the benefits of accepting the land outweigh the costs and risks associated with mitigating the flood risk.

Benefits other than avoided physical damage are difficult to measure. They are associated with future damage that does not occur because of the mitigation activity, cleanup that is not required because of the mitigation activity, and service that is not interrupted because flooding does not affect normal operation of the facility. In addition, benefits accrue over long periods of time, thus making it more difficult to make a direct comparison of the benefits with the up-front costs of mitigation. Mitigation costs can be more readily expressed in terms of the higher costs of a flood-free site, or the initial capital costs of work designed to resist flood damage. Thus, without a full accounting of both benefits and costs, decisionmakers may not be able to make fully informed decisions. Some questions that should be answered include:

- If the site is flood-prone and the building is out of the flood hazard area or is elevated on fill, what are the average annual cleanup costs associated with removal of sand, mud, and debris deposited by floods of varying frequencies?

- If the facility building is elevated by means other than fill, will periodic inundation of the exposed foundation elements cause higher average annual maintenance costs?

- If the facility is protected with floodproofing measures, what are the costs of annual inspections, periodic maintenance and replacement of materials, and staff training and periodic drills?

- If the critical facility meets only the minimum elevation requirements, what are the average annual damage and cleanup costs over the anticipated useful life of the building, including the occurrence of floods that exceed the design flood elevation?

❍ How do long-term costs associated with periodic inundation compare to up-front costs of selecting a different site or building to a higher level of protection?

❍ If the facility is located in a hurricane-prone community, how should the facility design account for low probability, but high impact, storm surge flooding?

❍ If access to the facility is periodically restricted due to flooding, especially long-duration flooding, what are the cost effects? How often should an alternate location be provided to continue normal operations?

2.2.1.2 Identifying Flood Hazards at Critical Facilities Sites

As part of site selection and to guide locating a new critical facility and other improvements on a site, facility owners, planners, and designers should investigate site-specific flood hazard characteristics. Similarly, when examining existing critical facilities and when planning improvements or rehabilitation work, an important step is to determine the site characteristics and flood hazards. The best available information should be examined, including flood hazard maps, records of historical flooding, storm surge maps, and advice from local experts and others who can evaluate flood risks. Table 2-3 in Section 2.5 outlines questions that should be answered prior to initiating site layout and design work.

2.2.1.3 Critical Facilities as Emergency Shelters

Emergency managers regularly identify facilities (especially schools) to serve as short-term and long-term shelters. Schools are attractive sites for shelters because they have kitchen facilities designed to serve many people, restroom facilities likely to be adequate for many people, and plenty of space for cots in gymnasiums, cafeterias, and wide corridors.

New schools that will function as emergency shelters warrant a higher degree of protection than other schools and should be appropriately designed as critical facilities (see Section 1.3 for an overview on performance-based design). If located in, or adjacent to, flood hazard areas, it is appropriate to provide protection for the building and utility systems to at least the 0.2-percent-annual-chance (500-year) flood level or, at a minimum, 2 to 3 feet above the DFE. Additional guidance on hazard-resistant shelters is found in FEMA 361, *Design and Construction Guidance for Community Shelters*.

Additional measures that may be appropriate for consideration when flood-prone critical facilities are used as shelters include the following:

- Wastewater service must be functional during conditions of the flooding.
- Emergency power service must be provided.
- Dry ground access is important, in the event flooding exceeds design levels.

2.2.2 VULNERABILITY: WHAT FLOODING CAN DO TO EXISTING CRITICAL FACILITIES

Existing flood-prone facilities are susceptible to damage, the nature and severity of which is a function of site-specific flood characteristics. As described below, damage may include: site damage, structural and nonstructural building damage, destruction or impairment of utility service equipment and loss of contents.

Regardless of the nature and severity of damage, flooded facilities typically are not functional while cleanup and repairs are undertaken. The length of closure, and thus the impact on the ability of the facility to become operational, depends on the severity of the damage and lingering health hazards. Sometimes repairs are put on hold pending a decision on whether a facility should be rebuilt at the flood-prone site. When damage is substantial, rehabilitation or reconstruction is allowed only if compliance with flood-resistant design requirements is achieved (see Section 2.1.3.2).

2.2.2.1 Site Damage

The degree of site damage associated with flooding is a function of several variables related to the characteristics of the flood, as well as the site itself.

Erosion and scour: All parts of a site subject to flooding by fast moving water could experience erosion, and local scour could occur around any permanent obstructions to flow. Graded areas, filled areas, and cut or fill slopes are especially susceptible. Stream and channel bank erosion, and erosion of coastal shorelines, are natural phenomena that may, over time, threaten site improvements and buildings.

Debris and sediment removal: Even when buildings are not subject to water damage, floods can produce large quantities of debris and sediment that can damage a site and be expensive to remove.

Landscaping: Grass, trees, and plants suffer after floods, especially long-duration flooding that prevents oxygen uptake, and coastal flooding that stresses plants that are not salt-tolerant. Fast-moving floodwaters and waves also can uproot plants and trees.

Fences: Some types of fences that are relatively solid can significantly restrict the free flow of floodwaters and trap floating debris. Fences can be damaged by flowing water, and can be knocked down under pressure of flowing water or if the buildup of debris results in significant loads (see Figure 2-12).

Accessory structures: Accessory structures can sustain both structural and nonstructural damage. In some locations, such structures can be designed and built using techniques that minimize damage potential, without requiring elevation above the DFE.

Access roads: Access roads that extend across flood-prone areas may be damaged by erosion, washout of drainage culverts, failure of fill and bedding materials, and loss of surface (see Figure 2-13). Road damage could prevent uninterrupted access to a facility and thus impair its functionality.

Figure 2-12:
Katrina's storm surge flooding knocked down this fence adjacent to a fire station (2005).

Figure 2-13:
Flooding caused the failure of this road bed.
SOURCE: U.S. ARMY CORPS OF ENGINEERS

Parking lots and parking garages: Paved parking lots may be damaged by failure of bedding materials and loss of driving surface. Vehicles left in parking lots and parking garages could also be damaged. Most large parking garages are engineered structures that can be designed to allow for the flow of water.

Stormwater management facilities and site drainage: Site improvements such as swales and stormwater basins may be eroded, filled with sediments, or clogged by debris.

2.2.2.2 Structural Damage

Structural damage includes all damage to the load-bearing portions of a building. Structural damage can be caused by each of the characteristics of flooding described in Section 2.1.1.

Damage to other components of buildings is described below, including saturation of materials (Section 2.2.2.3), utility service equipment (Section 2.2.2.4), and contents (Section 2.2.2.5).

Depth: The hydrostatic load or pressure against a wall or foundation is directly related to the depth of water (refer to Figure 2-9). Standard stud and siding, or unreinforced brick veneer walls, may collapse under hydrostatic loads associated with relatively shallow water. Reinforced masonry walls perform better than unreinforced masonry walls (see Figure 2-14), although an engineering analysis is required to determine performance. Walls and floors of below-grade areas (basements) are particularly susceptible to damage by hydrostatic pressure. When soils are saturated, pressures against below-grade walls are a function of the total depth of water, including the depth below-grade and the weight of the saturated soils.

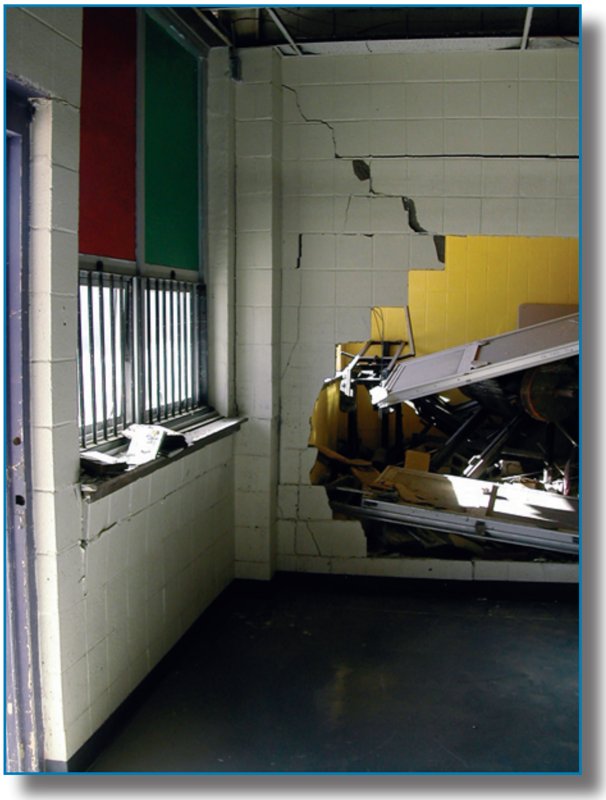


Figure 2-14: Interior unreinforced masonry walls of the Port Sulphur High School in Louisiana were damaged by hydrostatic loads associated with Hurricane Katrina's storm surge (2005).

Buoyancy and uplift: If below-grade areas are essentially watertight, buoyancy or uplift forces can float a building out of the ground or rupture concrete floors (see Figure 2-15). Buildings that are not adequately anchored can be floated or pushed off foundations. Although rare for large and heavy critical facility buildings, this is a concern for outbuildings and portable (temporary) units.

Figure 2-15: Concrete floor ruptured by hydrostatic pressure (buoyancy). Hurricane Katrina (2005)

Duration: Long duration saturation can cause dimensional changes and contribute to deterioration of wood members. By itself, saturation is unlikely to result in significant structural damage to masonry construction. Saturation of soils, a consequence of long duration flooding, increases pressure on below-grade foundation walls.

Velocity, wave action, and debris impacts: Each of these components of dynamic loads can result in structural damage if buildings are not designed to resist overturning, repetitive pounding by waves, or short-duration impact loads generated by floating debris.

Erosion and scour: Structural damage is associated with foundation failure when erosion or scour results in partial or complete removal of supporting soil (see Figure 2-16). Erosion of slopes, especially unprotected slopes, can lead to slope failures and loss of foundation supporting soil.

Figure 2-16:
Scour around the foundation of this building contributed to significant damage.

2.2.2.3 Nonstructural Damage

Many flood-prone buildings are exposed to floodwaters that are not fast moving, or that may be relatively shallow and not result in structural damage. Simple inundation and saturation of the building and finish materials can result in significant and costly nonstructural damage, including long-term health complications associated with mold. Floodwaters often are contaminated with chemicals, petroleum products, or sewage. Under such circumstances, recovery generally involves removal of nonstructural materials and finishes because cleanup and decontamination is expensive and time-consuming. Damage to contents is discussed in Section 2.2.2.5.

Nonstructural damage can vary as a function of the duration of water exposure. Some materials are not recoverable even after very brief inundation, while others remain serviceable if in contact with water for only a few hours. Use of water-resistant materials will help to minimize nonstructural damage caused by saturation and reduce the costs of cleanup and restoration to service (see *Flood-Resistant Materials Requirements*, FIA-TB-2).

Wall finishes: Painted concrete and concrete masonry walls usually resist water damage, provided the type of paint can be readily cleaned, such as high strength epoxy paints. Tiled walls may be acceptable, depending on the type of adhesive and foundation (gypsum board substrate and wood-framed walls with tile typically do not remain stable).

Flooring: Many critical facilities have durable floors that resist water damage. Ground floors often are slab-on-grade and finished with tile or sheet goods. Flooring adhesives in use since the early 1990s likely are latex-based and tend to break down when saturated. Most carpeting, even the indoor-outdoor kind, is difficult to clean. Wood floors are particularly susceptible to saturation damage, although short duration inundation may not cause permanent de-formation of some wood floors. However, because of low tolerance for surface variations, gymnasium floors in schools are particu-larly sensitive and tend to warp after flooding of any duration (see Figure 2-17).

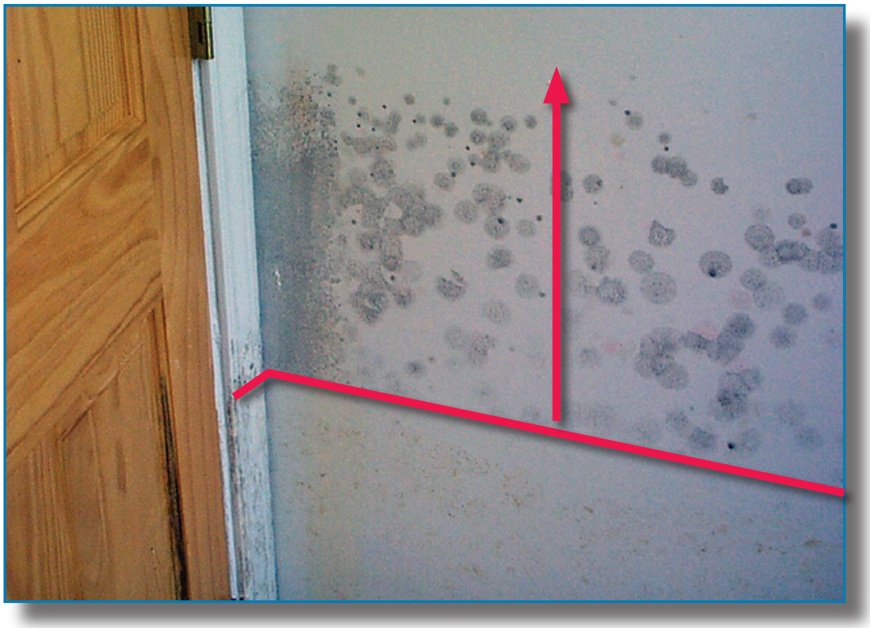
Figure 2-17:
This parquet wood gymnasium floor was damaged by dimensional changes due to saturation. Hurricane Katrina (2005)

Wall and wood components: When soaked for long periods of time, some building components change composition or shape. Most types of wood will swell when wetted and, if dried too quickly, will crack, split or warp. Plywood can delaminate and wood door and window frames may swell and become unstable. Gypsum wallboard, wood composition panels, other wall materials, and wood cabinetry not intended for wet locations can fall apart (see Figure 2-18). The longer these materials are wet, the more moisture, sediment, and pollutants they absorb. Some wall materials, such as the paper facing on gypsum wallboard, "wick" standing water, resulting in damage above the actual high-water line (see Figure 2-19).

Figure 2-18: Damaged walls and cabinets

Figure 2-19: Water damage and mold growth extend above the water line

SOURCE: OAK RIDGE NATIONAL LABORATORY



Metal components: Metal structural components are unlikely to be permanently damaged by short-term inundation. However, hollow metal partitions are particularly susceptible when they come into contact with water because they cannot be thoroughly dried and cleaned. Depending on the degree of corrosion protection on the metal, repetitive flooding by saline coastal waters may contribute to long-term corrosion.

Metal connectors and fasteners: Depending on the composition of the metal, repetitive flooding, especially by saline coastal waters, may contribute to long-term corrosion. Connectors and fasteners are integral to the structural stability of buildings; therefore, failure caused by accelerated corrosion would jeopardize the building.

2.2.2.4 Utility System Damage

Utility system service equipment that is exposed to flooding is vulnerable to damage. Damage may result in a total loss, or may require substantial cleaning and restoration efforts. The degree of damage varies somewhat as a function of the characteristics of flooding. Certain types of equipment and installation measures will help minimize damage and reduce the costs of cleanup and restoration to service.

Displacement of equipment and appliances: Installation below the flood level exposes equipment and appliances to various flood forces, including drag resulting from flowing water and buoyancy. Gas-fired appliances are particularly dangerous: flotation can separate appliances from gas sources, resulting in fires and explosive situations. Displaced equipment may dislodge lines from fuel oil tanks, contributing to the threat of fires and causing water pollution and environmental damage.

Elevators: If located in areas subject to flooding, elevator component equipment and controls will be damaged, and communication between floors will be impaired.

Corrosion: Corrosion related to inundation of equipment and appliances may not be apparent immediately, but can increase maintenance demand and shorten the useful life of some equipment and appliances.

Electrical systems and components: Electrical systems and components, and electrical controls of heating, ventilation, and air conditioning systems, are subject to damage simply by getting wet, even for short durations. Unless specifically designed for wet locations, switches and other electrical components can short out due to deposits of sediment, or otherwise not function even when allowed to dry before operation. Wiring and components that have been submerged may be functional, although generally it is more cost-effective to discard flooded outlets, switches, and other less expensive components than to attempt thorough cleaning.

Communications infrastructure: Critical communications infrastructure, such as control panels and wiring for warning systems, 911 systems, and regular telephone and wireless networks, are most susceptible to failure during emergencies if located in below-grade basements.

Specialized piping: Unprotected piping for medical gas supply systems may be damaged and threaten care that depends on uninterrupted supply of oxygen and other gasses for the treatment of patients.

Ductwork damage: Ductwork is subject to two flood-related problems. Flood forces can displace ductwork, and saturated insulation can overload support straps, causing failure.

Mold and dust: Furnaces, air handlers, and ductwork that have been submerged must be thoroughly cleaned and sanitized. Otherwise, damp conditions contribute to the growth of mold and accumulated sediment can be circulated throughout the critical facility, causing respiratory problems. Fiberglass batt or cellulose insulation that has been submerged cannot be sanitized and must be replaced. In sensitive environments, ductwork should be replaced rather than cleaned.

Gas-fired systems: Water-borne sediment can impair safe functioning of jets and controls in gas-fired furnaces and water heaters, necessitating professional cleaning and inspection prior to restoration of service. Control equipment (valves, electrical switches, relays, temperature sensors, circuit breakers, and fuses) that have been submerged may pose an explosion and fire hazard and should be replaced.

Emergency power generators: Generators that are installed at-grade are susceptible to inundation and will be out of service after a flood (see Figure 2-20).

Tanks (underground): Underground storage tanks are subjected to significant buoyant forces and can be displaced, especially when long-duration flooding occurs. Computations of stability should be based on the assumption that the tank is empty in order to maximize safety. Tank inlets, fill openings, and vents should be above the DFE, or designed to prevent the inflow of floodwaters or outflow of tank contents during flood conditions.

Tanks (aboveground): Aboveground storage tanks are subject to buoyant forces and displacement caused by moving water. Standard strapping of propane tanks may be inadequate for the anticipated loads. Tank inlets, fill openings, and vents should be above the DFE, or designed to prevent the inflow of floodwaters or outflow of tank contents during flood conditions.

Public Utility Service: Damage to public utility service (potable water supply and wastewater collection) can affect operations and may cause damage to critical facilities:

Figure 2-20:
Although it was anchored and not displaced by floodwaters, this generator was out of service after being submerged.

- Potable water supply systems may become contaminated if public water distribution lines or treatment facilities are damaged, or if wellheads are submerged.

- During heavy rains, sewers back up from infiltration and inflow of stormwater into the sewer lines and manholes, cross connections between storm and sanitary sewers, and flooded wastewater treatment plants. Sewer backup into a critical facility poses a major health hazard. Even when the water has receded, exposed building components, finish materials, and contents are contaminated, and usually must be removed because adequate cleaning is difficult, if not impossible.

2.2.2.5 Contents Damage

Critical facilities may contain high-value contents that can be damaged and become unrecoverable when subjected to flooding. For the purpose of this discussion, the term “contents” includes items such as furniture, appliances, computers, laboratory equipment and materials, records, and specialized machinery. The following types of contents are often considered a total loss.

Furniture: In long-duration flooding, porous woods become saturated and swollen, and joints may separate. Furniture with coverings or pads generally cannot be restored. Metal furniture is difficult to thoroughly dry and clean, is subject to corrosion, and typically is discarded. Some wood furniture may be recoverable after brief inundation.

Computers: Flood-damaged computers and peripheral equipment cannot be restored after inundation, although special recovery procedures may be able to recover information on hard drives.

Communications equipment: Even though some communications equipment may be able to be restored with appropriate cleaning, the loss of functionality would seriously impair the ability of the facility to provide critical services immediately after a flood. Equipment with printed circuit boards generally cannot be restored.

Office records and police files: When facilities are located in flood-prone space, valuable records may be lost. Although expensive, some recovery of computerized and paper records may be possible with special procedures (see Figure 2-21).

Health care equipment and laboratory materials: Most medical and health care equipment cannot be cleaned and restored to safe functioning, and would need to be replaced. Depending on the nature of laboratory materials and chemicals, complete disposal or special cleanup procedures may be required.

Kitchen goods and equipment: Floodwaters can dislodge appliances that can float and damage other equipment (see Figure 2-22). Stainless steel equipment generally has cleanable surfaces that can be disinfected and restored to service. Because of contamination, all food stuffs must be discarded.

Vehicles associated with critical facilities: If left in flood-prone areas, fire engines, police cars, ambulances, and other vehicles require replacement or cleaning to be serviceable and may not be functional and available for service immediately after a flood.

Figure 2-21:
Medical records saturated by floodwaters

SOURCE: HANCOCK MEDICAL CENTER

Figure 2-22:
Kitchen appliances and equipment from Port Sulphur High School were displaced and damaged by Hurricane Katrina floodwaters (2005).

2.3 REQUIREMENTS AND BEST PRACTICES IN SPECIAL HAZARD AREAS

2.3.1 RISK REDUCTION IN "A ZONES"

Flood hazard areas designated as A Zones on FIRMs are areas where significant wave action is not expected (see Section 2.1.1.2). A Zones are found along riverine bodies of water (rivers, streams, creeks, etc.), landward of V Zones, and on some open coastlines that do not have mapped V Zones. When constructing a critical facility on a site affected by an A Zone flood hazard, site design is influenced by several constraints, such as the presence of flood hazard areas, wetlands, poor soils, steep slopes, sensitive habitats, mature tree stands, and the environmental requirements set by the various regulatory authorities and the agency that approves development plans.

Four aspects of the design of flood-resistant buildings and sites are described in this section: site modifications, elevation considerations, flood-resistant materials, and floodproofing considerations. Section 2.3.5 addresses related facilities, including access roads, utility installations, water and wastewater systems, storage tanks, and accessory structures.

2.3.1.1 Site Modifications

When sites being considered for critical facilities are affected by flood hazards, planners and designers may want to evaluate the feasibility of certain site modifications in order to provide an in-

Site modifications are not appropriate in floodways along riverine waterways, where obstructions to flows can increase flood elevations. Engineering analyses are required to determine the impact of such modifications.

creased level of protection to buildings. The evaluations involve engineering analyses to determine whether the desired level of protection is cost-effective, and whether the proposed site modifications alter the floodplain in ways that could increase flooding. The effectiveness of typical site modifications and their ramifications must be examined for each specific site.

Earthen fill: Fill can be placed in the flood hazard area for the purpose of elevating a site above the design flood elevation. If the fill is placed and compacted so as to be stable during the rise and fall of floodwaters, and if the fill is protected from erosion, then modifying a site with fill to elevate a facility is preferred over other methods of elevation. Not only will buildings be less exposed to flood forces, but, under some circumstances (such as long duration floods), critical facilities may be able to continue to function. Whether nonstructural fill is placed solely to modify the site, or structural fill is placed for the purpose of elevating buildings, placement of fill can change flooding characteristics, including increased flooding on other properties. Engineering analyses can be conducted to determine whether eliminating floodplain storage by filling will change the direction of the flow of water, create higher flow velocities, or increase the water surface elevation in other parts of the floodplain. Fill is a less effective elevation method in flood hazard areas exposed to wave action, such as the banks of wide rivers, back bays, or Coastal A Zones, because wave action may erode the fill and adequate armoring or other protection methods can be expensive.

Excavation: Excavation alone rarely results in significantly altering the floodplain on a given parcel of land. Excavation that modifies a site is more commonly used in conjunction with fill in order to offset or compensate for the adverse impacts of fill.

Earthen levee: A levee is a specially designed barrier that modifies the floodplain by keeping the water away from certain areas (see Figure 2-23). Levees are significant structures that require detailed, site-specific geotechnical investigations; engineering analyses to identify whether flooding will be made worse on other properties; structural and site design to suit existing constraints; design of interior drainage (on the land side); and long-term commitment for maintenance, inspection, and repairs. It is important to remember that areas behind levees are protected only up to a certain design flood level—once overtopped or breeched, most levees fail and catastrophic flooding results. Levees that protect critical facilities usually are designed for at least the 0.2-percent-annual-chance flood (500-year) and have freeboard to increase the factor of safety.

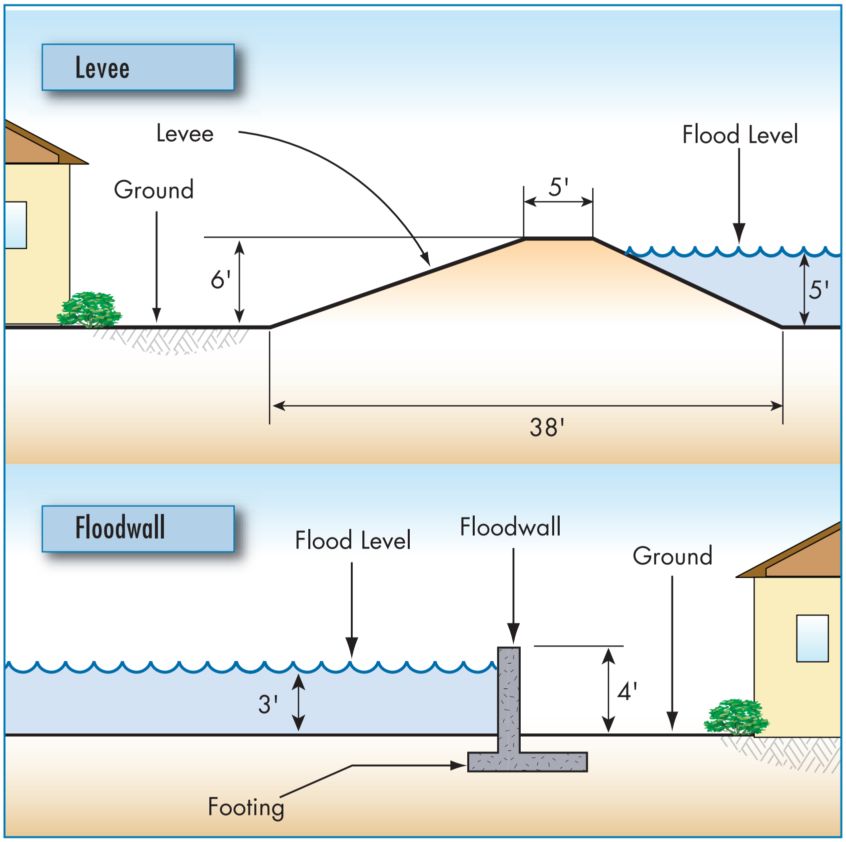


Figure 2-23: Schematic of typical earthen levee and permanent floodwall

Floodwall: Floodwalls are similar to levees in that they provide protection to certain areas (see Figure 2-23). Failure or overtopping of a floodwall can result in catastrophic flooding. A floodwall is a significant structure that is designed to hold back water of a certain depth based on the design flood for the site. Generally, due to design factors, floodwalls are most effective in areas with relatively shallow flooding and minimal wave action. As with levees, designs must accommodate interior drainage on the land side, and maintenance and operations are critical for adequate performance.

Floodwalls that protect essential and critical facilities usually are designed for the 0.2-percent-annual-chance flood (500-year) and have freeboard to increase the factor of safety.

2.3.1.2 Elevation Considerations

"Lowest floor" is the floor of the lowest enclosed area (including the basement). An unfinished or flood-resistant enclosure, usable solely for parking of vehicles, building access, or storage in an area other than a basement, is not the lowest floor, provided the enclosure is built in compliance with applicable requirements.

The selection of the appropriate method of elevating a critical facility in an A Zone flood hazard area depends on many factors, including cost, level of safety and property protection determined as acceptable risk, nature of the flood hazard area, and others. Methods of elevation are described below. The minimum elevation requirement is that the lowest floor (including the basement) must be at or above the DFE (plus freeboard, if desired or required). Table 2-1 in Section 2.1.3.4 summarizes the elevation requirements in ASCE 24. Given the importance of critical facilities, elevation of the lowest floor to or above the 0.2 percent-annual-chance flood (500-year) elevation is crucial.

ASCE 7 outlines methods to determine design loads and load combinations in flood hazard areas, including hydrostatic loads, hydrodynamic loads, wave loads, and debris impact loads. ASCE 24 addresses design requirements for structures in flood hazard areas.

For elevation methods other than fill, the area under elevated buildings in A Zones may be used only for limited purposes: parking, building access, and limited storage (crawlspaces are treated as enclosures, see below). Owners and designers are cautioned that enclosures below the design flood elevation are exposed to flooding and the contents will be damaged or destroyed by floodwaters. The walls surrounding an enclosure must have flood openings that are intended to equalize interior and exterior water levels during rising and falling flood conditions, to prevent differential hydrostatic pressures that could lead to structural damage. The enclosed area must not contain utilities and equipment (including ductwork) below the required elevation.

Communities may require a registered design professional to certify that buildings elevated on fill are reasonably safe from flooding. FEMA NFIP Technical Bulletin 10 (2001) discusses criteria for this certification.

Slab-on-grade foundation on structural fill: This is considered to be the safest method to elevate a building in many flood hazard areas, except those where waves and high velocity flows may cause erosion. Structural fill can be placed so that, when water rises up to the DFE, it will not touch the building (see Figure 2-24) and building access is maintained. The fill must be designed to minimize adverse impacts, such as increasing flood elevations on adjacent properties, increasing erosive velocities, and causing local drainage problems. To ensure stability, especially as floodwaters recede and the soils drain, fill must be designed for the anticipated water depths and duration. A geotechnical engineer or soil scientist may need to examine underlying soils to determine if the bearing capacity is sufficient to carry the added weight of fill, or if consolidation over time may occur. In addition, the effects of long-term compaction of the fill should be considered, and may prompt additional elevation as a factor of safety. The horizontal extent of fill from the foundation should be designed to facilitate access by emergency and fire vehicles, with a minimum 25-foot width recommended. Designers are cautioned to avoid excavating a basement into fill without added structural protection (and certification that the design meets requirements for dry floodproofing), due to the potential for significant hydrostatic loads and uplift on basement floors.

Figure 2-24: Municipal building elevated on fill

Stem wall foundations: Stem wall foundations have a continuous perimeter grade beam, or perimeter foundation wall, that is backfilled with compacted earth to the underside of the concrete floor slab (see Figure 2-25). Because this foundation type is backfilled and has no crawlspace, hydrostatic pressures are minimized. Stem wall foundations are designed to come in contact with floodwaters on the exterior. They are more stable than perimeter wall foundations with crawlspaces, but could experience structural damage if undermined by local scour and erosion. Designs must account for anticipated debris and ice impacts, and incorporate methods and materials to minimize impact damage.

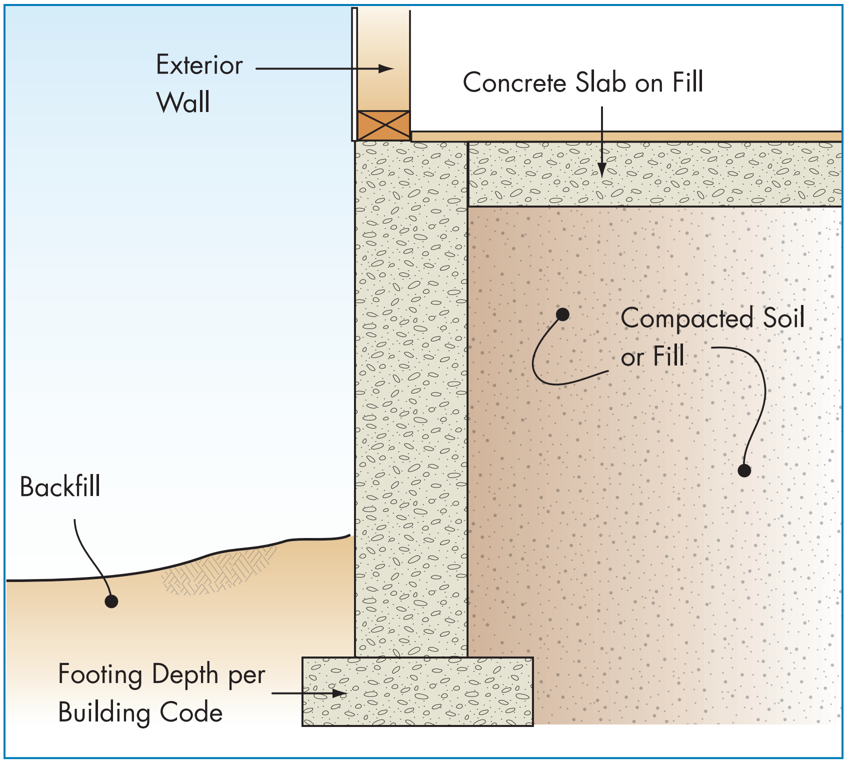


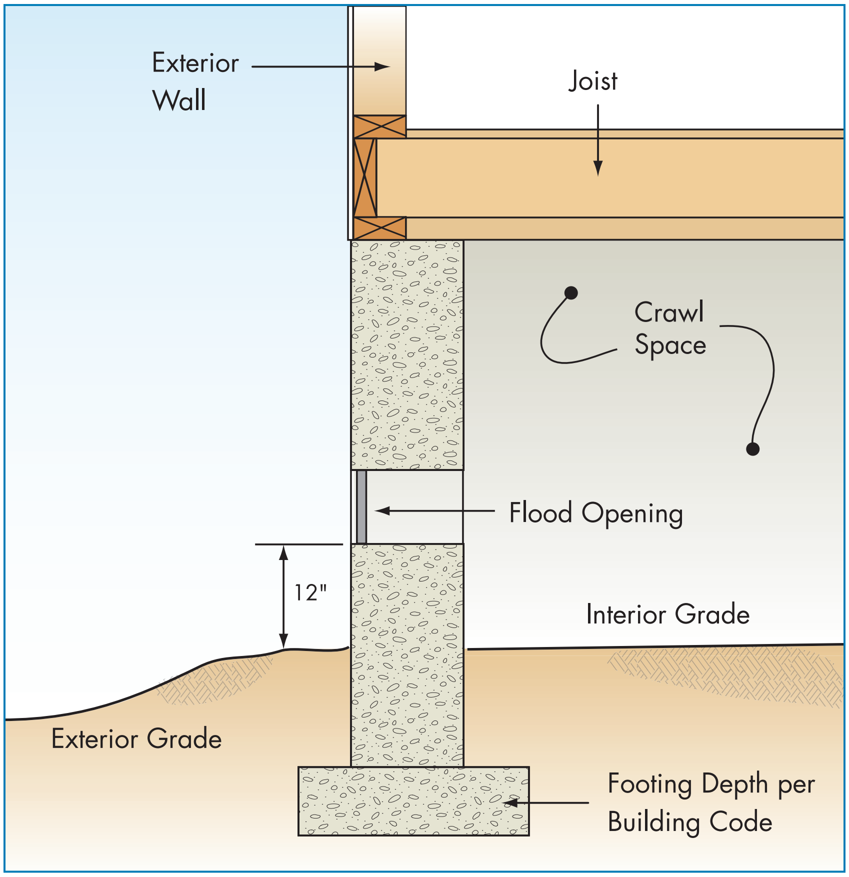
Figure 2-25: Typical stem wall foundation

Columns or shear wall foundations (open foundations): Open foundations consist of vertical load bearing members (columns, piers, pilings, and shear walls) without solid walls connecting the vertical members. Open foundations minimize changes to the floodplain and local drainage patterns, and the area under the building can be used for parking or other uses (see Figure 2-26). The design of the vertical members must also account for hydrodynamic loads and debris and ice impact loads. Flood loads on shear walls are reduced if they are oriented parallel to the anticipated direction of flow. Erodible soils may be present and local scour may occur; both must be accounted for in designs by extending the load-bearing members and foundation elements well below the expected scour depth. Depending on the total height of the elevated facility, the design may need to take into consideration the increased exposure to wind and uplift, particularly where breaking waves are expected.

Figure 2-26: School elevated on columns

Continuous perimeter walls (enclosed foundations with crawlspace): Unlike stem wall foundations, continuous perimeter walls enclose an open area or crawlspace (see Figure 2-27). The perimeter walls must have flood openings that are intended to equalize interior and exterior water levels automatically during changing flood conditions to prevent differential hydrostatic pressures that could lead to structural damage. Flood openings may be engineered and certified for the required performance level, or must meet prescriptive requirements (notably, the opening must provide at least 1 square inch of net open area for each square foot of area enclosed). Perimeter wall design must also account for hydrodynamic loads, and debris and ice impact loads. Enclosed crawlspaces must not contain utilities or equipment (including ductwork) below the required elevation. Designers must provide adequate underfloor ventilation and subsurface drainage to minimize moisture problems after flooding.

Figure 2-27: Typical crawlspace with flood openings



Pier supports for manufactured and portable units: Manufactured buildings and portable units must be elevated above the DFE (plus freeboard, if required). Pier supports must account for hydrodynamic loads and debris and ice impact loads and units must be anchored to resist wind loads. Although written specifically for manufactured housing units, FEMA 85, *Manufactured Home Installation in Flood Hazard Areas*, has useful information that is applicable to portable units.

2.3.1.3 Flood-Resistant Materials

All structural materials, nonstructural (finish) materials, and connectors that are used below certain elevations (see Table 2-2) should be flood-resistant. Flood-resistant materials have sufficient strength, rigidity, and durability to adequately resist flood loads and damage due to saturation. They are building materials that are capable of withstanding direct and prolonged contact with floodwaters without sustaining any damage that requires more than cosmetic repair. As defined in ASCE 24, the term “prolonged contact” means partial or total inundation by floodwaters for 72 hours for non-coastal areas (fresh water) or 12 hours for coastal areas.

FEMA NFIP Technical Bulletin FIA-TB-2, *Flood-Resistant Materials Requirements,* provides some additional information. Many types of materials and application products are classified by degrees of resistance to flood damage.

In general, materials that are exposed to floodwaters are to be capable of resisting damage, deterioration, corrosion, or decay. Typical construction materials range from highly resistant to not at all resistant to water damage. FEMA NFIP Technical Bulletin FIA-TB-2 contains tables with building materials, classified based on flood resistance (Table 2-2).

In areas away from the coast, exposed structural steel should be primed, coated, plated, or otherwise protected against corrosion. Secondary components such as angles, bars, straps, and anchoring devices, as well as other metal components (plates, connectors, screws, bolts, nails angles, bars, straps, and the like) should be stainless steel or hot-dipped galvanized after fabrication.

Table 2-2: Classes of Flood-Resistant Materials

NFIP	Class	Class Description
Acceptable	5	Highly resistant to floodwater damage. Materials in this class are permitted for partially enclosed or outside uses with essentially unmitigated flood exposure.
	4	Resistant to floodwater damage. Materials in this class may be exposed to and/or submerged in floodwaters in interior spaces and do not require special waterproofing protection.
Unacceptable	3	Resistant to clean water damage. Materials in this class may be submerged in clean water during periods of intentional flooding.
	2	Not resistant to water damage. Materials in this class require essentially dry spaces that may be subject to water vapor and slight seepage.
	1	Not resistant to water damage. Materials in this class require dry conditions.

SOURCE: FROM U.S. ARMY CORPS OF ENGINEERS, *FLOODPROOFING REGULATIONS* (1995).

Concrete and masonry that are designed and constructed in compliance with applicable standards are generally considered to be flood-resistant. However, masonry facings are undesirable finishes unless extra anchoring is added to prevent separation (see Figure 2-28). Wood and timber members exposed to flood waters should be naturally decay resistant species or pressure treated with appropriate preservatives.

Structural steel and other metal components exposed to corrosion should be stainless steel or hot-dipped galvanized after fabrication.

Figure 2-28:
Brick facing separated from the masonry wall at Port Sulpher High School, LA.

2.3.1.4 Dry Floodproofing Considerations

Dry floodproofing involves a combination of design and special features that are intended to prevent the entry of water into a building and its utilities while also resisting flood forces. It involves structural reinforcement so that exterior walls are sufficiently robust to withstand the loads described in Section 2.1.2 (hydrostatic pressure, hydrodynamic loads, wave loads, and debris impact loads). Exterior walls must also be designed to prevent infiltration and seepage of water, whether through the wall itself or through any openings, including where utility lines penetrate the envelope. Floodproofed buildings constructed on permeable soils require additional design attention, because they are susceptible to hydrostatic pressure from below.

Communities that participate in the NFIP will require that a registered professional engineer or architect develop or review the structural design, specifications, and plans, and certify that the dry floodproofing design and methods of construction to be used are in accordance with accepted standards of practice. The standards of practice require that the building, together with attendant utility and sanitary facilities, be designed so that it is watertight, with walls substantially impermeable to the passage of water and with structural components having the capability of resisting hydrostatic and hydrodynamic loads and effects of buoyancy associated with the design flood event.

According to the NFIP regulations, nonresidential buildings and nonresidential portions of mixed-use buildings may be dry floodproofed. Areas used for living and sleeping purposes in health care facilities and dormitory rooms at fire stations may not be dry floodproofed. Although floodproofing of the nonresidential spaces is allowed, careful consideration must be given to the possible risk to occupants and additional physical damage.

All flood protection measures are designed for certain flood conditions. Therefore, there is some probability that the design will be exceeded (i.e., water will rise higher than accounted for in the design). When this happens to a dry floodproofed building, the consequences can be catastrophic. As a general rule, dry floodproofing is a poor choice for new critical facilities when avoidance of the floodplain or elevation methods to raise the building above the flood level can be applied. Floodproofing may be acceptable for retrofitting existing buildings under certain circumstances (see Section 2.4.4).

A number of dry floodproofing limitations and requirements are specified in ASCE 24:

- Dry floodproofing is limited to areas where flood velocities at the site are less than or equal to 5 feet per second.
- If human intervention is proposed, such as measures to protect doors and windows, the flood warning time shall be a minimum of 12 hours unless the community operates a flood

warning system and implements a notification procedure that provides sufficient time to undertake the measures requiring intervention.

- At least one door satisfying building code requirements for an exit door or primary means of escape must be provided above the level of protection.

- An emergency plan, approved by the community and posted in at least two conspicuous locations, is required in floodproofed buildings; the plan is to specify the location of panels and hardware, methods of installation, conditions that activate deployment, a schedule for routine maintenance of any aspect that may deteriorate over time, and periodic practices and drills.

Windows and doors that are below the flood level used for dry floodproofing design present significant potential failure points. They must be specially designed units (see Figure 2-29) or be fitted with gasketed, mountable panels that are designed for the anticipated flood conditions and loads. Generally speaking, it is difficult to protect window and door openings from water more than a few feet deep. The framing and connections must be specifically designed for these protective measures, or water pressure may cause window and door frames to separate from the building.

The documents *Flood Resistant Design and Construction* (ASCE 24-05), *Flood Proofing: How to Evaluate Your Options* (USACE, 1993), *Flood Proofing Regulations* (USACE, 1995), *Floodproofing Non-Residential Structures* (FEMA 102, 1986), *Non-Residential Floodproofing – Requirements and Certification* (FIA-TB-3 [FEMA NFIP, 1993]), *Flood Proofing Systems & Techniques* (USACE, 1984) provide additional information about floodproofing.

Dry floodproofing is required to extend to 1 or 2 feet above the BFE (see Table 2-1). For the purpose of obtaining NFIP flood insurance, the floodproofing must extend at least 1 foot above the BFE, or the premiums will be very high. Therefore, a higher level of protection is recommended.

Floodproofing techniques are considered to be permanent measures if they are always in place and do not require any specific human intervening action to be effective. Use of contingent floodproofing measures that require installation or activation, such as window shields or inflatable barriers, Dry floodproofed critical facilities must never be considered safe for occupancy during periods of high water; floodproofing measures are intended only to reduce physical damage.

may significantly reduce the certainty that floodproofing will be effective. Rigorous adherence to a periodic maintenance plan is critical to ensure proper functioning. The facility must have a formal, written plan, and people responsible for implementing the measures must be informed and trained. These measures also depend on the timeliness and credibility of the warning. In addition, floodproofing devices often rely on flexible seals that require periodic maintenance and that, over time, may deteriorate and become ineffective. Therefore, a maintenance plan must be developed and a rigorous annual inspection and training must be conducted.

Figure 2-29: Permanent watertight doors for deep water

SOURCE: PRESRAY CORPORATION

Safety of occupants is a significant concern with dry floodproofed buildings. Regardless of the degree of protection provided, dry floodproofed buildings should not be occupied during flood events, because failure or overtopping of the floodproofing measures is likely to cause catastrophic structural damage. When human intervention is required, the people responsible for implementing those measures remain at risk while at the building, even if a credible warning system is in place, because of the many uncertainties associated with predicting the onset of flood conditions.

2.3.2 RISK REDUCTION IN "V ZONES"

Flood hazard areas designated as "V Zones" on FIRMs are relatively narrow areas along open coasts and lake shores where the base flood conditions are expected to produce 3-foot or higher waves. V Zones, sometimes called coastal high hazard areas or special flood hazard areas subject to high-velocity wave action, are found on the Pacific, Gulf, and Atlantic coasts, and around the Great Lakes.

Every effort should be made to locate critical facilities outside of V Zones, because the destructive nature of waves makes it difficult to design a building to be fully functional during and after a flood event. This is particularly true in coastal areas subject to hurricane surge flooding (see Section 2.3.4). However, when a decision is made to build a critical facility in a V Zone or Coastal A Zone, the characteristics of the site and the nature of the flood hazards must be examined prior to making important design decisions.

Beach front areas with sand dunes pose special problems. Manmade alterations of sand dunes are not allowed unless analyses indicate that such modifications will not increase potential flood damage. The site modifications described in Section 2.3.1.1 that may be used in some A Zones to reduce flood hazards generally are not feasible in V Zones because of wave forces and potential erosion and scour. In particular, structural fill is not allowed as a means to raise a building site above the flood level.

The NFIP and ASCE 24 do not allow use of dry floodproofing measures to protect nonresidential structures in V Zones.

2.3.2.1 Elevation Considerations

The selection of the appropriate method of elevating a critical facility in a V Zone flood hazard area depends on many factors, including cost, desired level of safety and property protection, and the nature of the flood hazard area. The NFIP regulations and the building codes require the elevation of the bottom of the lowest horizontal structural member of the lowest floor (including basement) to be at or above the DFE (plus freeboard, where required). Given the importance of critical facilities, elevation to or above the 0.2-percent-annual-chance flood (500-year) elevation is appropriate and strongly recommended.

Communities that participate in the NFIP will require that a registered professional engineer or architect develop or review the structural design, specifications, and plans, and certify that the design and methods of construction to be used are in accordance with accepted standards of practice. The standards of practice require that the foundation and structure attached thereto is anchored to resist flotation, collapse, and lateral movement due to the effects of wind and water loads acting simultaneously on all building components. Water loading values shall be those associated with the base flood conditions, and wind loading values shall be those required by applicable State or local building codes and standards.

Buildings in V Zones must be elevated using open foundations, which consist of vertical load bearing members (columns, piers, pilings, and shear walls) without solid walls connecting the vertical members. The design of the vertical members must also account for hydrodynamic loads and debris impact loads. Flood loads on shear walls are reduced if the walls are oriented parallel to the anticipated direction of flow. Since erodible soils may be present and local scour may occur, both conditions must be accounted for in designs of load-bearing members and foundations.

The area under elevated buildings in V Zones may be used only for limited purposes: parking, building access, and limited storage. Owners and designers are cautioned that enclosures below the DFE are exposed to flooding. Areas under elevated buildings may be open or enclosed by lattice walls or screening. However, if areas are enclosed by solid walls, the walls must be specifically designed to break away under certain flood loads to allow the free passage of floodwaters under the building. Breakaway walls are non-load bearing walls, i.e., they do not provide structural support for the building. They must be designed and constructed to collapse under the impact of floodwaters in such a way that the supporting foundation system and the structure are not affected.

2.3.2.2 Flood-Resistant Materials

Section 2.3.1.3 addresses the general requirement that all structural materials, nonstructural (finish) materials, and connectors that are used below certain elevations are to be flood-resistant materials. In coastal areas, airborne salt aerosols and inundation with saline water increase the potential for corrosion of some metals. Structural steel and other metal components that are exposed to corrosive environments should be stainless steel or hot-dipped galvanized after fabrication.

2.3.3 RISK REDUCTION IN "COASTAL A ZONES"

Coastal A Zones are areas of the mapped floodplain where breaking waves that are between 1.5 to 3 feet high are expected under base flood conditions. Coastal A Zones are part of the area shown as the A Zone on a FIRM, landward of the mapped V Zone or landward of open coasts that do not have a V Zone. FIRMs do not distinguish between Coastal A Zones and A Zones. Designers should determine whether Coastal A Zone conditions are likely to occur at a critical facility site because of the anticipated wave action and loads. This determination is based on an examination of the site and its surroundings, the actual surveyed ground elevations, and the predicted stillwater elevations found in the Flood Insurance Study.

Coastal A Zones are present where two conditions exist: where the expected floodwater depth is sufficient to support waves 1.5 to 3 feet high, and where such waves can actually occur (see Figure 2-30). The first condition occurs where stillwater depths (vertical distance between the stillwater elevation and the ground) are more than 2 feet deep. The second condition occurs where there are few obstructions between the shoreline and the site. The stillwater depth requirement is necessary, but is not sufficient by itself to warrant designation as a Coastal A Zone, because obstructions in the area may block wind and dampen waves. Obstructions that may dampen waves include buildings, locally high ground, and dense tree stands.

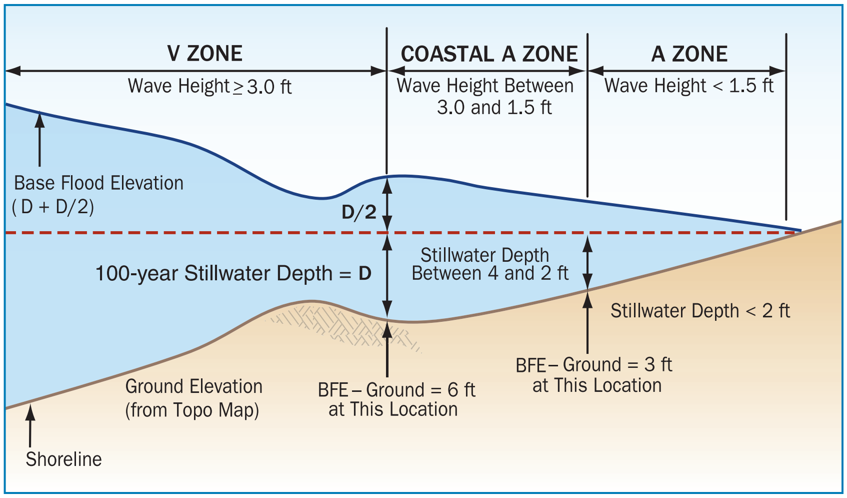


Figure 2-30:
Flood hazard zones in coastal areas

Although the NFIP regulations and the model building codes allow dry floodproofing of nonresidential buildings in flood hazard areas where waves are predicted to be between 1.5 and 3 feet during the base flood (called Coastal A Zones), designers are cautioned to fully consider the additional forces associated with wave impacts, which may make dry floodproofing a less feasible alternative.

Field observations and laboratory research have determined that flooding with breaking waves between 1.5 and 3 feet high produces more damage than flooding of similar depths without waves. Therefore, ASCE 24 specifically requires application of the NFIP's V Zone design requirements in Coastal A Zones. Section 2.3.2.1 addresses elevation requirements and foundation types, and Section 2.3.2.2 addresses flood-resistant materials, used in V Zones and Coastal A Zones. The designers are advised to pay special attention to two additional considerations:

- Debris loads may be significant in Coastal A Zones landward of V Zones where damaged buildings, piers, and boardwalks can produce battering debris. Foundations designed to account for debris loads will minimize damage.

- Especially in high wind regions, designers must pay special attention to the entire roof-to-foundation load path when designing and specifying connections. If designed to meet V Zone requirements, designs for buildings in Coastal A Zones will account for simultaneous wind and flood forces. Corrosion-resistant connections are especially important for the long-term integrity of the structure.

2.3.4 RISK REDUCTION IN HURRICANE STORM SURGE AREAS

Coastal communities along the Atlantic and Gulf coasts are subject to storm surge flooding generated by hurricanes and tropical storms. Depending on a number of variables, storm surge flood depths may significantly exceed the BFE. In addition, waves are likely to be larger than predicted for the base flood, and will occur in areas where significant wave action during the base flood is not expected. Application of the minimum requirements related to elevation of the lowest floor and foundation design does not result in flood resistance for such extreme conditions. The following special considerations will provide a greater degree of protection for critical facilities located in areas subject to storm surges.

Higher foundations: Foundations should be designed to elevate the building so that the lowest horizontal structural members are higher than the minimum required elevation. Additional elevation not only reduces damage that results from lower probability events, but the cost of Federal flood insurance is usually lower. However, accessibility may be affected and there will be some additional construction costs that must be balanced against avoided future damage and a higher likelihood that a facility can be more rapidly restored to full function.

Scour and erosion: Storm surge flooding and waves can cause scour and erosion, even at locations that are some distance from the shoreline. Foundation designs for critical facilities in coastal communities should account for some erosion and local scour of supporting soil during low probability surge events.

Water-borne debris: Storm surge flooding can produce large quantities of floating debris, even at locations that are some distance from the shoreline. Debris damages nonstructural building components and, in some cases, prolonged battering can lead to structural failure. Foundation designs for critical facilities in coastal communities should account for debris loads. This is especially important where damage to other buildings in the area may generate additional debris, thereby increasing the loads.

Continuous load path: Especially in high wind regions, designers should pay special attention to the entire roof-to-foundation load path when designing and specifying connections. Connections must be capable of withstanding simultaneous wind and flood forces. Poorly connected buildings may fail or float off of foundations when floodwaters and waves are higher than the design flood elevation. Corrosion-resistant connections are critical for the long-term integrity of the structure, and should be inspected and maintained periodically.

Emergency equipment: Equipment that is required for emergency functioning during or immediately after a storm surge event, such as emergency generators and fuel tanks, is best installed well above the design flood elevation.

Occupancy of surge-prone areas: Designers and owners should plan to use the lowest elevated floor for non-critical uses that, even if exposed to flooding more severe than the design flood, will not impair critical functioning during post-flood recovery.

2.3.5 RISK REDUCTION FOR RELATED FACILITIES

Critical facilities do not exist as purely independent buildings. They usually are accompanied by a variety of related facilities, such as utility installations both inside and outside of buildings, gas and electric services, water and wastewater services, above-ground or underground storage tanks, accessory structures and outbuildings, and access roads and parking lots.

2.3.5.1 Access Roads

Access roads to critical facilities should be designed to provide safe access at all times, to minimize impacts on flood hazard areas, to minimize damage to the road itself, and to minimize exposing vehicles to dangerous situations. Depending on the site and specific flood characteristics, balancing those elements can be difficult. Designers should take the following into consideration.

Safety factors: Although a critical facility's access road may not be required to carry regular traffic like other surface streets, a flood-prone road always presents a degree of risk to public safety. To minimize those risks, some State or local regulatory authorities require that access roads be designed so that the driving surface is no more than 1 to 2 feet below the DFE. To maximize evacuation safety, two separate accesses to different feeder roads are recommended. In some circumstances, especially long-duration flooding where a critical facility is built on fill, dry access may allow continued operations.

Floodplain impacts: Engineering analyses may be required to document the effects on flood elevations and flow patterns if large volumes of fill are required to elevate a road to minimize or eliminate flooding above the driving surface.

Drainage structure and road surface design: The placement of multiple drainage culverts, even if not needed for local drainage, can facilitate the passage of floodwaters and minimize the potential for a road embankment to act as a dam. Alternatively, an access road can be designed with a low section over which high water can flow without causing damage. Embankments should be designed to remain stable during high water and as waters recede. They should be sloped and protected to resist erosion and scour. Similarly, the surface and shoulders of roads that are intended to flood should be designed to resist erosion. The increased resistance to erosion may be accomplished by increasing the thickness of the road base.

2.3.5.2 Utility Installations

Utilities associated with new critical facilities in flood hazard areas must be protected either by elevation or special design and installation measures. Utilities subject to this provision include all systems, equipment, and fixtures, including mechanical, electrical, plumbing, heating, ventilating, and air conditioning. Potable water systems (wellheads and distribution lines) and wastewater collection lines are addressed in Section 2.3.5.3.

Utility systems and equipment are best protected when elevated above the DFE (plus freeboard, if required). In some cases, equipment can be located inside protective floodproofed enclosures, although it must be recognized that flooding that exceeds the design level of such an enclosure will adversely affect the equipment (see Figure 2-31). Designers should pay particular attention to underfloor utilities and ductwork to ensure that they are properly elevated. Plumbing conduits, water supply lines, gas lines and electric cables that must extend below the DFE should be located, anchored, and protected to resist the effects of flooding. Equipment that is outside of elevated building also must be elevated:

For more information on utility installations, see *Protecting Building Utilities from Flood Damage: Principles and Practices for the Design and Construction of Resistant Building Utility Systems* (FEMA 348, 1999).

- In A Zones, equipment may be affixed to raised support structures or mounted on platforms that are attached to or cantilevered from the primary structure.
- In V Zones and Coastal A Zones, equipment may be affixed to raised support structures designed for the flood conditions (waves, debris impact, erosion, and scour) or mounted on platforms that are attached to or cantilevered from the primary structure. If an enclosure is constructed under the elevated building, the designer must take care that utilities and attendant equipment are not mounted on or pass through walls that are intended to break away.

Figure 2-31: Equipment room with watertight door

SOURCE: PRESRAY CORPORATION

Although it is difficult to achieve, the model building codes and NFIP regulations provide an alternative that allows utility systems and equipment to be located below the DFE. This alternative requires that such systems and equipment be designed, constructed, and installed to prevent floodwaters from entering or accumulating within the components during flood events.

2.3.5.3 Potable Water and Wastewater Systems

New installations of potable water systems and wastewater collection systems are required to resist flood damage, including damage associated with infiltration of floodwaters and discharge of effluent. Health concerns arise when water supply systems are exposed to floodwaters. Contamination from flooded sewage systems poses additional health and environmental risks. Onsite water supply wellheads should be located on land elevated from the surrounding landscape to allow contaminated surface water and runoff to drain away. Well casings should extend above the design flood elevation, and casings should be sealed with a tight-fitting, floodproof, and vermin-proof well cap. The space between the well casing and the side of the well must be sealed to minimize infiltration and contamination by surface waters.

Sewer collection lines should be located and designed to avoid infiltration and backup due to rising floodwaters. Devices designed to prevent backup are available and are recommended to provide an added measure of protection.

Onsite sewage systems usually are not used as the primary sewage disposal system for new critical facilities. However, it would be prudent for owners, planners, and designers to consider a backup onsite sewage system if a facility's functionality will be impaired if the public system is affected by flooding. Designers are advised that local or State health departments may impose constraints that limit or prevent locating septic fields in floodplain soils or within a mapped flood hazard area. If allowed, septic fields should be located on the highest available ground to minimize inundation and impairment by floodwaters. An alternative to a septic field is installation of a holding tank that is sized to contain wastewater for a period of time, perhaps a few days if the municipal system is expected to be out of service.

2.3.5.4 Storage Tank Installations

Aboveground and underground storage tanks located in flood hazard areas must be designed to resist flotation, collapse, and lateral movement. ASCE 24 specifies that aboveground tanks are to be elevated or constructed, installed and anchored to resist at least 1.5 times the potential buoyant and other flood forces under design flood conditions, assuming the tanks are empty. Similarly, underground tanks are to be anchored to resist at least 1.5 times the potential buoyant forces under design flood conditions, assuming the tanks are empty. In all cases, designers are cautioned to address hydrodynamic loads and debris impact loads that may affect tanks that are exposed to floodwaters. Vents and fill openings or cleanouts should be elevated above the DFE or designed to prevent the inflow of floodwaters or outflow of the contents of tanks.

2.3.5.5 Accessory Structures

Depending on the type of accessory structures, full compliance with floodplain management regulations is appropriate and may be required. For example, buildings or portable classrooms that serve educational purposes (e.g., offices, classrooms), even if detached from the primary school building, are not considered to be accessory in nature and must be elevated and protected to the same standards as other buildings.

Some minor accessory structures need not fully comply, but may be "wet floodproofed" using techniques that allow them to flood while minimizing damage. Examples include small storage sheds, garages, and restrooms. Accessory structures must be anchored to resist flotation, collapse, and lateral movement. Flood-resistant materials must be used and utilities must be elevated above the DFE (plus freeboard, if required). Openings in walls must be provided to allow the free inflow and outflow of floodwaters to minimize the hydrostatic loads that can cause structural damage. Because wet floodproofed accessory buildings are designed to flood, critical facility staff must be aware that contents will be damaged.

2.4 RISK REDUCTION FOR EXISTING CRITICAL FACILITIES

2.4.1 INTRODUCTION

Section 2.2.2 describes the type of damage that can be sustained by critical facilities that already are located in flood hazard areas. The vulnerability of these facilities can be reduced if they can be made more resistant to flood damage. Decisionmakers may take such action when flood hazards are identified and there is a desire to undertake risk reduction measures proactively. Interest may be prompted by a flood or by the requirement to address flood resistance as part of proposed substantial improvement or an addition. Some questions and guidance intended to help identify building characteristics of importance when considering risk reduction measures for existing facilities are included in the checklist in Section 2.5.

Owners and operators of public and not-for-profit critical facilities should be aware of the importance of flood insurance coverage for facilities that are located in the flood hazard areas shown on NFIP maps. If not insured for flood peril, the amount of flood insurance that should have been in place will be deducted from any Federal disaster assistance payment that would otherwise have been made available. A particular facility may have to absorb up to $1 million in unreimbursed flood damage per building, because the NFIP offers $500,000 in building coverage and $500,000 in contents coverage for nonresidential buildings (coverage limits as of early 2006).

Work on existing buildings and sites is subject to codes and regulations, and the appropriate regulatory authority with jurisdiction should be consulted. With respect to reducing flood risks, work generally falls into the categories described in the following subsections.

2.4.2 SITE MODIFICATIONS

A plan to modify the site of an existing facility that is subject to flooding requires careful examination by an experienced professional engineer. Determining the suitability of a specific measure requires a complex evaluation of many factors, including the nature of flooding and the nature of the site. The first part of Table 2-3 in Section 2.5 identifies elements that influence the choice of mitigation measures applicable to existing sites. Some flood characteristics may make it infeasible to apply site modification measures to existing facilities (e.g., depths greater than 3 to 4 feet, very high velocities, insufficient warning because of flash flooding or rapid rate of rise, and very long duration).

A common problem with all site modifications is the matter of site access. Depending on the topography of the site, construction of barriers to floodwaters may require special access points. Access points may be protected with manually installed stop-logs or designed gates that drop in, slide, or float into place. Whether activated by automatic systems or manually operated, access protection requires sufficient warning time.

Other significant constraining factors include poor soils and insufficient land area which can make site modifications either infeasible or very costly. A critical facility may be among several buildings and properties that can be protected, increasing the benefits. For any type of barrier, rainfall that collects on the land side must be accounted for in the design, whether through adequately sized stormwater storage basins constructed on land set aside for this purpose, or by providing large-capacity pumps to move collected water to the water side of the barrier.

Each of these site modification measures described below has limitations, including the fact that floods larger than the design flood will exceed the level of protection.

Regrading the site (berm): Where a facility is exposed to relatively shallow flooding and sufficient land area is available, regrading the site or constructing an earthen berm may provide adequate protection.

Earthen levee: Earthen levees are engineered structures that are designed to keep water away from land area and buildings. Hydraulic analyses and geotechnical investigations are required to determine their feasibility and effectiveness. For existing sites, constraints include the availability of land (levees have a large "footprint" and require large land areas), cost (including availability of suitable fill material and long-term maintenance), and difficulties with site access. Levees are rarely used to protect a single site, although they may offer a reasonable solution for a group of buildings. Locating levees and floodwalls within a designated floodway is generally not allowed. Rapid onset flooding makes it impractical to design a flood levee with access points that require installation of a closure system. Earthen levees may also be subject to high velocity flows that cause erosion and affect their stability.

Permanent floodwall: Floodwalls are freestanding, permanent engineered structures that are designed to prevent encroachment of floodwaters. Typically, a floodwall is located some distance from a building, so that structural modification of the existing building is not required. Floodwalls may protect only the low side of a site (in which case they must "tie" into high ground) or completely surround a site (which may affect access because special closure structures are required and must be installed before the onset of flooding, see Figure 2-32).

Figure 2-32:
A masonry floodwall with multiple engineered openings protected the Oak Grove Lutheran School in Fargo, ND from flooding in 2001.

SOURCE: FLOOD CENTRAL AMERICA, LLC

Mobilized floodwall: This category of flood protection measures includes fully engineered flood protection structures that have permanent features (foundation and vertical supports) and features that require human intervention when a flood is predicted (horizontal components called planks or stop-logs). Mobilized floodwalls have been used to protect entire sites, or to tie into permanent floodwalls or high ground. Because of the manpower and time required for proper placement, these measures are better suited to conditions that allow long warning times.

2.4.3 ADDITIONS

All model building codes generally treat additions as new construction and require additions to critical facilities in flood hazard areas to be elevated or dry floodproofed to minimize exposure to flooding. However, full compliance with the code and NFIP requirements is only required if an addition is a substantial improvement (i.e., the cost of the addition plus all other work equals or exceeds 50 percent of the market value of the building). Designers are cautioned that existing buildings as well may be required to be brought into compliance with the flood-resistant provisions of the code or local ordinances if the addition is structurally connected to the existing building.

For more information on additions and substantial improvements, see *Answers to Questions About Substantially Damaged Buildings* (FEMA 213, 1991).

Section 2.3.1.2 outlines elevation options that are applicable to additions in A Zones (see Section 2.3.2.1 for elevation considerations applicable to additions in V Zones). Elevation of an addition on fill may not be feasible unless structural fill can be placed adjacent to the existing building. Utility service equipment for additions must meet the requirements for new installations (see Section 2.3.5.2).

With respect to code compliance and designing additions to resist flood damage, one of the more significant issues that may come up is ease of access. If the lowest floor of the existing facility is below the DFE, steps, ramps, or elevators will be required for the transition to the new addition. Some jurisdictions may wish to allow variances to the requirement for elevation, because alternative means of access are available, such as ramps and elevators.

Under the regulations of the NFIP and FEMA guidance, it is not considered appropriate to grant such a variance.

2.4.4 REPAIRS, RENOVATIONS, AND UPGRADES

Every critical facility that is considered for upgrades and renovations, or that is being repaired after substantial damage from any cause, must be examined for structural integrity and stability to determine compatibility with structural modifications that may be required to achieve acceptable performance. When an existing facility is located in a flood hazard area, that examination should include consideration of measures to resist flood damage and reduce risks.

The model building codes and the regulations of the NFIP require that work constituting "substantial improvement" of an existing building be in compliance with the flood-resistant provisions of the code. Non-substantial improvements should take into account measures to reduce future flood damage, such as those described in Section 2.4.8, and wet floodproofing measures that allow water to enter the building to avoid structural damage, as well as emergency measures (see Section 2.4.9).

Additional information on rehabilitation of existing buildings is provided in *Flood Proofing: How to Evaluate Your Options* (USACE, 1993), *Floodproofing Non-Residential Structures* (FEMA 102), *Floodproofing—Requirements and Certification* (FIA-TB-3), and *Engineering Principles and Practices for Retrofitting Flood-prone Buildings* (FEMA 259, 1995). Although written primarily for homes, this last reference contains very detailed checklists and worksheets that can be modified. They also provide some guidance for evaluating the costs and benefits of various measures.

Compliance with flood-resistant provisions means the existing building must be elevated or dry floodproofed. Both options can be difficult for existing critical facilities, given the typical use, size, and complexity of some of these buildings. Retrofit dry floodproofing (described in Section 2.4.5) is generally limited to water depths of 3 feet or less, unless the structural capacity of the buildings have been assessed by a qualified design professional and found to be capable of resisting the anticipated loads.

Elevating an existing building presents an entirely different set of challenges and also requires detailed structural engineering analyses. It involves the same equipment and methods used to move other types of buildings; expert building movers have successfully moved large, heavy, and complex buildings, sometimes by segmenting them. A critical facility that is elevated in-place must meet the same performance standards set for new construction.

2.4.5 RETROFIT DRY FLOODPROOFING

Modification of an existing building may be required or desired in order to address exposure to design flood conditions. Modifications that may be considered include construction of a reinforced supplementary wall, measures to counter buoyancy (especially if there is below-grade space), installation of special watertight door and window barriers (see Figure 2-33), and providing watertight seals around the points of entry of utility lines. The details of structural investigations and structural design of such protection measures are beyond the scope of this manual.

"Dry floodproofing" refers to measures and methods to render a building envelope substantially impermeable to floodwater.

Figure 2-33: Boulder Community Hospital, Boulder, CO installed this permanently mounted floodgate in a low floodwall; the floodgate swings to the left to close off the door that leads to the mechanical equipment room.

Because of the tremendous flood loads that may be exerted on a building not originally designed for such conditions, detailed structural engineering evaluations are required to determine whether an existing building can be dry floodproofed. The following elements must be examined:

- The strength of the structural system
- Whether non-load bearing walls can resist anticipated loads; secondary walls can be constructed immediately adjacent to existing walls, with a waterproof membrane, to provide adequate strength
- The effects of buoyancy on the walls and floors of below-grade areas
- Effective means to install watertight doors and windows, or mountable panels
- Protection where utilities enter the building
- Methods to address seepage, especially where long-duration flooding is anticipated
- Whether there is sufficient time for human intervention measures, given the availability of official warnings of predicted flood conditions

Application of waterproofing products or membranes directly to exterior walls may minimize infiltration of water, although there are concerns with durability and limitations on use (this measure is most effective for shallow, short-duration flooding). Retrofit measures that require human intervention are considered emergency measures and are discussed in Section 2.4.9.

2.4.6 UTILITY INSTALLATIONS

Some aspects of an existing flood-prone critical facility's utility systems may be modified to reduce damage. The effectiveness of such measures depends not only on the nature of the flooding, but the type of utility and the degree of exposure. Table 2-3 in Section 2.5 lists some questions that will help facility planners and designers to examine risk reduction measures.

Even if a facility is unlikely to sustain extensive structural damage from flooding, high costs and delayed reoccupancy may result from flood-damaged utility systems. The risk reduction design measures described below can be applied, whether undertaken as part of large-scale retrofits of existing buildings, or as separate projects.

Additional guidance on improving the flood resistance of utility installations in existing buildings is found in FEMA 348, *Protecting Building Utilities From Flood Damage: Principles and Practices for the Design and Construction of Flood Resistant Building Utility Systems.*

Relocate from below-grade areas: The most vulnerable utility installations are those located below grade, and the most effective protection measure is to relocate them to properly elevated floors or platforms that are at least 2 feet above the DFE. The complexity of rerouting pipes, conduits, ductwork, electrical service, lines, and connections will depend on site-specific factors.

Elevate components: Whether located inside or outside of the building, some components of utility systems can be elevated-in-place on platforms, including electric transformers, communications switch boxes, water heaters, air conditioning compressors, furnaces, boilers, and heat pumps (see Figure 2-34).

Figure 2-34:
Elevated utility box

Anchor tanks and raise openings: Existing tanks can be elevated or anchored, as described in Section 2.3.5.4. If anchored below the DFE, tank inlets, vents, fill pipes, and openings should be elevated above the DFE, or fitted with covers designed to prevent the inflow of floodwaters or outflow of the contents of the tanks.

Protect components: If utility components cannot be elevated, it may be feasible to construct watertight enclosures, or enclosures with watertight seals that require human intervention to install when flooding is predicted.

Elevate control equipment: Control panels, gas meters, and electrical panels can be elevated, even if the equipment they service cannot be protected.

Separate electrical controls: Where areas within an existing facility are flood-prone, separation of control panels and electrical feeders will facilitate shutdown before floodwaters arrive, and help protect workers during cleanup.

Protect against electrical surges: Current fluctuations and service interruptions are common in areas affected by flooding. Equipment and sensitive electrical components can be protected by installing surge protection and uninterruptible power supplies.

Connections for portable generators: Pre-wired portable generator connections allow for quick, failure-free connection and disconnection of the generators when needed for continued functionality.

2.4.7 POTABLE WATER AND WASTEWATER SYSTEMS

All plumbing fixtures that are connected to the potable water system may become weak points in the system if they allow floodwaters to contaminate the system. Relocating the uses that require plumbing to elevated floors and removing the fixtures that are below the DFE provides protection. Wellheads can be sealed with watertight casings or protected within sealed enclosures.

Wastewater system components become sources of contamination during floods. Rising floodwaters may force untreated sewage to backup through toilets. Specially designed back-flow devices can be installed, or restrooms below the DFE can be provided with overhead piping that may require specially designed pumps to operate properly. Septic tanks can be sealed and anchored.

2.4.8 OTHER DAMAGE REDUCTION MEASURES

A number of steps can be taken to make existing facilities in flood hazard areas more resistant to flood damage, which also facilitates rapid recovery, cleanup, and reoccupancy. Whether these measures are applicable to a specific facility depends, in part, on the characteristics of the flood hazard and the characteristics of the building itself. Facility planners and designers should consider the following:

- ❍ Rehabilitate and retrofit the building envelope with openings specifically designed to allow floodwaters to flow in and out to minimize hydrostatic pressure on walls (called wet floodproofing, see Figure 2-35). Although it allows water to enter the building, this measure minimizes the likelihood of major structural damage. Walls that enclose interior spaces would also be retrofitted with openings.

Figure 2-35:
The enclosed entry and storage area to the right of the fire truck bays were retrofitted with flood openings.

SOURCE: SMART VENT, LLC

❍ Replace interior walls that have cavities with flood-resistant construction or removable panels to facilitate cleanup and drying.

❍ Abandon the use of below-grade areas (basements) by filling them in to prevent structural damage.

❍ Permanently relocate high-value or sensitive functions that are often found on the ground floor of critical facilities (e.g., offices, records, libraries, and computer laboratories) to higher floors or elevated additions.

❍ Install backflow devices in sewer lines.

❍ Pre-plan actions to move high-value contents from the lower floors to higher floors when a flood warning is issued.

❍ Replace wall, flooring, and finish materials with flood-resistant materials.

❍ Use epoxy or other impervious paints on concrete and other permeable surfaces to minimize contamination.

❍ Install separate electric circuits and ground fault interrupter circuit breakers in areas that will flood. Emergency measures should be provided so that electrical service can be shut down to avoid electrocution hazards.

❍ Relocate chemicals to storage areas not subject to flooding.

2.4.9 EMERGENCY MEASURES

Emergency response to flooding is outside the scope of this manual. However, it is appropriate to examine feasible emergency measures that may provide some protection. The following discussion pertains only to emergency measures that have been used to reduce flood damage to older buildings that are already located in flood hazard areas. These measures do not achieve compliance with building and life safety codes, they may not provide protection to occupants, and they can experience a high frequency of failure depending on human factors related to deployment.

Emergency barriers are measures of "last resort," and should be used only when a credible flood warning with adequate lead-time is available and dependable. These measures have varying degrees of success, depending on the available manpower, skill required, long-term maintenance of materials and equipment, suitability for site-specific flood conditions, and having enough advanced warning. Complete evacuation of protected buildings is required, as these measures should not be considered adequate protection for occupants. Furthermore, emergency barriers are not acceptable in lieu of designed flood resistant protection for new buildings.

Sandbag walls: Unless emergency placement is planned well in advance or under the direction of trained personnel, most sandbag barriers are not constructed in accordance with proper practices, leading to leakage and failures. Because of the intensive work effort and length of time required for protection from even relatively shallow water, sandbag walls are not a reliable protection measure. To be effective, sandbags and sand should be stockpiled and checked regularly to ensure that sandbags have not deteriorated. Sandbags have some other drawbacks, including high disposal costs and their tendency to absorb pollutants from contaminated floodwaters, which necessitates disposal as hazardous waste.

Water-filled barriers: A number of vendors make water-filled barriers that can be assembled with relative ease, depending on the source of water for filling. The barriers must be specifically sized for the site. Training and annual drills are important so that personnel know how to place and deploy the barriers. Proper storage, including cleaning after deployment, is necessary to protect the materials over long periods of time.

Panels for doors: For shallow and short-duration flooding, panels of sturdy material can be made to fit doorways to minimize the entry of floodwaters. Effectiveness is increased significantly if a flexible gasket or sealant is provided, and the mounting hardware is designed to apply even pressure. Personnel must know where the materials are stored and be trained in their deployment. A number of vendors make special doors for permanent installation and drop-in panels or barriers that are designed to be watertight (see Figure 2-36).

Figure 2-36:
Example of an aluminum flood barrier used for flooding less than 3 feet deep.

SOURCE: SAVANNAH TRIMS

2.5 CHECKLIST FOR BUILDING VULNERABILITY OF FLOOD-PRONE CRITICAL FACILITIES

The Checklist for Building Vulnerability of Flood-Prone Critical Facilities (Table 2-3) is a tool that can be used to help assess site-specific flood hazards and building vulnerability. The checklist is useful during site selection, preliminary design of a new building, or when considering rehabilitation of an existing facility. In addition to examining building design issues that affect vulnerability, the checklist also helps users to examine the functionality of the critical and emergency systems upon which most critical facilities depend. The checklist is organized into separate sections, so that each section can be assigned to a subject expert for greater accuracy of the examination. The results should be integrated into a master vulnerability assessment to guide the design process and the choice of appropriate mitigation measures.

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities

Vulnerability Sections	Guidance	Observations
Site Conditions		
Is the site located near a body of water (with or without a mapped flood hazard area)? Is the site in a flood hazard area shown on the community's map (FIRM or other adopted map)? If so, what is the flood zone?	All bodies of water are subject to flooding, but not all have been designated as a floodplain on FIRMs. Flood hazard maps usually are available for review in local planning and permit offices. Electronic versions of the FIRMs may be available online at www.fema.gov. Paper maps may be ordered by calling (800) 358-9616.	

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Site Conditions (continued)		
(continued) Is the site affected by a regulatory floodway ? Is the site located in a storm surge inundation zone (or tsunami inundation area)?	(continued) Development in floodways, where floodwaters typically are fast and deep, must be supported by engineering analyses. In coastal communities, even sites at some distance inland from the shoreline may be exposed to extreme storm surge flooding. Storm surge maps may be available at State or local emergency management offices.	
What is the DFE (or does an analysis have to be done to determine the DFE)? What is the minimum protection level required by regulatory authorities? Does the FIS or other study have information about the 500-year flood hazard area? Has FEMA issued post-disaster advisory flood elevations and maps? What are the expected depths of flooding at the site (determined using flood elevations and ground elevations)?	Reference the FIS for flood profiles and data tables. Site-specific analyses should be performed by qualified engineers. Check with regulatory authorities to determine the required level of protection. If a major flood event has affected the community, FEMA may have issued new flood hazard information, especially if areas not shown on the FIRMs have been affected. Sometimes these maps are adopted and replace the FIRMs; sometimes the new data are advisory only.	
Has the site been affected by past flood events? What is the flood of record?	Records of actual flooding augment studies that predict flooding, especially if historic events resulted in deeper or more widespread flooding. Information may be available from local planning, emergency management, and public works agencies, or State agencies, the U.S. Army Corps of Engineers, or the Natural Resources Conservation Service. The flood of record is often a lower probability event (with higher flood elevations) than the 100-year flood.	

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Site Conditions (continued)		
What is the expected velocity of floodwaters on the site? Are waves expected to affect the site?	Velocity is a factor in computing loads associated with hydrodynamic forces, including drag on building surfaces. Approximations of velocity may be interpolated from data in the FIS Floodway Data Table if the waterway was studied using detailed methods, application of approximation methods based on continuity, local observations and sources, or site-specific studies. Waves can exert considerable dynamic forces on buildings and contribute to erosion and scour. Wind-driven waves occur in areas subject to coastal flooding and where unobstructed winds affect wide floodplains (large lakes and major rivers). Standing waves may occur in riverine floodplains where high velocities are present.	
Is there information on how quickly floodwaters may affect the site? What is the expected duration of flooding?	Warning time is a key factor in the safe and orderly evacuation of critical facilities. Certain protective measures may require adequate warning so that actions can be taken by skilled personnel. Duration has bearing on the stability of earthen fills, access to a site and emergency response, and durability of materials that come into contact with water. Records of actual flooding are the best indicator of duration as most floodplain analyses do not examine duration.	
Is there a history of flood-related debris problems or erosion on the site?	Site design should account for deposition of debris and sediment, as well as the potential for erosion-related movement of the shoreline or waterway. Buildings exposed to debris impact or undermining by scour and erosion should be designed to account for these conditions.	
Is the site within an area predicted to flood if a levee or floodwall fails or is overtopped? Is the site in an area predicted to be inundated if an upstream dam were to fail?	Flood protection works may be distant from sites and not readily observable. Although a low probability event, failure or overtopping can cause unexpected and catastrophic damage because the protected lands are not regulated as flood hazard areas.	

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Site Conditions (continued)		
	(continued) The effects of an upstream dam failure are not shown on the FIRMs or most flood hazard maps prepared locally. Although dam failure generally is considered an unlikely event, the potential threat should be evaluated due to the catastrophic consequences. (Note: owners of certain dams should have emergency action plans geared toward notification and evacuation of vulnerable populations and critical facilities.)	
Does the surrounding topography contribute to the flooding at the site? Is there a history of local surface drainage problems due to inadequate site drainage?	If areas with poor local drainage and frequent flooding cannot be avoided, filling, regrading, and installation of storm drainage facilities may be required.	
Given the nature of anticipated flooding and soils, is scour around and under the foundation likely?	Scour-prone sites should be avoided, in part due to likely long-term maintenance requirements. Flooding that is high velocity or accompanied by waves is more likely to cause scour, especially on fills, or where local soils are unconsolidated and subject to erosion.	
Has water from other sources entered the building (i.e., high groundwater, water main breaks, sewer backup, etc.)? Is there a history of water intrusion through floor slabs or well-floor connections? Are there underground utility systems or areaways that can contribute to basement flooding? Are there stormwater sewer manholes upslope of window areas or openings that allow local drainage to enter the basement/lower floor areas?	These questions pertain to existing facilities that may be impaired by water from sources other than the primary source of flooding. The entire building envelope, including below-grade areas, should be examined to identify potential water damage.	

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Site Conditions (continued)		
Is at least one access road to the site/building passable during flood events? Are at-grade parking lots located in flood-prone areas? Are below-grade parking areas susceptible to flooding?	Access is increasingly important as the duration of flooding increases. For the safety of occupants, most critical facilities should not be occupied during flood events. Areas where vehicles could be affected should have signage to warn users of the risk. Emergency response plans should include notification of car owners.	
Are any portions of the building below the Design Flood Elevation? Has the building been damaged in previous floods?	For existing buildings, it is important to determine which portions are vulnerable in order to evaluate floodproofing options. If flood depths are expected to exceed 2 or 3 feet, dry floodproofing may not be feasible. Alternatives include modifying the use of flood-prone areas.	
Are any building spaces below-grade (basements)?	Below-grade spaces and their contents are most vulnerable to flooding and local drainage problems. Rapid pump out of below-grade spaces can unbalance forces if the surrounding soil is saturated, leading to structural failure. If below-grade spaces are intended to be dry floodproofed, the design must account for buoyant forces.	
Are any critical building functions occupying space that is below the elevation of the 500-year flood or the Design Flood Elevation? Can critical functions be relocated to upper levels that are above predicted flood elevations? If critical functions cannot be relocated, is floodproofing feasible? If critical functions must continue during a flood event, have power, supplies, and access issues been addressed?	New critical facilities built in flood hazard areas should not have any functions occupying flood-prone spaces (other than parking, building access and limited storage). Existing facilities in floodplains should be examined carefully to identify the best options for protecting functionality and the structure itself.	

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Site Conditions (continued)		
Have critical contents (files, computers, servers, equipment, research, and data) been located on levels of the facility above the flood elevations? Are critical records maintained off-site?	For existing facilities that are already located in flood hazard areas, the nature of the facility may require continued use of flood-prone space. However, the potential for flooding should be recognized and steps taken to minimize loss of expensive equipment and irreplaceable data. If critical contents cannot be permanently located on higher floors, a flood response plan should take into account the time and attention needed to move such contents safely.	
Building Envelope		
Are there existing floodproofing measures in place below the expected flood elevation? What is the nature of these measures and what condition are they in? Is there an annual inspection and maintenance plan? Is there an "action plan" to implement floodproofing measures when flooding is predicted? Do the building operators/occupants know what to do when a flood warning is issued?	Floodproofing measures are only as good as the design and their condition, especially if many years have passed since initial installation. Floodproofing measures that require human intervention are entirely dependent on the adequacy of advance warning, and the availability and ability of personnel to properly install the measures.	
For existing buildings, what types of openings penetrate the building envelope below the 500-year flood elevation or the DFE (doors, windows, cracks, vent openings, plumbing fixtures, floor drains, etc.)?	For dry floodproofing to be effective, every opening must be identified and measures taken to permanently seal or to prepare special barriers to resist infiltration. Sewage backflow can enter through unprotected plumbing fixtures.	
Are flood-resistant materials used for structural and nonstructural components and finishes below the 500-year elevation or the DFE?	Flood-resistant materials are capable of withstanding direct and prolonged contact with floodwaters without sustaining damage that requires more than cosmetic repair. Contact is considered to be prolonged if it is 72 hours or longer in freshwater flooding areas, or 12 hours or longer in areas subject to coastal flooding.	

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Utility Systems		
Is the potable water supply for the facility protected from flooding? If served by a well, is the wellhead protected?	Operators of critical facilities that depend on fresh water for continued functionality should learn about the vulnerability of the local water supply system and the system's plans for recovery of service in the event of a flood.	
Is the wastewater service for the building protected from flooding? Are any manholes below the DFE? Is infiltration of floodwaters into sewer lines a problem? If the site is served by an onsite system that is located in a flood-prone area, have backflow valves been installed?	Most waste lines exit buildings at the lowest elevation. Even buildings that are outside of the floodplain can be affected by sewage backups during floods.	
Are there any aboveground or underground tanks on the site in flood hazard areas? Are they installed and anchored to resist flotation during the design flood? Are tank openings and vents elevated above the 500-year elevation or the DFE, or otherwise protected to prevent entry of floodwater or exit of product during a flood event?	Dislodged tanks become floating debris that pose special hazards during recovery. Lost product causes environmental damage. Functionality may be impaired if tanks for heating fuel, propane, or fuel for emergency generators are lost or damaged.	
Mechanical Systems		
Are air handlers, HVAC systems, ductwork, and other mechanical equipment and systems located above the 500-year elevation or the DFE? Are the vents and inlets located above flood level, or sealed to prevent entry of floodwater?	In existing buildings, utility equipment that is critical for functionality should be relocated to higher floors or into elevated additions.	

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Plumbing and Gas Systems		
Are plumbing fixtures and gas-fired equipment (meters, pilot light devices/burners, etc.) located above the 500-year elevation or the DFE?	In existing buildings, utility equipment that is critical for functionality should be relocated to higher floors or into elevated additions.	
Is plumbing and gas piping that extends below flood levels installed to minimize damage?	Piping that is exposed could be impacted by debris.	
Electrical Systems		
Are electrical systems, including backup power generators, panels, and primary service equipment, located above the 500-year elevation or the DFE? Are pieces of electrical stand-by equipment and generators equipped with circuits to turn off power? Are the switches and wiring required for safety (minimal lighting, door openers) located below the flood level designed for use in damp locations?	In existing buildings, utility equipment that is critical for functionality should be relocated to higher floors or into elevated additions.	
Fire Alarm Systems		
Is the fire alarm system located above the 500-year elevation or the DFE?	In existing buildings, utility equipment that is critical for functionality should be relocated to higher floors or into elevated additions.	
Communications and IT Systems		
Are the communication/IT systems located above the 500-year elevation or the DFE?		

Table 2-3: Checklist for Building Vulnerability of Flood-Prone Critical Facilities (continued)

Vulnerability Sections	Guidance	Observations
Structural		
What is the construction type and the foundation type and what is the load bearing capacity? Has the foundation been designed to resist hydrostatic and hydrodynamic flood loads? If the building has below-grade areas, are the lower floor slabs subject to cracking and uplift?	If siting in a floodplain is unavoidable, new facilities are to be designed to account for all loads and load combinations, including flood loads. Building spaces below the design flood level can be dry floodproofed, although it must be recognized that higher flood levels will overtop the protection measures and may result in severe damage. Dry floodproofing creates large unbalanced forces that can jeopardize walls and foundations that are not designed to resist the hydrostatic and hydrodynamic loads.	
If the building is elevated on a crawlspace an open foundation, are there any enclosed areas?	New buildings may have enclosures below the flood elevation provided the use of the enclosures is limited (crawlspace, parking, building access, limited storage). In addition, the enclosures must have flood openings to automatically allow for inflow and outflow of floodwaters to minimize differential hydrostatic pressure. Existing buildings that are elevated and have enclosures below the flood elevation can be retrofit with flood openings.	
For an existing building with high value uses below the flood elevation, is the building suitable for elevation-in-place or can it be relocated to higher ground?	Elevating a building provides better protection than dry floodproofing. Depending on the type and soundness of the foundation, even large buildings can be elevated on a new foundation or moved to a site outside of the floodplain.	

2.6 REFERENCES AND SOURCES OF ADDITIONAL INFORMATION

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American Society of Civil Engineers, Structural Engineering Institute, *Minimum Design Loads for Buildings and Other Structures*, ASCE/SEI 7-05, Reston, VA, 2005.

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FEMA, *Design and Construction Guidance for Community Shelters,* FEMA 361, Washington, DC, July 2000.

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FEMA, *Protecting Building Utilities From Flood Damage: Principles and Practices for the Design and Construction of Flood Resistant Building Utility Systems,* FEMA 348, Washington, DC, November 1999.

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- *User's Guide to Technical Bulletins*, FIA-TB-0, April 1993.
- *Openings in Foundation Walls,* FIA-TB-1, April 1993.
- *Flood-Resistant Materials Requirements*, FIA-TB-2, April 1993.
- *Non-Residential Floodproofing—Requirements and Certification*, FIA-TB-3, April 1993.
- *Elevator Installation*, FIA-TB-4, April 1993.
- *Free-of-Obstruction Requirements*, FIA-TB-5, April 1993.
- *Below-Grade Parking Requirements*, FIA-TB-6, April 1993.
- *Wet Floodproofing Requirements*, FIA-TB-7, December 1993.
- *Corrosion Protection for Metal Connections in Coastal Areas*, FIA-TB-8, 1996.
- *Design and Construction Guidance for Breakaway Walls Below Elevated Coastal Buildings*, FIA-TB-9, 1999.
- *Ensuring That Structures Built on Fill In or Near Special Flood Hazard Areas Are Reasonably Safe From Flooding*, FIA-TB-10, 2001.
- *Crawlspace Construction for Buildings Located in Special Flood Hazard Areas*, FIA-TB-11, 2001.

International Code Council, Inc., *ICC Performance Code for Buildings and Facilities*, Country Club Hills, IL, 2003.

International Code Council, Inc., *International Building Code*, Country Club Hills, IL, 2003.

International Code Council, Inc. and FEMA, *Reducing Flood Losses Through the International Codes, Meeting the Requirements of the National Flood Insurance Program* (2nd Edition), Country Club Hills, IL, 2005.

National Fire Protection Association, *Building Construction and Safety Code* (NFPA 5000), Quincy, MA, 2003.

U.S. Army Corps of Engineers, *Flood Proofing Regulations*, EP 1165-2-314, Washington, DC, 1995.

U.S. Army Corps of Engineers, National Flood Proofing Committee, *Flood Proofing – How To Evaluate Your Options*, Washington, DC, July 1993.

U.S. Army Corps of Engineers, *Flood Proofing Programs, Techniques and References,* Washington, DC, 1996.

U.S. Army Corps of Engineers, *Flood Proofing Performance—Successes & Failures*, Washington, DC, 1998.

Organizations and Agencies:

FEMA: FEMA's regional offices (www.fema.gov) can be contacted for advice and guidance on NFIP mapping and regulations.

NFIP State Coordinating offices help local governments to meet their floodplain management obligations, and may provide technical advice to others; the offices are listed by the Association of State Floodplain Managers, Inc. (www.floods.org/stcoor.htm).

State departments of education or agencies that coordinate State funding and guidelines for critical facilities may have State-specific requirements.

U.S. Army Corps of Engineers: District offices offer Flood Plain Management Services (www.usace.army.mil/inet/functions/cw/).

FEMA publications may be obtained at no cost by calling (800) 480-2520, faxing a request to (301) 497-6378, or downloaded from the library/publications section online at http://www.fema.gov.

MAKING CRITICAL FACILITIES SAFE FROM HIGH WIND

3

3.1 GENERAL DESIGN CONSIDERATIONS

Wind with sufficient speed to cause damage to weak critical facilities can occur anywhere in the United States and its territories. Even a well-designed, constructed, and maintained critical facility may be damaged in a wind event much stronger than one the building was designed for. However, except for tornado damage, this scenario is a rare occurrence. Rather, most damage occurs because various building elements have limited wind resistance due to inadequate design, poor installation, or material deterioration. Although the magnitude and frequency of strong windstorms vary by locale, all critical facilities should be designed, constructed, and maintained to minimize wind damage (other than that associated with tornadoes—see Section 3.5).

This chapter discusses structural, building envelope, and nonstructural building systems, and illustrates various types of wind-induced damage that affect them. Numerous examples of best practices pertaining to new and existing critical facilities are presented as recommended design guidelines. Incorporating those practices applicable to specific projects will result in greater wind resistance reliability and will, therefore, decrease expenditures for repair of wind-damaged facilities, provide enhanced protection for occupants, and avoid disruption of critical services.

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1. The U.S. territories include American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. ASCE provides basic wind speed criteria for all but Northern Mariana Islands.

3.1.1 NATURE OF HIGH WINDS

A variety of windstorm types occur in different areas of the United States. The characteristics of the types of storms that can affect the site should be considered by the design team. The primary storm types are listed below.

Straight-line wind: This type of wind generally blows in a straight line and is the most common. Straight-line wind speeds range from very low to very high. High winds associated with intense low pressure can last for approximately a day at a given location. Straight-line winds occur throughout the United States and its territories.

Down-slope wind: Wind blowing down the slope of mountains is referred to as down-slope wind. Down-slope winds with very high speeds frequently occur in Alaska and Colorado. In the continental United States, mountainous areas are referred to as "special wind regions" (see Figure 3-1). Neither ASCE 7 nor model building codes provide specific wind speeds in special wind regions. ASCE 7 does provide guidance on how to determine design wind speeds in these regions. If the local building department has not established the basic speed, use of regional climatic data and consultation with a wind engineer or meteorologist is advised.

ASCE 7, *Minimum Design Loads for Buildings and Other Structures*, provides guidance for determining wind loads on buildings. The IBC and NFPA 5000 refer to ASCE 7 for wind load determination.

Thunderstorm: This type of storm can form rapidly and produce high wind speeds. Approximately 10,000 severe thunderstorms occur in the United States each year, typically in the spring and summer. They are most common in the Southeast and Midwest. Besides producing high winds, they often create heavy rain and sometimes spawn tornadoes and hail storms. Thunderstorms commonly move through an area quite rapidly, causing high winds for only a few minutes at a given location. However, thunderstorms can also stall and become virtually stationary.

Downburst: Also known as a microburst, this is a powerful downdraft associated with a thunderstorm. When the downdraft reaches the ground, it spreads out horizontally, and may form one or more horizontal vortex rings around the downdraft. The outflow is typically 6,000 to 12,000 feet across, and the vortex ring may rise 2,000 feet above the ground. The lifecycle of a downburst is usually 15 to 20 minutes. Observations suggest that approximately 5 percent of all thunderstorms produce a downburst, which can result in significant damage in a localized area.

Northeaster (nor'easter): A northeaster is a cyclonic storm occurring off the east coast of North America. These winter weather events are notorious for producing heavy snow, rain, and high waves and wind. A nor'easter gets its name from the continuously strong northeasterly winds blowing in from the ocean ahead of the storm and over the coastal areas. These storms may last for several days.

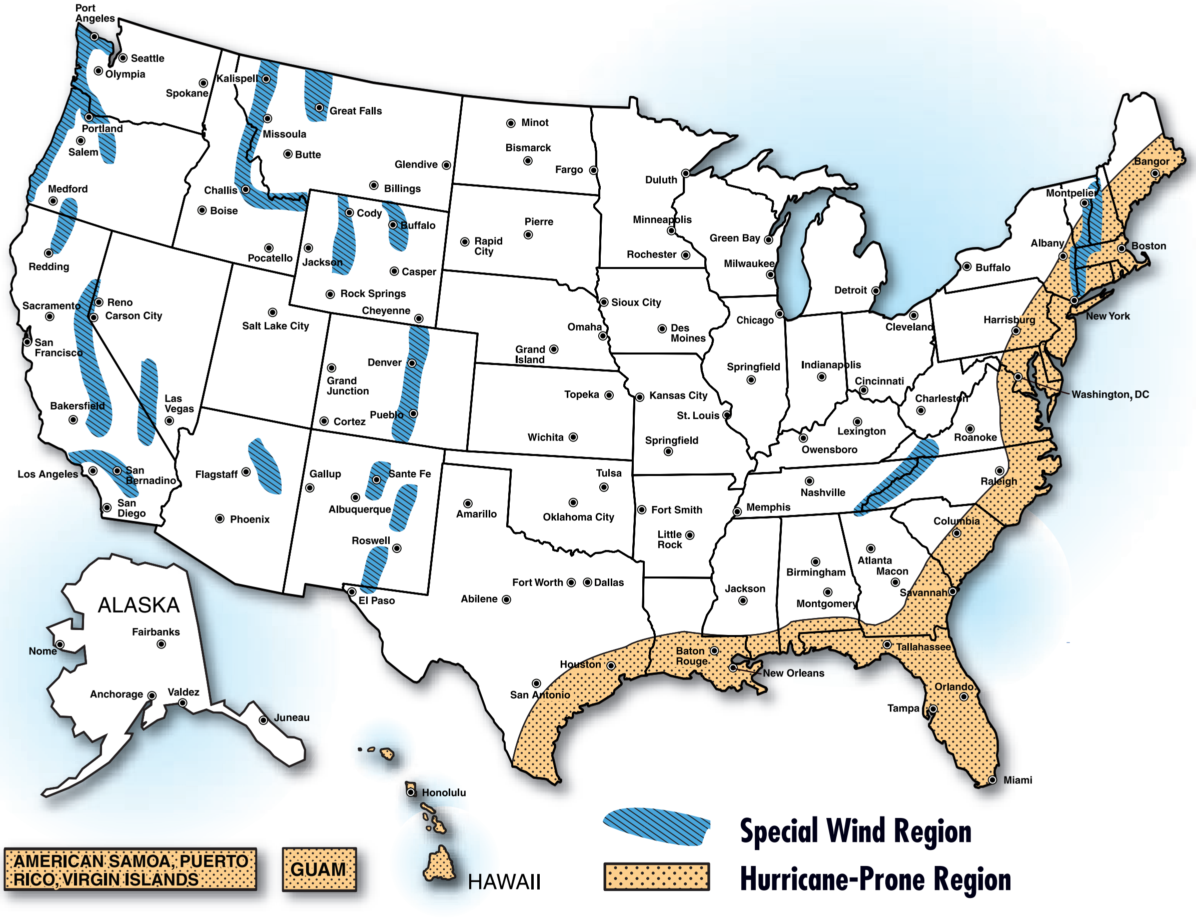


Figure 3-1: Hurricane-prone regions and special wind regions

SOURCE: ADAPTED FROM ASCE 7-05

Hurricane: This is a system of spiraling winds converging with increasing speed toward the storm's center (the eye of the hurricane). Hurricanes form over warm ocean waters. The diameter of the storm varies and can be between 50 and 600 miles. A hurricane's forward movement (translational speed) can vary between approximately 5 miles per hour (mph) to more than 25 mph. Besides being capable of delivering extremely strong winds for several hours and moderately strong winds for a day or more, many hurricanes also bring very heavy rainfall. Hurricanes also occasionally spawn tornadoes. The Saffir-Simpson Hurricane Scale (see Table 3-1) categorizes the intensity of hurricanes. The five-step scale ranges from Category 1 (the weakest) to Category 5 (the strongest). Hurricane-prone regions are defined in Section 3.1.3.

The Saffir-Simpson Hurricane Scale is based on measurements of sustained wind speeds in hurricanes; these measurements are taken over open water. The wind speeds described in the Saffir-Simpson Hurricane Scale are used to prepare storm response actions and are not intended to be used for building design. Design wind loads on buildings should be determined using the basic wind speeds given in ASCE 7.

Of all the storm types, hurricanes have the greatest potential for devastating a large geographical area and, hence, affect the greatest number of people. The terms "hurricane," "cyclone," and "typhoon" describe the same type of storm. The term used depends on the region of the world where the storm occurs. See Figure 3-1 for hurricane-prone regions.

Table 3-1: Saffir-Simpson Hurricane Scale

Strength	Sustained Wind Speed (mph)*	Gust Wind Speed (mph)**	Pressure (millibar)
Category 1	74-95	89-116	>980
Category 2	96-110	117-134	965-979
Category 3	111-130	135-159	945-964
Category 4	131-155	160-189	920-944
Category 5	>155	>189	<920

* 1-minute sustained over open water

** 3-second gust over open water

Tornado: This is a violently rotating column of air extending from the base of a thunderstorm to the ground. The Fujita scale categorizes tornado severity based on observed damage. The six-step scale ranges from F0 (light damage) to F5 (incredible damage). Weak tornadoes (F0 and F1) are most common, but strong tornadoes (F2 and F3) frequently occur. Violent tornadoes (F4 and F5) are rare. Tornado path widths are typically less than 1,000 feet; however, widths of approximately 2.5 miles have been reported. Wind speed rapidly decreases with increased distance from the center of a tornado. A critical facility on the periphery of a strong or violent tornado could be subjected to moderate to high wind speeds, depending upon the distance from the core of the tornado. However, even though the wind speed at a given facility might not be great, a facility on the periphery could still be impacted by many large pieces of wind-borne debris. Tornadoes are responsible for the greatest number of wind-related deaths each year in the United States. Figure 3-2 shows the frequency of tornado occurrence for a period between 1950 and 1998, and Figure 3-3 shows the design wind speeds recommended by FEMA for designing community shelters.

The majority of the tornadoes spawned during hurricanes are classified as F2 or weaker. However, a few F3 and at least two F4 tornadoes have been reported.

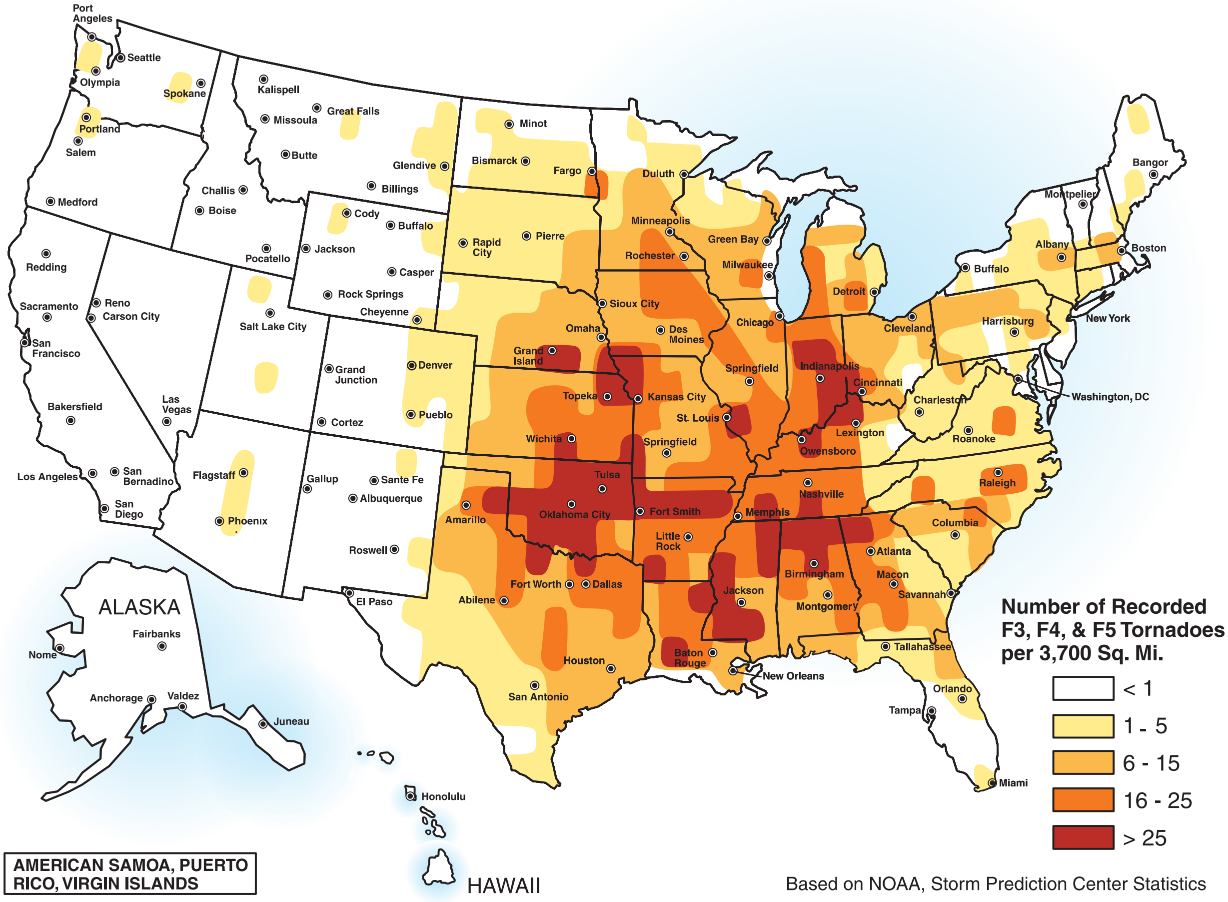
Beginning in February 2007, the National Weather Service will use the Enhanced Fujita Scale (EF-Scale) to categorize tornado severity. This new scale has six steps, ranging from EF0 to EF5. The new scale was developed by Texas Tech University's Wind Science and Engineering Center. See www.spc.noaa.gov/efscale/ for further information on the EF-Scale.

3.1.2 PROBABILITY OF OCCURRENCE

Via the importance factor,[2] ASCE 7 requires Category III and IV buildings to be designed for higher wind loads than Category I and II buildings (see Section 1.1.1). Hence, critical facilities designed in accordance with ASCE 7 have greater resistance to stronger, rarer storms. When designing a critical facility, design professionals should consider the following types of winds.

Routine winds: In many locations, winds with low to moderate speeds occur daily. Damage is not expected to occur during these events.

[2] The importance factor accounts for the degree of hazard to human life and damage to property. Importance factors are given in ASCE 7.



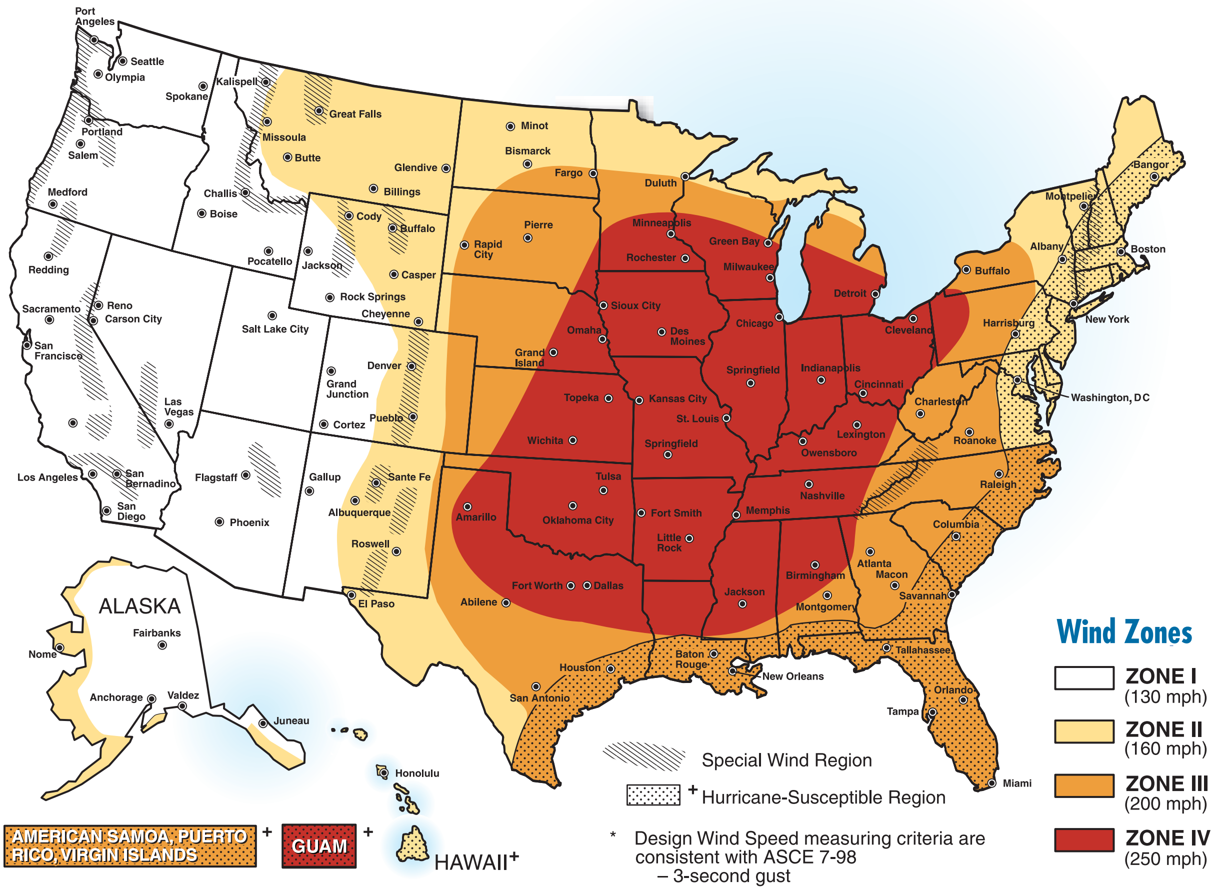
Number of Recorded F3, F4, & F5 Tornadoes per 3,700 Sq. Mi.

Based on NOAA, Storm Prediction Center Statistics

Figure 3-2: Frequency of recorded F3, F4, and F5 tornadoes (1950-1998)

Stronger winds: At a given site, stronger winds (i.e., winds with a speed in the range of 70 to 80 mph peak gust, measured at 33 feet in Exposure C — refer to Section 3.1.3) may occur from several times a year to only once a year or even less frequently. This is the threshold at which damage normally begins to occur to building elements that have limited wind resistance due to problems associated with inadequate design, insufficient strength, poor installation, or material deterioration.

Design level winds: Critical facilities exposed to design level events and events that are somewhat in excess of design level should experience little, if any damage. Actual storm history, however, has shown that design level storms frequently cause extensive building envelope damage. Structural damage also occurs, but less



* Design Wind Speed measuring criteria are consistent with ASCE 7-98
– 3-second gust
– 33 feet above grade
– Exposure C

Figure 3-3: Design wind speeds for community shelters

frequently. Damage incurred in design level events is typically associated with inadequate design, poor installation, or material deterioration. The exceptions are wind-driven water infiltration and wind-borne debris (missiles) damage. Water infiltration is discussed in Sections 3.3.3.1, 3.3.3.2, and 3.3.3.3.

Tornadoes: Although more than 1,200 tornadoes typically occur each year in the United States, the probability of a tornado occurring at any given location is quite small. The probability of occurrence is a function of location. As shown in Figure 3-2, only a few areas of the country frequently experience tornadoes, and tornadoes are very rare in the west. The Oklahoma City area is the most active location, with 112 recorded tornadoes between 1890 and 2003 (www.spc.noaa.gov/faq/tornado/#History).

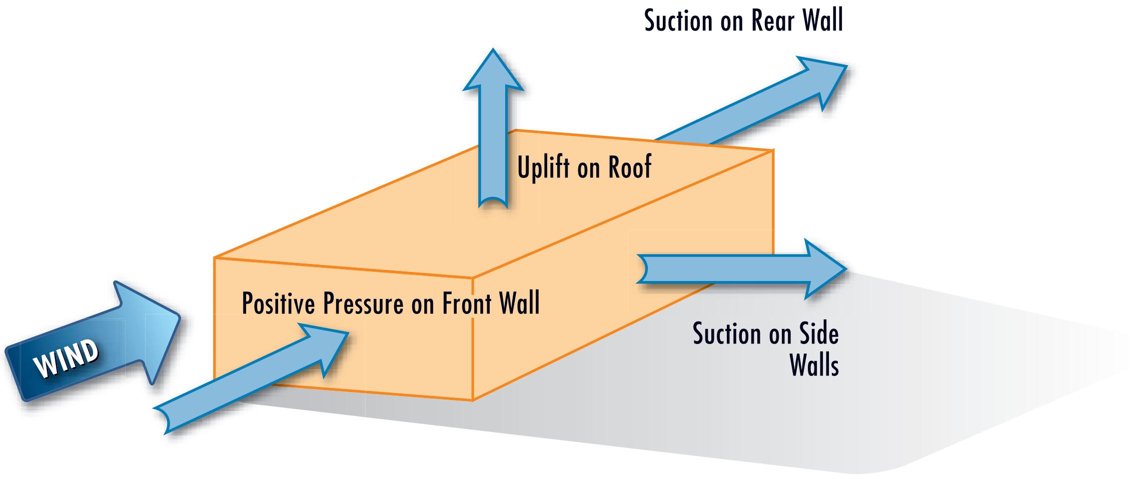
Missile damage is very common during hurricanes and tornadoes. Missiles can puncture roof coverings, many types of exterior walls, and glazing. The IBC does not address missile-induced damage except for glazing in wind-borne debris regions. (Wind-borne debris regions are limited to portions of hurricane-prone regions.) In hurricane-prone regions, significant missile-induced building damage should be expected, even during design level hurricane events, unless special enhancements are incorporated into the building's design (discussed in Section 3.4).

Well designed, constructed, and maintained critical facilities should experience little if any damage from weak tornadoes, except for window breakage. However, weak tornadoes often cause building envelope damage because many critical facilities have wind resistance deficiencies. Most critical facilities experience significant damage if they are in the path of a strong or violent tornado because they typically are not designed for this type of storm.

3.1.3 WIND/BUILDING INTERACTIONS

When wind interacts with a building, both positive and negative (i.e., suction) pressures occur simultaneously (see Figure 3-4). Critical facilities must have sufficient strength to resist the applied loads from these pressures to prevent wind-induced building failure. Loads exerted on the building envelope are transferred to the structural system, where in turn they must be transferred through the foundation into the ground. The magnitude of the pressures is a function of the following primary factors.

Figure 3-4:
Schematic of wind-induced pressures on a building



Exposure: The characteristics of the terrain (i.e., ground roughness and surface irregularities in the vicinity of a building) influence the wind loading. ASCE 7 defines three exposure categories, Exposures B, C, and D. Exposure B is the roughest terrain category and Exposure D is the smoothest. Exposure B includes urban, suburban, and wooded areas. Exposure C includes flat open terrain with scattered obstructions and areas adjacent to water surfaces in hurricane-prone regions (which are defined below under "basic wind speed"). Exposure D includes areas adjacent to water surfaces outside hurricane-prone regions, mud flats, salt flats, and unbroken ice. Because of the wave conditions generated by hurricanes, areas adjacent to water surfaces in hurricane-prone regions are considered to be Exposure C rather than the smoother Exposure D. The smoother the terrain, the greater the wind pressure; therefore, critical buildings located in Exposure C would receive higher wind loads than those located in Exposure B, even at the same basic wind speed.

For additional exposure information, see the *Commentary* of ASCE 7, which includes several aerial photographs that illustrate the different terrain conditions associated with Exposures B, C, and D.

Basic wind speed: ASCE 7 specifies the basic wind speed for determining design wind loads. The basic wind speed is measured at 33 feet above grade in Exposure C (flat open terrain). If the building is located in Exposure B or D, rather than C, an adjustment for the actual exposure is made in the ASCE 7 calculation procedure.

Since the 1995 edition of ASCE 7, the basic wind speed measurement has been a 3-second peak gust speed. Prior to that time, the basic wind speed was a fastest-mile speed (i.e., the speed averaged over the time required for a mile-long column of air to pass a fixed point).[3] Most of the United States has a basic wind speed (peak gust) of 90 mph, but much higher speeds occur in Alaska and in hurricane-prone regions. The highest speed, 170 mph, occurs in Guam.

Hurricane-prone regions include Atlantic and Gulf coastal areas (where the basic wind speed is greater than 90 mph), Hawaii, and the U.S. territories in the Caribbean and South Pacific (see Figure 3-1).

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[3] Peak gust speeds are about 15 to 20 mph higher than fastest-mile speeds (e.g., a 90-mph peak basic wind speed is equivalent to a 76-mph fastest-mile wind speed). IBC Chapter 16 provides a table of equivalent basic wind speeds.

The MWFRS is an assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface. The C&C are elements of the building envelope that do not qualify as part of the main wind-force resisting system.

In the formula for determining wind pressures, the basic wind speed is squared. Therefore, as the wind speed increases, the pressures are exponentially increased, as illustrated in Figure 3-5. This figure also illustrates the relative difference in pressures exerted on the main wind-force resisting system (MWFRS) and the components and cladding (C&C) elements.

Topography: Abrupt changes in topography, such as isolated hills, ridges, and escarpments, cause wind to speed up. Therefore, a building located near a ridge would receive higher wind pressures than a building located on relatively flat land. ASCE 7 provides a procedure to account for topographic influences.

Building height: Wind speed increases with height above the ground. Taller buildings are exposed to higher wind speeds and greater wind pressures. ASCE 7 provides a procedure to account for building height.

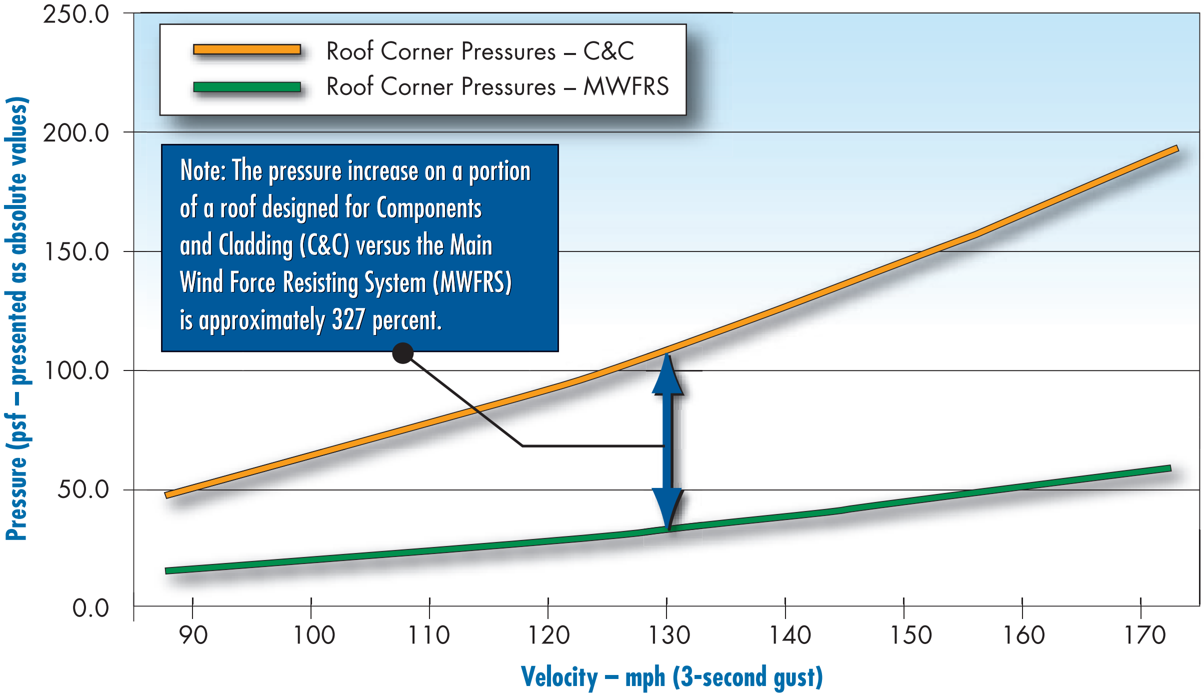


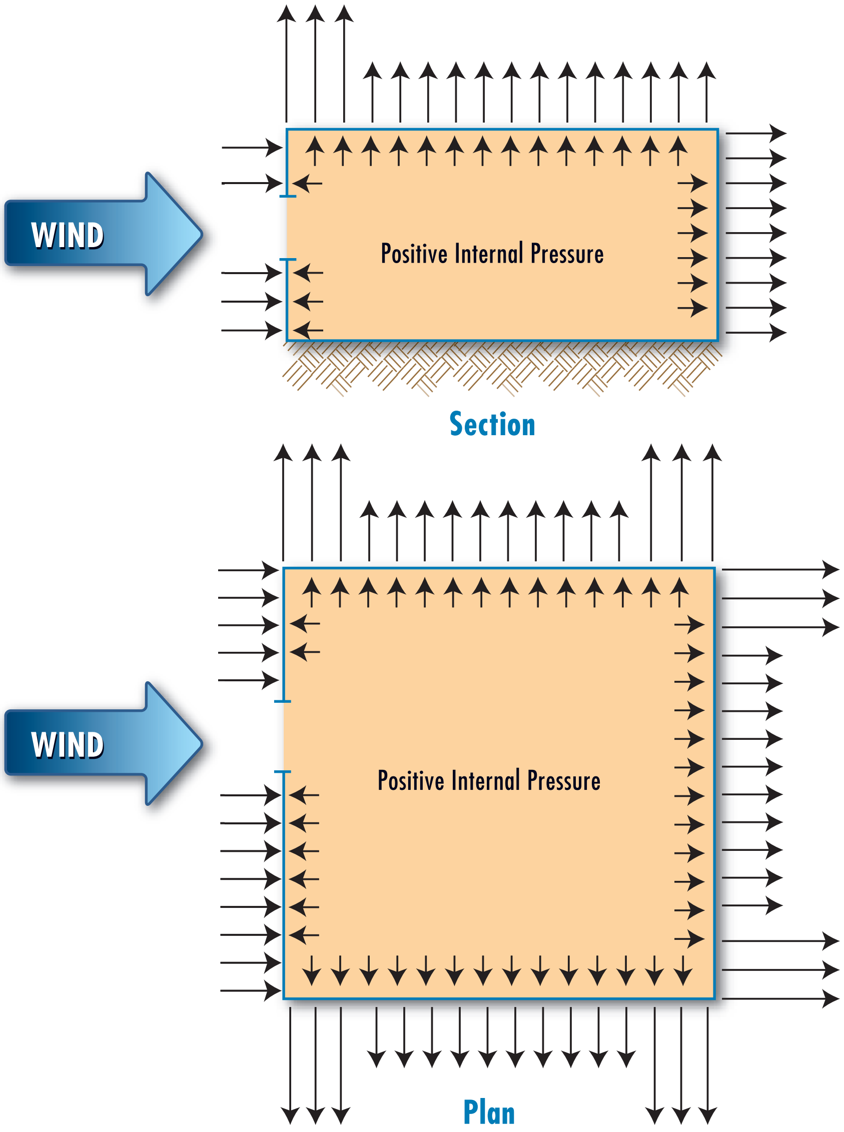
Figure 3-5: Wind pressure as a function of wind speed

Internal pressure (building pressurization/depressurization): Openings through the building envelope, in combination with wind interacting with a building, can cause either an increase in the pressure within the building (i.e., positive internal pressure), or it can cause a decrease in the pressure (i.e., negative internal pressure). Building envelope openings occur around doors and window frames, and by air infiltration through walls that are not absolutely airtight. A door or window left open, or glazing that is broken during a storm, can greatly influence the magnitude of the internal pressure.

Wind striking an exterior wall exerts a positive pressure on the wall, which forces air through openings and into the interior of the building (this is analogous to blowing up a balloon). At the same time that the windward wall is receiving positive pressure, the side and rear walls are experiencing negative (suction) pressure from winds going around the building. As this occurs, air within the building is pulled out at openings in these walls. As a result, if the porosity of the windward wall is greater than the combined porosity of the side and rear walls, the interior of the building is pressurized. But if the porosity of the windward wall is lower than the combined porosity of the side and rear walls, the interior of the building is depressurized (this is analogous to letting air out of a balloon).

When a building is pressurized, the internal pressure pushes up on the roof. This push from below the roof is combined with suction on the roof above, resulting in an increased upward wind pressure on the roof. The internal pressure also pushes on the side and rear walls. This outward push is combined with the suction on the exterior side of these walls (see Figure 3-6). When a building becomes fully pressurized (e.g., due to window breakage or soffit failure), the loads applied to the exterior walls and roof are significantly increased. The rapid build-up of internal pressure can also blow down interior partitions and blow suspended ceiling boards out of their support grid. The breaching of a small window can be sufficient to cause full pressurization of the facility's interior.

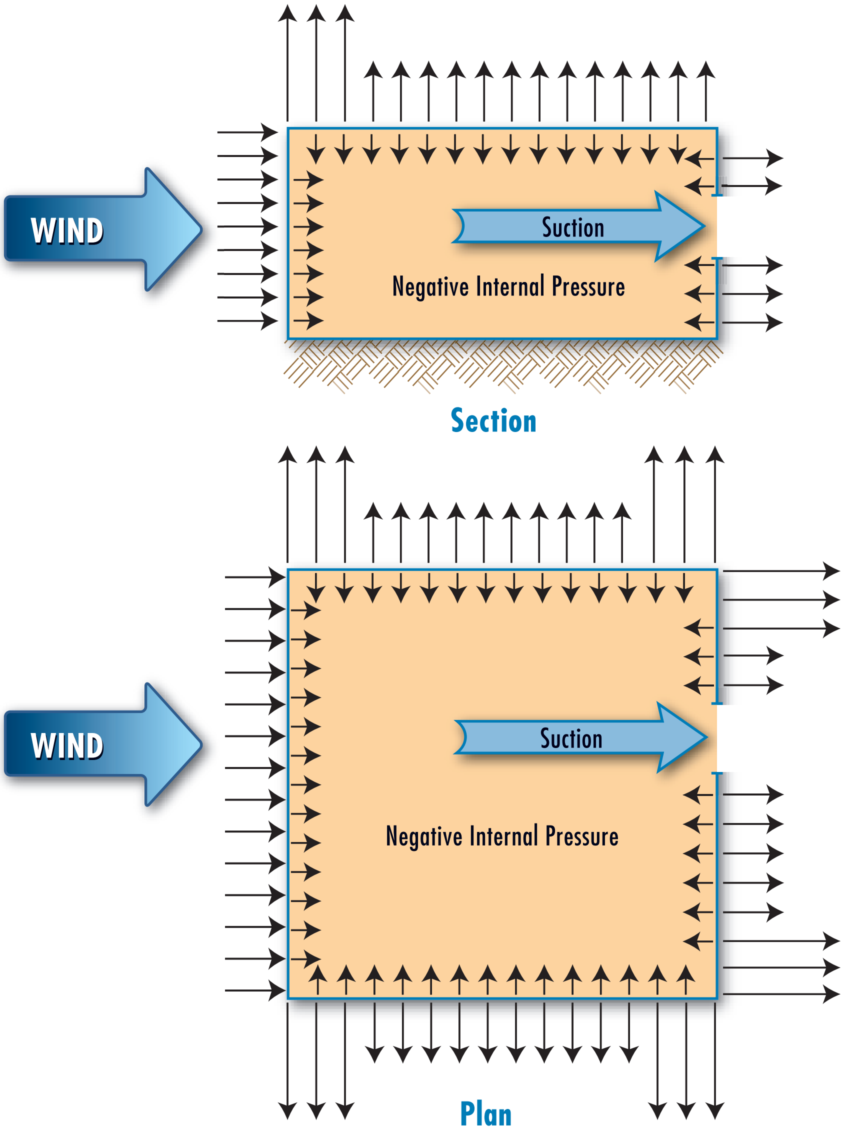
Figure 3-6:
Schematic of internal pressure condition when the dominant opening is in the windward wall



NOTE: Arrows indicate direction and magnitude of applied force.

When a building is depressurized, the internal pressure pulls the roof down, which reduces the amount of uplift exerted on the roof. The decreased internal pressure also pulls inward on the windward wall, which increases the wind load on that wall (see Figure 3-7).

The ASCE 7 wind pressure design procedure accounts for the influence of internal pressure on the wall and roof loads, and it provides positive and negative internal pressure coefficients for



NOTE: Arrows indicate direction and magnitude of applied force.

Figure 3-7:
Schematic of internal pressure condition when the dominant opening is in the leeward wall

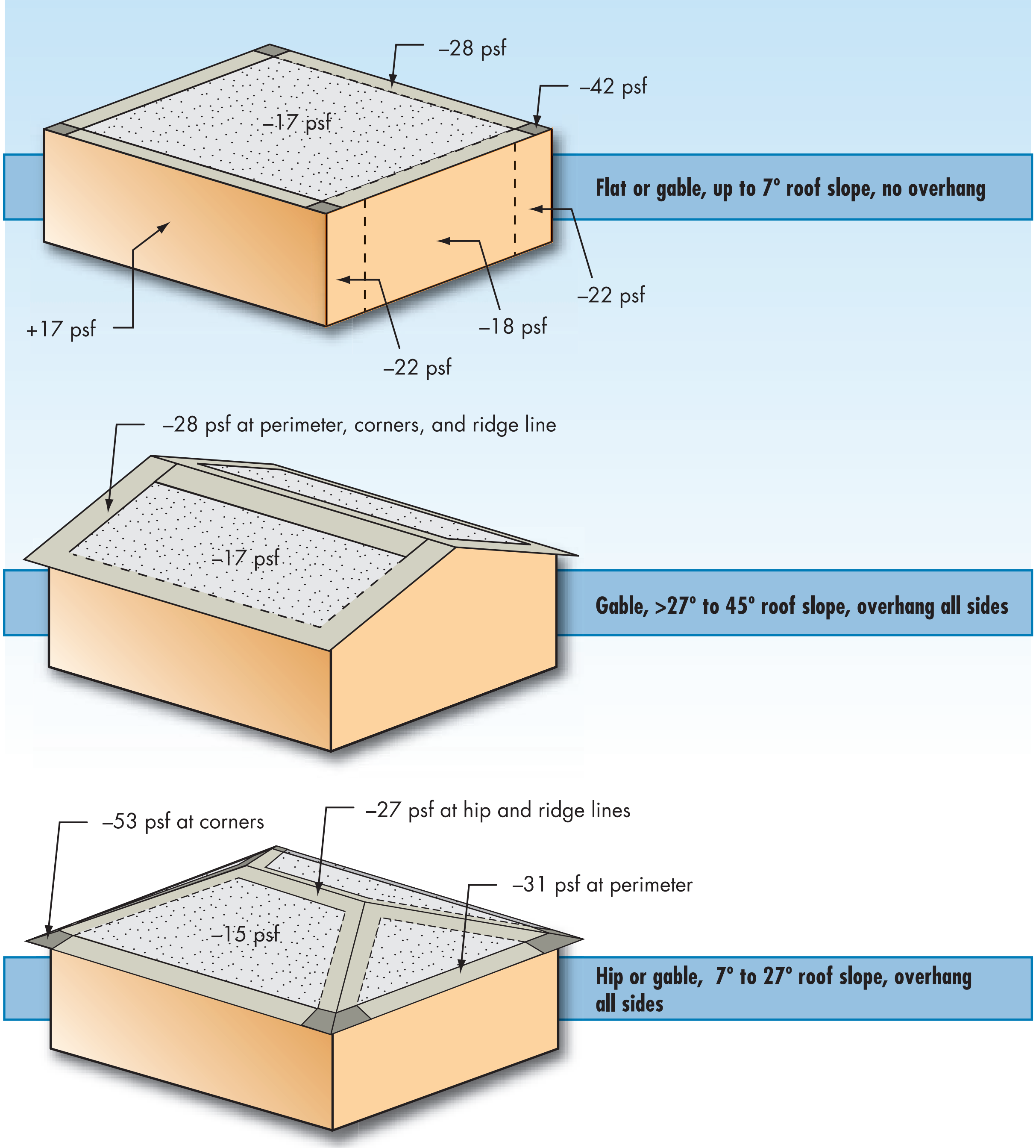
use in load calculations. Buildings that are designed to accommodate full pressurization are referred to as partially enclosed buildings. Buildings that are only intended to experience limited internal pressurization are referred to as enclosed buildings. Buildings that do not experience internal pressurization are referred to as open buildings (such as covered walkways and most parking garages).

Building shape: The highest uplift pressures occur at roof corners because of building aerodynamics (i.e., the interaction between the wind and the building). The roof perimeter has a somewhat lower load compared to the corners, and the field of the roof has still lower loads. Exterior walls typically have lower loads than the roof. The ends (edges) of walls have higher suction loads than the portion of wall between the ends. However, when the wall is loaded with positive pressure, the entire wall is uniformly loaded. Figure 3-8 illustrates these aerodynamic influences. The negative values shown in Figure 3-8 indicate suction pressure acting upward from the roof surface and outward from the wall surface. Positive values indicate positive pressure acting inward on the wall surface.

Aerodynamic influences are accounted for by using external pressure coefficients in load calculations. The value of the coefficient is a function of the location on the building (e.g., roof corner or field of roof) and building shape as discussed below. Positive coefficients represent a positive (inward-acting) pressure, and negative coefficients represent negative (outward-acting [suction]) pressure. External pressure coefficients for MWFRS and C&C are listed in ASCE 7.

Building shape affects the value of pressure coefficients and, therefore, the loads applied to the various building surfaces. For example, the uplift loads on a low-slope roof are larger than the loads on a gable or hip roof. The steeper the slope, the lower the uplift load. Pressure coefficients for monoslope (shed) roofs, sawtooth roofs, and domes are all different from those for low-slope and gable/hip roofs.

Building irregularities, such as re-entrant corners, bay window projections, a stair tower projecting out from the main wall, dormers, and chimneys can cause localized turbulence. Turbulence causes wind speed-up, which increases the wind loads in the vicinity of the building irregularity, as shown in Figures 3-9 and 3-10. Figure 3-9 shows the aggregate ballast on a hospital's single-ply membrane roof blown away at the re-entrant corner and in the vicinity of the corners of the wall projections at the window bays. The irregular wall surface created turbulence, which led to wind speed-up and loss of aggregate in the turbulent flow areas.



NOTE: Design pressures all assume an enclosed building with the same basic wind speed of 90 mph, Exposure B, 30′ roof height, and an importance factor of 1.15

Figure 3-8: Relative roof uplift pressures as a function of roof geometry, roof slope, and location on roof, and relative positive and negative wall pressures as a function of location along the wall

Figure 3-9: Aggregate blow-off associated with building irregularities. Hurricane Hugo (South Carolina, 1989)

Information pertaining to load calculations is presented in Section 3.3.1.2. For further general information on the nature of wind and wind-building interactions, see *Buildings at Risk: Wind Design Basics for Practicing Architects*, American Institute of Architects, 1997.

Figure 3-10 shows a stair tower at a hospital that caused turbulence resulting in wind speed-up. The speed-up increased the suction pressure on the base flashing along the parapet behind the stair tower. The built-up roof's base flashing was pulled out from underneath the coping because its attachment was insufficient to resist the suction pressure. The base flashing failure propagated and caused a large area of the roof membrane to lift and peel. Some of the wall covering on the stair tower was also blown away. Had the stair tower not existed, the built-up roof would likely not have been damaged. To avoid damage in the vicinity of building irregularities, attention needs to be given to the attachment of building elements located in turbulent flow areas.

To avoid the roof membrane damage shown in Figure 3-10, it would be prudent to use corner uplift loads in lieu of perimeter uplift loads in the vicinity of the stair tower, as illustrated in Figure 3-11. Wind load increases due to building irregularities can be identified by wind tunnel studies; however, wind tunnel studies are rarely performed for critical facilities. Therefore, identification of wind load increases due to building irregularities will normally be based on the designer's professional judgment. Usually load increases will only need to be applied to the building envelope, and not to the MWFRS.

Figure 3-10:
The irregularity created by the stair tower (covered with a metal roof) caused turbulence resulting in wind speed-up and roof damage. Hurricane Andrew (Florida, 1992)

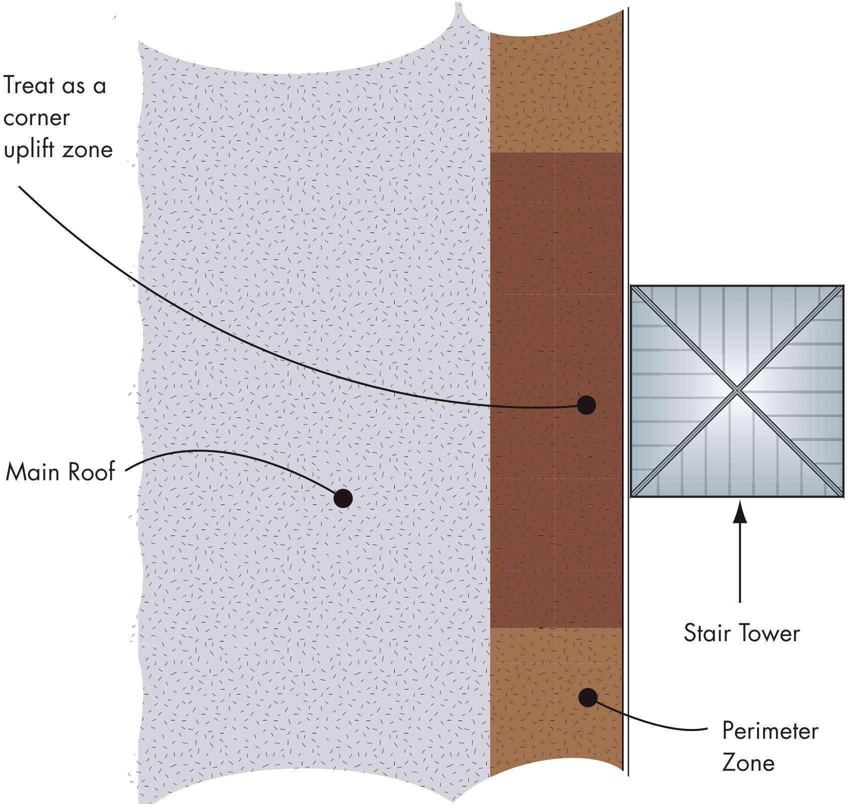


Figure 3-11:
Plan view of a portion of the building in Figure 3-10 showing the use of a corner uplift zone in lieu of a perimeter uplift zone on the low-slope roof in the vicinity of the stair tower

3.1.4 BUILDING CODES

The IBC is the most extensively used model code. However, in some jurisdictions NFPA 5000 may be used. In other jurisdictions, one of the earlier model building codes, or a specially written State or local building code, may be used. The specific scope and/or effectiveness and limitations of these other building codes will be somewhat different than those of the IBC. It is incumbent upon the design professionals to be aware of the specific code (including the edition of the code and local amendments) that has been adopted by the authority having jurisdiction over the location of the critical facility.

3.1.4.1 Scope of Building Codes

With respect to wind performance, the scope of the model building codes has greatly expanded since the mid-1980s. Some of the most significant improvements are discussed below.

Recognition of increased uplift loads at the roof perimeter and corners: Prior to the 1982 edition of the Standard Building Code (SBC), Uniform Building Code (UBC), and the 1987 edition of the National Building Code (NBC), these model codes did not account for the increased uplift at the roof perimeter and corners. Therefore, critical facilities designed in accordance with earlier editions of these codes are very susceptible to blow-off of the roof deck and/or roof covering.

Adoption of ASCE 7 for design wind loads: Although the SBC, UBC, and NBC permitted use of ASCE 7, the 2000 edition of the IBC was the first model code to require ASCE 7 for determining wind design loads. ASCE 7 has been more reflective of the current state of the knowledge than the earlier model codes, and use of this procedure typically has resulted in higher design loads.

Roof coverings: Several performance and prescriptive requirements pertaining to wind resistance of roof coverings have been incorporated into the model codes. The majority of these additional provisions were added after Hurricanes Hugo (1989) and Andrew (1992). Poor performance of roof coverings was widespread in both of those storms. Prior to the 1991 edition of the SBC and UBC, and the 1990 edition of the NBC, these model codes were essentially silent on roof covering wind loads and test methods for determining uplift resistance. Code improvements continued to be made through the 2006 edition of the IBC, which added a provision that prohibits aggregate roof surfaces in hurricane-prone regions.

ASCE 7 requires impact-resistant glazing in wind-borne debris regions within hurricane-prone regions. Impact-resistant glazing can either be laminated glass, polycarbonate, or shutters tested in accordance with standards specified in ASCE 7. The wind-borne debris load criteria were developed to minimize property damage and to improve building performance. The criteria were not developed for occupant protection. Where occupant protection is a specific criterion, the more conservative wind-borne debris criteria given in FEMA 361, *Design and Construction Guidance for Community Shelters* is recommended.

Glazing protection: The 2000 edition of the IBC was the first model code to address wind-borne debris requirements for glazing in buildings located in hurricane-prone regions (via reference to the 1998 edition of ASCE 7). The 1995 edition of ASCE 7 was the first edition to address wind-borne debris requirements.

Parapets and rooftop equipment: The 2003 edition of the IBC was the first model code to address wind loads on parapets and rooftop equipment (via reference to the 2002 edition of ASCE 7, which was the first edition of ASCE 7 to address these elements).

3.1.4.2 Effectiveness and Limitations of Building Codes

A key element of an effective building code is for a community to have an effective building department. Building safety depends on more than the codes and the standards they reference. Building safety results when trained professionals have the resources and ongoing support they need to stay on top of the latest advancements in building safety. An effective building safety system provides uniform code interpretations, product evaluations, and professional development and certification for inspectors and plan reviewers. Local building departments play an important role in helping to ensure buildings are designed and constructed in accordance with the applicable building codes. Meaningful plan review and inspection by the building department are particularly important for critical facilities.

General limitations to building codes include the following:

- Because codes are adopted and enforced on the local or State level, the authority having jurisdiction has the power to eliminate or modify wind-related provisions of a model code, or write its own code instead. In places where important wind-related provisions of the current model code are not adopted and enforced, critical facilities are more susceptible to wind damage. Additionally, a significant time lag often exists between the time a model code is updated and the time it is implemented by the authority having jurisdiction. Buildings designed to the minimum requirements of an outdated code are, therefore, not taking advantage of the current state of the knowledge. These buildings are prone to poorer wind performance compared to buildings designed according to the current model code.

- Adopting the current model code alone does not ensure good wind performance. The code is a minimum tool that should be used by knowledgeable design professionals in conjunction with their training, skills, professional judgment, and the best practices presented in this manual. To achieve good wind performance, in addition to good design, the construction work must be effectively executed, and the building must be adequately maintained and repaired.

- Critical facilities need to perform at a higher level than required by codes and standards. See Section 1.3 on performance based design.

IBC 2006: The 2006 edition of the IBC is believed to be a relatively effective code, provided that it is properly followed and enforced. Some limitations of the 2006 IBC have, however, been identified:

- With respect to hurricanes, the IBC provisions pertaining to building envelopes and rooftop equipment do not adequately address the special needs of critical facilities. For example: (1) they do not account for water infiltration due to puncture of the roof membrane by missiles; (2) they do not adequately address the vulnerabilities of brittle roof coverings (such as tile) to missile-induced damage and subsequent progressive failure; (3) they do not adequately address occupant protection with respect to missiles; (4) they do not adequately address protection of equipment in elevator penthouses; (5) they do not account for interruption of water service or prolonged interruption of electrical power; and (6) the current requirements for shelters are limited. All of these elements are of extreme importance for critical facilities, which need to remain operational before, during, and after a disaster. Guidance to overcome these shortcomings is given in Section 3.4.

- The 2006 IBC does not account for tornadoes; therefore, except for weak tornadoes, it is ineffective for this type of storm.[4] Guidance to overcome this shortcoming is given in Section 3.5.

The 2000, 2003, and 2006 IBC rely on several referenced standards and test methods developed or updated in the 1990s. Prior to adoption, most of these standards and test methods had not been validated by actual building performance during design level wind events. The hurricanes of 2004 and 2005 provided an opportunity to evaluate the actual performance of buildings designed and constructed to the minimum provisions of the IBC. Building performance evaluations conducted by FEMA revealed the need for further enhancements:

- A limitation of the 2006 IBC pertains to some of the test methods used to assess wind and wind-driven rain resistance of building envelope components. However, before this code limitation can be overcome, research needs to be conducted and new test methods need to be developed.

The International Code Council (ICC) is developing a consensus standard, ICC/NSSA Standard for the Design and Construction of Storm Shelters, to provide basic requirements for the design and construction of emergency shelters in areas affected by hurricanes and tornadoes. If it is adopted by a community when it becomes available in early 2007, it will provide design and construction standards for buildings intended to resist the impact of high winds and wind-borne debris. This stand-alone standard will be linked to the IBC and IRC. It is the intent of the ICC that the shelter standard be incorporated by reference into the IBC and IRC in 2009. FEMA should be consulted prior to designing or constructing shelters to the ICC/NSSA standard with FEMA funds to ensure all program requirements are met, as some components may need to be designed to stricter criteria than those included in the consensus standard.

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[4] Except for glass breakage, code-compliant buildings should not experience significant damage during weak tornadoes.

- Except to the extent covered by reference to ASCE 7, the 2006 IBC does not address the need for continuity, redundancy, or energy-dissipating capability (ductility) to limit the effects of local collapse, and to prevent or minimize progressive collapse after the loss of one or two primary structural members, such as a column. Chapter 1 of ASCE 7 addresses general structural integrity, and the Chapter 1 Commentary provides some guidance on this issue.

3.2 CRITICAL FACILITIES EXPOSED TO HIGH WINDS

3.2.1 VULNERABILITY: WHAT HIGH WINDS CAN DO TO CRITICAL FACILITIES

This section provides an overview of the common types of wind damage and their ramifications.

3.2.1.1 Types of Building Damage

When damaged by wind, critical facilities typically experience a variety of building component damage. The most common types of damage are discussed below in descending order of frequency.

Roof: Roof covering damage (including rooftop mechanical, electrical, and communications equipment) is the most common type of wind damage. The school, illustrated in Figure 3-12, was being used as a hurricane shelter at the time a portion of the roof membrane blew off. In addition to the membrane damage, several pieces of rooftop equipment were damaged, and virtually all of the loose aggregate blew off and broke many windows in nearby houses. The cast-in-place concrete deck kept most of the water from entering the building.

Glazing: Exterior glazing damage is very common during hurricanes and tornadoes, but is less common during other storms. The glass shown in Figure 3-13 was broken by the aggregate from a built-up roof. The inner panes had several impact craters. In several of the adjacent windows, both the outer and inner panes were broken. The aggregate flew more than 245 feet (the estimated wind speed was 104 mph, measured at 33 feet in Exposure C).

Figure 3-12:
A portion of the built-up membrane lifted and peeled after the metal edge flashing lifted.
Hurricane Andrew (Florida, 1992)

Figure 3-13:
The outer window panes were broken by aggregate from a built-up roof.
Hurricane Hugo (South Carolina, 1989)

Wall coverings, soffits, and large doors: Exterior wall covering, soffit, and large door damage is common during hurricanes and tornadoes, but is less common during other storms. At the building shown in Figure 3-14, metal wall covering was attached to plywood over metal studs. The CMU wall behind the studs did not appear to be damaged. The building was located on the periphery of a violent tornado.

Wall collapse: Collapse of non-load-bearing exterior walls is common during hurricanes and tornadoes, but is less common during other storms (see Figure 3-15).

Figure 3-14: Collapsed metal stud wall—the wall was blown completely away in another part of the building. (Oklahoma, 1999)

Figure 3-15: The unreinforced CMU wall collapsed at a school during Hurricane Marilyn. (U.S. Virgin Islands, 1995)

Structural system: Structural damage (e.g., roof deck blow-off, blow-off or collapse of the roof structure, collapse of exterior bearing walls, or collapse of the entire building or major portions thereof) is the principal type of damage that occurs during strong and violent tornadoes (see Figure 3-16).

Figure 3-16:
The school wing was destroyed by a violent tornado. (Oklahoma, 1999)

3.2.1.2 Ramifications of Damage

The ramifications of building component damage on critical facilities are described below.

Property damage: Property damage requires repairing/replacing the damaged components (or replacing the entire facility), and may require repairing/replacing interior building components, furniture, and other equipment, and mold remediation. Even when damage to the building envelope is limited, such as blow-off of a portion of the roof covering or broken glazing, substantial water damage frequently occurs because heavy rains often accompany strong winds (particularly in the case of thunderstorms, tropical storms, hurricanes, and tornadoes). At the newly constructed gymnasium shown in Figure 3-17, the structural metal

Modest wind speeds can drive rain into exterior walls. Unless adequate provisions are taken to account for water infiltration (see Sections 3.3.3.1 to 3.3.3.3), damaging corrosion, dry rot, and mold can occur within walls.

roof panels were applied over metal purlins. The panels with 3-inch-high trapezoidal ribs at 24 inches on center detached from their concealed clips. A massive quantity of water entered the building and buckled the wood floor.

Figure 3-17:
A massive quantity of water entered the building after the roof blew off. Typhoon Paka (Guam, 1997)

Wind-borne debris such as roof aggregate, gutters, rooftop equipment, and siding blown from buildings can damage vehicles and other buildings in the vicinity. Debris can travel well over 300 feet in high-wind events.

Portable classrooms on school campuses are often particularly vulnerable to significant damage because they are seldom designed to the same wind pressures as permanent buildings. Portable classrooms are frequently blown over during high-wind events, because the anchoring techniques typically used are inadequate to secure the units to the ground. Wind-borne debris from portable classrooms, or an entire portable classroom, may strike the permanent school building and cause serious damage.

Ancillary buildings (such as storage buildings) adjacent to critical facilities are also vulnerable to damage. Although loss of these buildings may not be detrimental to the operation of the critical facility, debris from ancillary buildings may strike and damage the critical facility. The damaged building shown in

Figure 3-18 contained the hospital's supplies and maintenance shop. With the loss of this building, tents had to be set up to provide supply storage. Almost all of the tools and stock materials for repairs were lost.

Figure 3-18:
A hurricane-damaged, pre-engineered storage building adjacent to a hospital. Hurricane Charley (Florida, 2004)

Injury or death: Although infrequent, critical facility occupants or people outside the facility have been injured and killed when struck by collapsed building components (such as exterior masonry walls or the roof structure) or wind-borne debris. The greatest risk of injury or death is during strong hurricanes and strong/violent tornadoes.

Although people are not usually outside during hurricanes, it is not uncommon for people to seek shelter or assistance in critical facilities during a storm. Missiles, such as roof aggregate or tile shedding from a critical facility, could injure or kill late arrivals before they have a chance to enter the building.

Interrupted use: Depending on the magnitude of wind and water damage, it can take days, months, or more than a year to repair the damage or replace a facility. In addition to the costs associated with repairing/replacing the damage, other social and financial costs can be even more significant. The repercussions related to interrupted use of the critical facility can include the loss of emergency and first-responder services, lack of medical care, and the costs to rent temporary facilities. These additional costs can be quite substantial.

3.2.2 EVALUATING CRITICAL FACILITIES FOR RISK FROM HIGH WINDS

This section describes the process of hazard risk assessment. Although no formal methodology for risk assessment has been adopted, prior experience provides a sufficient knowledge base upon which a set of guidelines can be structured into a recommended procedure for risk assessment of critical facilities. The procedures presented below establish guidelines for evaluating the risk to new and existing buildings from wind storms other than tornadoes. These evaluations will allow development of a vulnerability assessment that can be used along with the site's wind regime to assess the risk to critical facilities.

In the case of tornadoes, neither the IBC nor ASCE 7 requires buildings (including critical facilities) to be designed to resist tornado forces, nor are occupant shelters required in buildings located in tornado-prone regions. Constructing tornado-resistant critical facilities is extremely expensive because of the extremely high pressures and missile impact loads that tornadoes can generate. Therefore, when consideration is voluntarily given to tornado design, the emphasis is typically on occupant protection, which is achieved by "hardening" portions of a critical facility for use as safe havens. FEMA 361 includes a comprehensive risk assessment procedure that designers can use to assist building owners in determining whether a tornado shelter should be included as part of a new critical facility. See Section 3.5 for the design of tornado shelters and other recommendations pertaining to critical facilities in tornado-prone regions.

In this manual, the term "tornado-prone regions" refers to those areas of the United States where the number of recorded F3, F4, and F5 tornadoes per 3,700 square miles is 6 or greater per year (see Figure 3-2). However, an owner of a critical facility may decide to use other frequency values (e.g., 1 or greater, 16 or greater, or greater than 25) in defining whether the building is in a tornado-prone area. In this manual, tornado shelters are recommended for all critical facilities in tornado-prone regions.

Where the frequency value is 1 or greater, and the facility does not have a tornado shelter, the best available refuge areas should be identified, as discussed in Section 3.5.

3.2.2.1 New Buildings

When designing new critical facilities, a two-step procedure is recommended for evaluating the risk from wind storms (other than tornadoes).

Step 1: Determine the basic wind speed from ASCE 7. As the basic wind speed increases beyond 90 mph, the risk of damage increases. Design, construction, and maintenance enhancements are recommended to compensate for the increased risk of damage (see Section 3.3).

Step 2: For critical facilities in hurricane-prone regions, refer to the design, construction, and maintenance enhancements recommended in Section 3.4.

For particularly important critical facilities (such as hospitals) in remote areas outside of hurricane-prone regions, it is recommended that robust design measures be considered to minimize the potential for disruption resulting from wind damage. Because of their remote location, disruption of such facilities could severely affect the occupants or community. Some of the recommendations in Section 3.4 may therefore be prudent.

3.2.2.2 Existing Buildings

The resistance of existing buildings is a function of their original design and construction, various additions or modifications, and the condition of building components (which may have weakened due to deterioration or fatigue). For existing buildings, a two-step procedure is also recommended.

Step 1: Calculate the wind loads on the building using the current edition of ASCE 7, and compare these loads with the loads for which the building was originally designed. The original design loads may be noted on the contract drawings. If not, determine what building code or standard was used to develop the original design loads, and calculate the loads using that code or standard. If the original design loads are significantly lower than current loads, upgrading the load resistance of the building envelope and/or structure should be considered. An alternative to comparing current loads with original design loads is to evaluate the resistance of the existing facility as a function of the current loads to determine what elements are highly overstressed.

Step 2: Perform a field investigation to evaluate the primary building envelope elements, rooftop equipment, and structural system elements, to determine if the facility was generally constructed as indicated on the original contract drawings. As part of the investigation, the primary elements should be checked for deterioration. Load path continuity should also be checked.

If the results of either step indicate the need for remedial work, see Section 3.6.

3.3 CRITICAL FACILITY DESIGN CONSIDERATIONS

3.3.1 GENERAL DESIGN CONSIDERATIONS

The performance of critical facilities in past wind storms indicates that the most frequent and the most significant factor in the disruption of the operations of these facilities has been the failure of nonstructural building components. While acknowledging the importance of the structural systems, Chapter 3 emphasizes the building envelope components and the nonstructural systems. According to the National Institute of Building Science (NIBS), the building envelope includes the below-grade basement walls and foundation and floor slab (although these are generally considered part of the building's structural system). The envelope includes everything that separates the interior of a building from the outdoor environment, including the connection of all the nonstructural elements to the building structure. The nonstructural systems include all mechanical, electrical, electronic, communications, and lightning protection systems. Historically, damage to roof coverings and rooftop equipment has been the leading cause of building performance problems during wind storms. Special consideration should be given to the problem of water infiltration through failed building envelope components, which can cause severe disruptions in the functioning of critical facilities.

The key to enhanced wind performance is paying sufficient attention to all phases of the construction process (including site selection, design, and construction) and to post-occupancy maintenance and repair.

3.3.1.1 Site

When selecting land for a critical facility, sites located in Exposure D (see Section 3.1.3 for exposure definitions) should be avoided if possible. Selecting a site in Exposure C or preferably in Exposure B would decrease the wind loads. Also, where possible, avoid selecting sites located on an escarpment or the upper half of a hill, where the abrupt change in the topography would result in increased wind loads.[6]

Trees with trunks larger than 6 inches in diameter, poles (e.g., light fixture poles, flag poles, and power poles), or towers (e.g., electrical transmission and large communication towers) should not be placed near the building. Falling trees, poles, and towers can severely damage a critical facility and injure the occupants (see Figure 3-19). Large trees can crash through pre-engineered metal buildings (which often house fire stations) and wood frame construction (which is commonly used for nursing homes). Falling trees can also rupture roof membranes and break windows.

Figure 3-19:
Had this tree fallen in the opposite direction, it would have landed on the school. Hurricane Ivan (Florida, 2004)

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[6] When selecting a site on an escarpment or the upper half of a hill is necessary, the ASCE 7 design procedure accounts for wind speed-up associated with this abrupt change in topography.

In the past, design professionals seldom performed load calculations on the building envelope (i.e., roof and wall coverings, doors, windows, and skylights) and rooftop equipment. These building components are the ones that have failed the most during past wind events. In large part they failed because of the lack of proper load determination and inappropriate design of these elements. It is imperative that design professionals determine the loads for the building envelope and rooftop equipment, and design them to accommodate such loads.

Providing at least two means of site egress is prudent for all critical facilities, but is particularly important for facilities in hurricane-prone regions. If one route becomes blocked by trees or other debris, or by floodwaters, the other access route may still be available.

3.3.1.2 Building Design

Good wind performance depends on good design (including details and specifications), materials, installation, maintenance, and repair. A significant shortcoming in any of these five elements could jeopardize the performance of a critical facility against wind. Design, however, is the key element to achieving good performance of a building against wind damage. Design inadequacies frequently cannot be compensated for with other elements. Good design, however, can compensate for other inadequacies to some extent. The following steps should be included in the design process for critical facilities.

Step 1: Calculate Loads

Calculate loads on the MWFRS, the building envelope, and rooftop equipment in accordance with ASCE 7 or the local building code, whichever procedure results in the highest loads. In calculating wind loads, design professionals should consider the following items.

Uplift loads on roof assemblies can also be determined from FM Global (FMG) Data Sheets. If the critical facility is FMG insured, and the FMG-derived loads are higher than those derived from ASCE 7 or the building code, the FMG loads should govern. However, if the ASCE 7 or code-derived loads are higher than those from FMG, the ASCE 7 or code-derived loads should govern (whichever procedure results in the highest loads).

Importance factor: The effect of using a 1.15 importance factor versus 1 is that the design loads for the MWFRS and C&C are increased by 15 percent. The importance factor for most critical facilities is required to be 1.15. However, ASCE 7 permits a factor of 1 for some critical facilities. For example, schools with an occupant load of less than 250 people are permitted to be designed with an importance factor of only 1 (provided they are not used as a shelter—if used as a shelter, schools are required to be designed with an importance factor of 1.15, regardless of occupant load). Other facilities where occupant load controls the importance factor include certain health care facilities, such as nursing homes with 50 or more residents, for which a factor of 1.15 is required. For nursing homes with less than 50 residents, a factor of 1 can be used. Some critical facilities are not specifically addressed in ASCE 7. For example, various buildings on a hospital campus, such as medical office buildings that are integrally connected to the hospital and various types of non-emergency treatment facilities (such as storage, cancer treatment, physical therapy, and dialysis) are not specifically required by ASCE 7 to be designed with a 1.15 factor. This manual recommends a value of 1.15 for all critical facilities.

Wind directionality factor: The ASCE 7 wind load calculation procedure incorporates a wind directionality factor (k_d). The directionality factor accounts for the reduced probability of maximum winds coming from any given direction. By applying the prescribed value of 0.85, the loads are reduced by 15 percent. Because hurricane winds can come from any direction, and because of the historically poor performance of building envelopes and rooftop equipment, this manual recommends a more conservative approach for critical facilities in hurricane-prone regions. A directionality factor of 1.0 is recommended for the building envelope and rooftop equipment (a load increase over what is required by ASCE 7). For the MWFRS, a directionality factor of 0.85 is recommended (hence, no change for MWFRS).

Step 2: Determine Load Resistance

When using allowable stress design, after loads have been determined, it is necessary to select a reasonable safety factor in order to determine the minimum required load resistance. For building envelope systems, a minimum safety factor of 2 is recommended. For anchoring exterior-mounted mechanical, electrical, and communications equipment (such as satellite dishes), a minimum safety factor of 3 is recommended. When using strength design, load combinations and load factors specified in ASCE 7 are used.

ASCE 7 provides criteria for combining wind loads with other types of loads (such as dead and flood loads) using allowable stress design.

When using allowable stress design, a safety factor is applied to account for reasonable variations in material strengths, construction workmanship, and conditions when the actual wind speed somewhat exceeds the design wind speed. For design purposes, the ultimate resistance an assembly achieves in testing is reduced by the safety factor. For example, if a roof assembly resisted an uplift pressure of 100 pounds per square foot (psf), after applying a safety factor of 2, the assembly would be suitable where the design load was 50 psf or less. Conversely, if the design load is known, multiplying it by the safety factor equals the minimum required test pressure (e.g., 50 psf design load multiplied by a safety factor of 2 equals a minimum required test pressure of 100 psf).

For structural members and cladding elements where strength design can be used, load resistance can be determined by calculations. For other elements where allowable stress design is used (such as most types of roof coverings), load resistance is primarily obtained from system testing.

The load resistance criteria need to be provided in contract documents. For structural elements, the designer of record typically accounts for load resistance by indicating the material, size, spacing, and connection of the elements. For nonstructural elements, such as roof coverings or windows, the load and safety factor can be specified. In this case, the specifications should require the contractor's submittals to demonstrate that the system will meet the load resistance criteria. This performance specification approach is necessary if, at the time of the design, it is unknown who will manufacture the system.

Regardless of which approach is used, it is important that the designer of record ensure that it can be demonstrated, via calculations or tests, that the structure, building envelope, and nonstructural systems (exterior-mounted mechanical, electrical, and communications equipment) have sufficient strength to resist design wind loads.

Connections are a key aspect of load path continuity between various structural and nonstructural building elements. In a window, for example, the glass must be strong enough to resist the wind pressure and must be adequately anchored to the window frame, the frame adequately anchored to the wall, the wall to the foundation, and the foundation to the ground. As loads increase, greater load capacity must be developed in the connections.

Step 3: Detailed Design

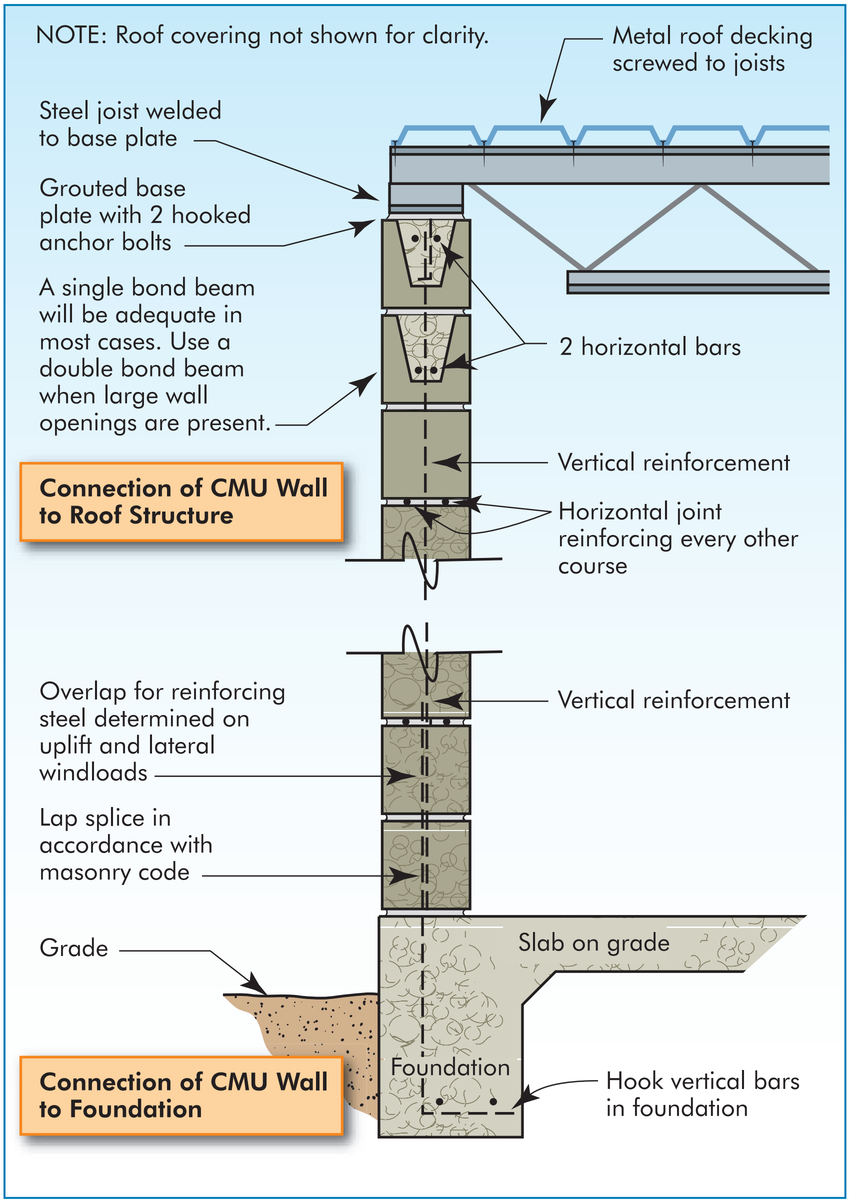
It is vital to design, detail, and specify the structural system, building envelope, and exterior-mounted mechanical, electrical, and communications equipment to meet the factored design loads (based on appropriate analytical or test methods). It is also vital to respond to the risk assessment criteria discussed in Section 3.2.2, as appropriate.

As part of the detailed design effort, load path continuity should be clearly indicated in the contract documents via illustration of connection details. Load paths need to accommodate design uplift, racking, and overturning loads. Load path continuity obviously applies to MWFRS elements, but it also applies to building envelope elements. Figure 3-20 shows a load path discontinuity between a piece of HVAC equipment and its equipment stand. The equipment on this new Federal courthouse blew away because it was resting on vibration isolators that provided lateral resistance, but no uplift resistance (also see Figure 3-75).

Figure 3-20:
Temporary coverings placed over two large openings in the roof that were left after the ductwork blew away. Hurricane Katrina (Mississippi, 2005)

Figure 3-21 illustrates the load path concept. Members are sized to accommodate the design loads. Connections are designed to transfer uplift loads applied to the roof, and the positive and negative loads applied to the exterior bearing walls, down to the foundation and into the ground. The roof covering (and wall covering, if there is one) is also part of the load path. To avoid blow-off, the nonstructural elements must also be adequately attached to the structure.

Figure 3-21: Illustration of load path continuity



As part of the detailed design process, special consideration should be given to the durability of materials and water infiltration.

Durability: Because some locales have very aggressive atmospheric corrosion (such as areas near oceans), special attention needs to be given to the specification of adequate protection for ferrous metals, or to specify alternative metals such as stainless steel. FEMA Technical Bulletin, *Corrosion Protection for Metal Connectors in Coastal Areas* (FIA-TB-8, 1996) contains information on corrosion protection. Attention also needs to be given to dry rot avoidance, for example, by specifying preservative-treated wood or developing details that avoid excessive moisture accumulation. Appendix J of the *Coastal Construction Manual,* (FEMA 55, 2000) presents information on wood durability.

Durable materials are particularly important for components that are inaccessible and cannot be inspected regularly (such as fasteners used to attach roof insulation). Special attention also needs to be given to details. For example, details that do not allow water to stand at connections or sills are preferred. Without special attention to material selection and details, the demands on maintenance and repair will be increased, along with the likelihood of failure of components during high winds.

Water infiltration (rain): Although prevention of building collapse and major building damage is the primary goal of wind-resistant design, consideration should also be given to minimizing water damage and subsequent development of mold from the penetration of wind-driven rain. To the extent possible, non-load-bearing walls and door and window frames should be designed in accordance with rain-screen principles. With this approach, it is assumed that some water will penetrate past the face of the building envelope. The water is intercepted in an air-pressure equalized cavity that provides drainage from the cavity to the outer surface of the building. See Sections 3.3.3.2 and 3.3.3.3, and Figure 3-40 for further discussion and an example.

Coastal environments are conducive to metal corrosion, especially in buildings within 3,000 feet of the ocean. Most jurisdictions require metal building hardware to be hot-dipped galvanized or stainless steel. Some local codes require protective coatings that are thicker than typical "off-the-shelf" products. For example, a G90 zinc coating (0.75 mil on each face) may be required. Other recommendations include the following:

- ❍ Use hot-dipped galvanized or stainless steel hardware. Reinforcing steel should be fully protected from corrosion by the surrounding material (masonry, mortar, grout, or concrete). Use galvanized or epoxy-coated reinforcing steel in situations where the potential for corrosion is high.
- ❍ Avoid joining dissimilar metals, especially those with high galvanic potential.
- ❍ Avoid using certain wood preservatives in direct contact with galvanized metal. Verify that wood treatment is suitable for use with galvanized metal, or use stainless steel.
- ❍ Metal-plate-connected trusses should not be exposed to the elements. Truss joints near vent openings are more susceptible to corrosion and may require increased corrosion protection.

Note: *Although more resistant than other metals, stainless steel is still subject to corrosion.*

Further information on the rain-screen principle can be found in the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

In conjunction with the rain-screen principle, it is desirable to avoid using sealant as the first or only line of defense against water infiltration. When sealant joints are exposed, obtaining long-lasting watertight performance is difficult because of the complexities of sealant joint design and installation (see Figure 3-40, which shows the sealant protected by a removable stop).

Step 4: Peer Review

If the design team's wind expertise and experience is limited, wind design input and/or peer review should be sought from a qualified individual. The design input or peer review could be arranged for the entire building, or for specific components such as the roof or glazing systems, that are critical and beyond the design team's expertise.

Regardless of the design team's expertise and experience, peer review should be considered when a critical facility:

- Is located in an area where the basic wind speed is greater than 90 mph (peak gust)—particularly if the facility is a hospital, or will be used as an EOC or hurricane shelter.
- Will incorporate a tornado shelter.

3.3.1.3 Construction Contract Administration

After a suitable design is complete, the design team should endeavor to ensure that the design intent is achieved during construction. The key elements of construction contract administration are submittal reviews and field observations, as discussed below.

Submittal reviews: The specifications need to stipulate the submittal requirements. This includes specifying what systems require submittals (e.g., windows) and test data (where appropriate). Each submittal should demonstrate the development of a load path through the system and into its supporting element. For example, a window submittal should show that the glazing has sufficient strength, its attachment to the frame is adequate, and the attachment of the frame to the wall is adequate.

During submittal review, it is important for the designer of record to be diligent in ensuring that all required documents are submitted and that they include the necessary information. The submittal information needs to be thoroughly checked to ensure its validity. For example, if an approved method used to demonstrate compliance with the design load has been altered or incorrectly applied, the test data should be rejected, unless the contractor can demonstrate the test method was suitable. Similarly, if a new test method has been developed by a manufacturer or the contractor, the contractor should demonstrate its suitability.

Field observations: It is recommended that the design team analyze the design to determine which elements are critical to ensuring high-wind performance. The analysis should include the structural system and exterior-mounted electrical equipment, but it should focus on the building envelope and exterior-mounted mechanical and communications equipment. After determining the list of critical elements to be observed, observation frequency and the need for special inspections by an inspection firm should be determined. Observation frequency and the need for special inspections will depend on the results of the risk assessment described in Section 3.2.2, complexity of the facility, and the competency of the general contractor, subcontractors, and suppliers.

See Section 3.4 for additional information pertaining to critical facilities located in hurricane-prone regions.

3.3.1.4 Post-Occupancy Inspections, Periodic Maintenance, Repair, and Replacement

The design team should advise the building owner of the importance of periodic inspections, maintenance, and timely repair. It is important for the building owner to understand that a facility's wind resistance will degrade over time due to exposure to weather unless it is regularly maintained and repaired. The goal should be to repair or replace items before they fail in a storm. This approach is less expensive than waiting for failure and then repairing the failed components and consequential damage.

The building envelope and exterior-mounted equipment should be inspected once a year by persons knowledgeable of the systems/materials they are inspecting. Items that require maintenance, repair, or replacement should be documented and scheduled for work. For example, the deterioration of glazing is often overlooked. After several years of exposure, scratches and chips can become extensive enough to weaken the glazing. Also, if an engineered film was surface-applied to glazing for wind-borne debris protection, the film should be periodically inspected and replaced before it is no longer effective.

A special inspection is recommended following unusually high winds. The purpose of the inspection is to assess whether the strong storm caused damage that needs to be repaired to maintain building strength and integrity. In addition to inspecting for obvious signs of damage, the inspector should determine if cracks or other openings have developed that may allow water infiltration, which could lead to corrosion or dry rot of concealed components.

See Section 3.4 for additional information pertaining to buildings located in hurricane-prone regions.

3.3.2 STRUCTURAL SYSTEMS

Based on post-storm damage evaluations, with the exception of strong and violent tornado events, the structural systems (i.e., MWFRS and structural components such as roof decking) of critical facilities have typically performed quite well during design wind events. There have, however, been notable exceptions; in these cases, the most common problem has been blow-off of the roof deck, but instances of collapse have also been documented (see Figure 3-22). The structural problems have primarily been caused by lack of an adequate load path, with connection failure being a common occurrence. Problems have also been caused by reduced structural capacity due to termites, workmanship errors (commonly associated with steel decks attached by puddle welds), and limited uplift resistance of deck connections in roof perimeters and corners (due to lack of code-required enhancement in older editions of the model codes).

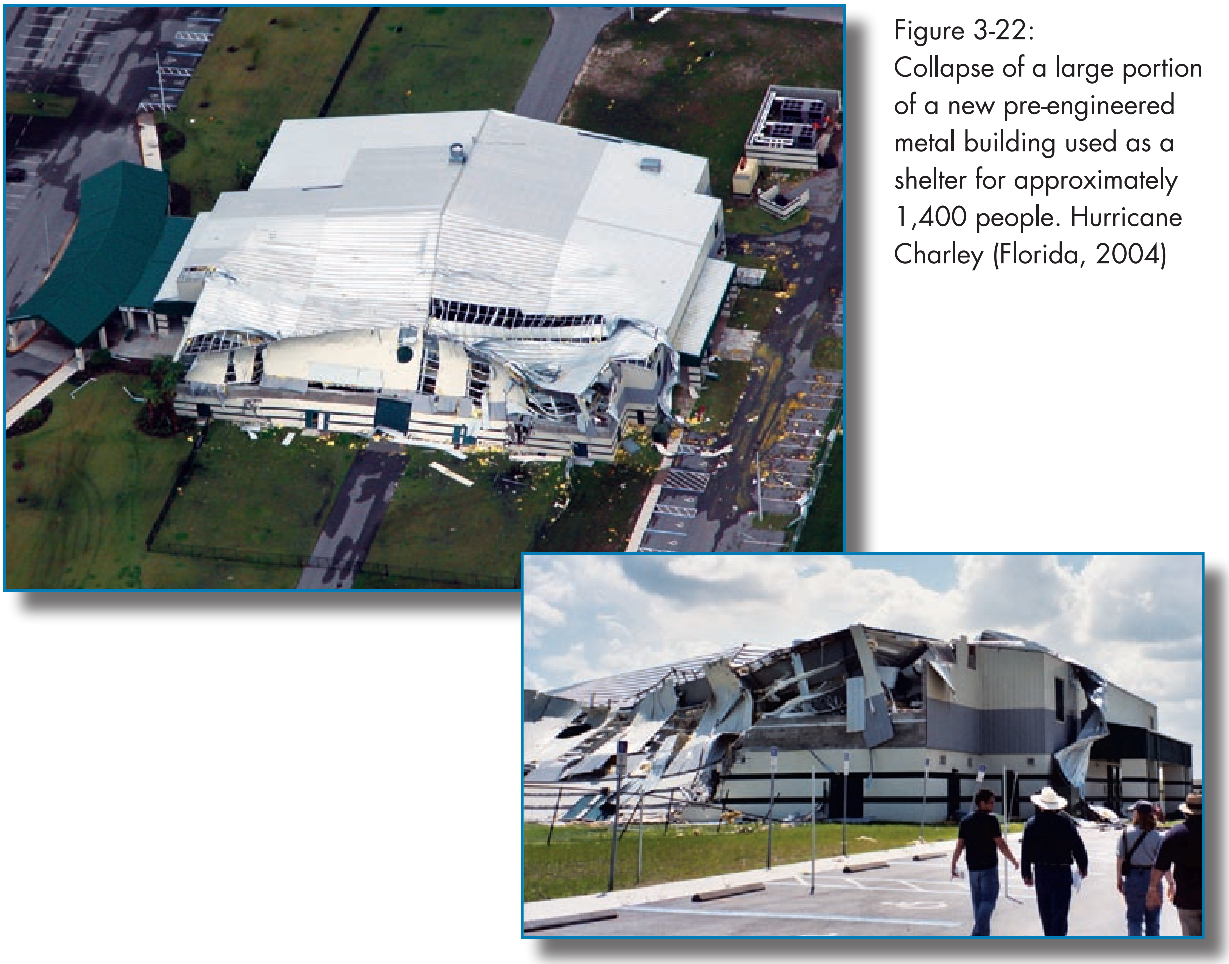


Figure 3-22:
Collapse of a large portion of a new pre-engineered metal building used as a shelter for approximately 1,400 people. Hurricane Charley (Florida, 2004)

With the exception of strong and violent tornado events, structural systems designed and constructed in accordance with the IBC should typically offer adequate wind resistance, provided attention was given to load path continuity and to the durability of building materials (with respect to corrosion and termites). However, the greatest reliability is offered by cast-in-place concrete. There are no known reports of any cast-in-place concrete buildings experiencing a significant structural problem during wind events, including the strongest hurricanes (Category 5) and tornadoes (F5).

The following design parameters are recommended for structural systems (see Section 3.4.2 for critical facilities located in hurricane-prone regions):

- If a pre-engineered metal building is being contemplated, special steps should be taken to ensure the structure has more redundancy than is typically the case with pre-engineered buildings.[7] Steps should be taken to ensure the structure is not vulnerable to progressive collapse in the event a primary bent (steel moment frame) is compromised or bracing components fail.

- Exterior load-bearing walls of masonry or precast concrete should be designed to have sufficient strength to resist external and internal loading when analyzed as C&C. CMU walls should have vertical and horizontal reinforcing and grout to resist wind loads. The connections of precast concrete wall panels should be designed to have sufficient strength to resist wind loads.

- For roof decks, concrete, steel, plywood, or oriented strand board (OSB) is recommended.

- For steel roof decks, it is recommended that a screw attachment be specified, rather than puddle welds or powder-driven pins. Screws are more reliable and much less susceptible to workmanship problems. Figure 3-23 shows decking that was attached with puddle welds. At most of the welds, there was only superficial bonding of the metal deck to the joist, as illustrated by this example. Only a small portion of the deck near the center of the weld area (as delineated by the circle) was well fused to the joist. Figures 3-24 and 3-25 show problems with acoustical decking attached with powder-driven pins. The pin shown on the left of Figure 3-25 is properly seated. However, the pin at the right did not penetrate far enough into the steel joist below.

- For attaching wood sheathed roof decks, screws, ring-shank, or screw-shank nails are recommended in the corner regions of the roof. Where the basic wind speed is greater than 90 mph, these types of fasteners are also recommended for the perimeter regions of the roof.

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[7] The structural system of pre-engineered metal buildings is composed of rigid steel frames, secondary members (including roof purlins and wall girts made of Z- or C-shaped members) and bracing.

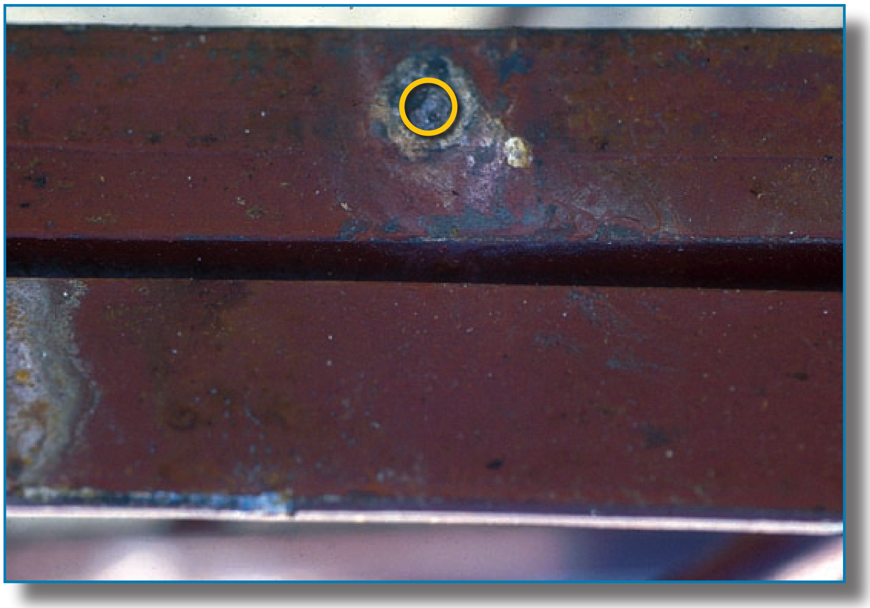


Figure 3-23:
View looking down at the top of a steel joist after the metal decking blew away. Only a small portion of the deck was well fused to the joist (circled area). Tornado (Oklahoma, 1999)

Figure 3-24:
Looking down at a sidelap of a deck attached with powder-driven pins. The washer at the top pin blew through the deck.

Figure 3-25:
View looking along a sidelap of a deck attached with powder-driven pins. The right pin does not provide adequate uplift and shear resistance.

- For precast concrete decks it is recommended that the deck connections be designed to resist the design uplift loads because the deck dead load itself is often insufficient to resist the uplift. The deck in Figure 3-26 had bolts to provide uplift resistance; however, anchor plates and nuts had not been installed. Without the anchor plates, the dead load of the deck was insufficient to resist the wind uplift load.

Figure 3-26:
Portions of this waffled precast concrete roof deck were blown off. Typhoon Paka (Guam, 1997)

- For precast Tee decks, it is recommended that the reinforcing be designed to accommodate the uplift loads in addition to the gravity loads. Otherwise, large uplift forces can cause member failure due to the Tee's own pre-stress forces after the uplift load exceeds the dead load of the Tee. This type of failure occurred at one of the roof panels shown in Figure 3-27, where a panel lifted because of the combined effects of wind uplift and pre-tension. Also, because the connections between the roof and wall panels provided very little uplift load resistance, several other roof and wall panels collapsed.

Figure 3-27:
Twin-Tee roof panel lifted as a result of the combined effects of wind uplift and pre-tension. Tornado (Missouri, May 2003)

- For buildings that have mechanically attached single-ply or modified bitumen membranes, designers should refer to the decking recommendations presented in the *Wind Design Guide for Mechanically Attached Flexible Membrane Roofs*, B1049 (National Research Council of Canada, 2005).

- If an FMG-rated roof assembly is specified, the roof deck also needs to comply with the FMG criteria.

- Walkway and entrance canopies are often damaged during high winds (see Figure 3-28). Wind-borne debris from damaged canopies can damage nearby buildings and injure people, hence these elements should also receive design and construction attention.

Figure 3-28:
The destroyed walkway canopy in front of a school became wind-borne debris. Hurricane Ivan (Florida, 2004)

ASCE 7-05 provides pressure coefficients for open canopies of various slopes (referred to as "free roofs" in ASCE 7). The free roof figures for MWFRS in ASCE 7-05 (Figures 6-18A to 6-18D) include two load cases, Case A and Case B. While there is no discussion describing the two load cases, they pertain to fluctuating loads and are intended to represent upper and lower limits of instantaneous wind pressures. Loads for both cases must be calculated to determine the critical loads. Figures 6-18A to 6-18C are for a wind direction normal to the ridge. For wind direction parallel to the ridge, use Figure 6-18D in ASCE 7-05.

3.3.3 BUILDING ENVELOPE

The following section highlights the design considerations for building envelope components that have historically sustained the greatest and most frequent damage in high winds.

3.3.3.1 Exterior Doors

For further general information on doors, see "Fenestration Systems" in the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php)

This section addresses primary and secondary egress doors, sectional (garage) doors, and rolling doors. Although blow-off of personnel doors is uncommon, it can cause serious problems (see Figure 3-29). Blown-off doors allow entrance of rain and tumbling doors can damage buildings and cause injuries.

Blown off sectional and rolling doors are quite common. These failures are typically caused by the use of door and track assemblies that have insufficient wind resistance, or by inadequate attachment of the tracks or nailers to the wall. At the relatively new fire station shown in Figure 3-30, two of the windward doors were pushed out of their tracks. At the third door, the track was pushed out from the nailer. With the collapse of these doors, the apparatus bay was fully pressurized. Because the connections between the trusses and the beam were too weak to accommodate the uplift load, the entire roof structure over the apparatus bay blew off.

Particular attention should be given to the design and installation of fire station apparatus bay doors which have been blown-in or blown-out frequently (see Figure 3-30). If doors blow inward, they can damage fire engines and ambulances and impair emergency response.

See Section 3.4.3.1 for critical facilities located in hurricane-prone regions.

Loads and Resistance

The IBC requires that the door assembly (i.e., door, hardware, frame, and frame attachment to the wall) be of sufficient strength to resist the positive and negative design wind pressure. Design professionals should require that doors comply with wind load testing in accordance with ASTM E 1233. Design professionals should also specify the attachment of the door frame to the wall (e.g., type, size, spacing, and edge distance of frame fasteners). For sectional and rolling doors attached to wood nailers, design professionals should also specify the attachment of the nailer to the wall.

For design guidance on attachment of door frames, see Technical Data Sheet #161, *Connecting Garage Door Jambs to Building Framing*, published by the Door & Access Systems Manufacturers Association, 2003 (available at www.dasma.com).

Figure 3-29:
Door on a hospital penthouse blown off its hinges during Hurricane Katrina (Mississippi, 2005)

Figure 3-30:
The roof structure over the apparatus bay blew off following the failure of sectional doors. Hurricane Charley (Florida, 2004)

Water Infiltration

Heavy rain that accompanies high winds (e.g., thunderstorms, tropical storms, and hurricanes) can cause significant wind-driven water infiltration problems. The magnitude of the problem increases with the wind speed. Leakage can occur between the door and its frame, the frame and the wall, and between the threshold and the door. When wind speeds approach 120 mph, some leakage should be anticipated because of the very high wind pressures and numerous opportunities for leakage path development.

Where corrosion is problematic, anodized aluminum or galvanized doors and frames, and stainless steel frame anchors and hardware are recommended.

The following recommendations should be considered to minimize infiltration around exterior doors.

Vestibule: Adding a vestibule allows both the inner and outer doors to be equipped with weatherstripping. The vestibule can be designed with water-resistant finishes (e.g., concrete or tile) and the floor can be equipped with a drain. In addition, installing exterior threshold trench drains can be helpful (openings must be small enough to avoid trapping high-heeled shoes). Note that trench drains do not eliminate the problem, since water can still penetrate at door edges.

Door swing: Out-swinging doors have weatherstripping on the interior side of the door, where it is less susceptible to degradation, which is an advantage when compared to in-swinging doors. Some interlocking weatherstripping assemblies are available for out-swinging doors.

For primary swinging entry/exit doors, exit door hardware is recommended to minimize the possibility of the doors being pulled open by wind suction. Exit hardware with top and bottom rods is more secure than exit hardware that latches at the jamb.

The successful integration of the door frame and the wall is a special challenge when designing doors. See Section 3.3.3.2 for discussion of this juncture.

ASTM E 2112 provides information pertaining to the installation of doors, including the use of sill pan flashings with end dams and rear legs (see Figure 3-31). It is recommended that designers use ASTM E 2112 as a design resource.

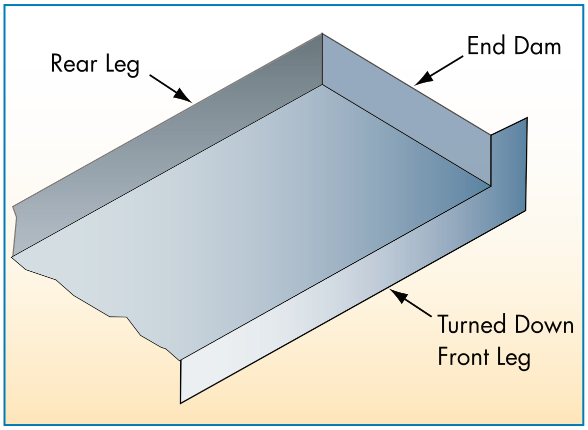


Figure 3-31:
Door sill pan flashing with end dams, rear leg, and turned-down front leg

Weatherstripping

A variety of pre-manufactured weatherstripping components is available, including drips, door shoes and bottoms, thresholds, and jamb/head weatherstripping.

Drips: These are intended to shed water away from the opening between the frame and the door head, and the opening between the door bottom and the threshold (see Figures 3-32 and 3-33). Alternatively, a door sweep can be specified (see Figure 3-33). For high-traffic doors, periodic replacement of the neoprene components will be necessary.

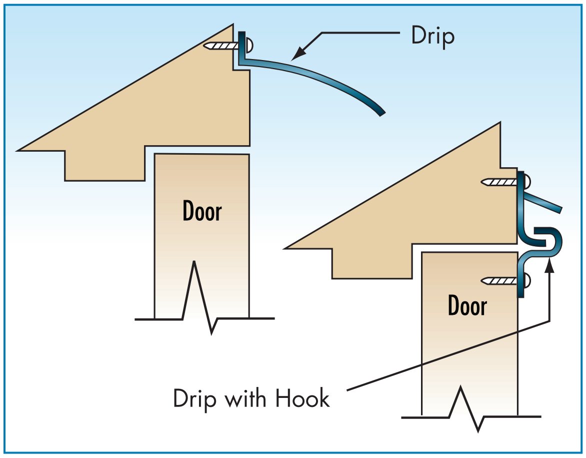


Figure 3-32:
Drip at door head and drip with hook at head

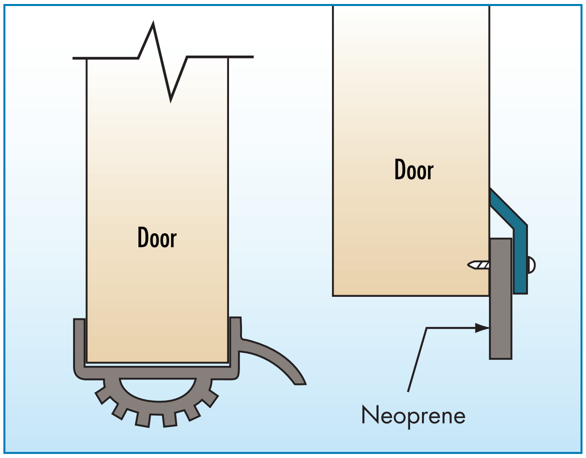


Figure 3-33:
Door shoe with drip and vinyl seal (left).
Neoprene door bottom sweep (right)

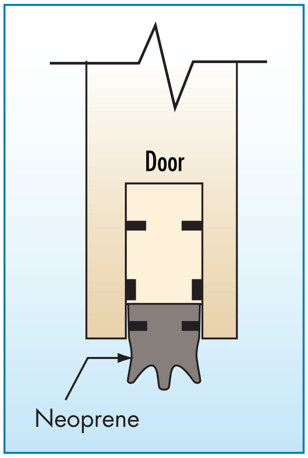
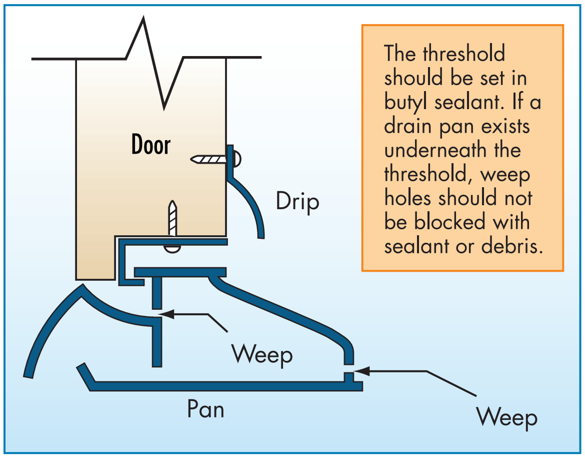


Figure 3-34:
Automatic door bottom

Door shoes and bottoms: These are intended to minimize the gap between the door and the threshold. Figure 3-33 illustrates a door shoe that incorporates a drip. Figure 3-34 illustrates an automatic door bottom. Door bottoms can be surface-mounted or mortised. For high-traffic doors, periodic replacement of the neoprene components will be necessary.

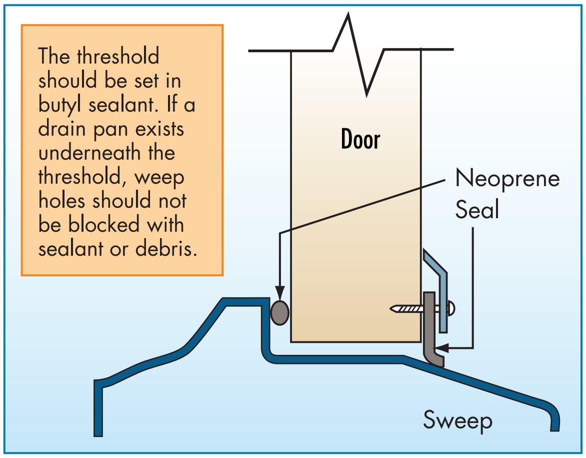
Thresholds: These are available to suit a variety of conditions. Thresholds with high (e.g., 1-inch) vertical offsets offer enhanced resistance to wind-driven water infiltration. However, the offset is limited where the thresholds are required to comply with the Americans with Disabilities Act (ADA), or at high-traffic doors. At other doors, high offsets are preferred.

Thresholds can be interlocked with the door (see Figure 3-35), or thresholds can have a stop and seal (see Figure 3-36). In some instances, the threshold is set directly on the floor. Where this is appropriate, setting the threshold in butyl sealant is recommended to avoid water infiltration between the threshold and the floor. In other instances, the threshold is set on a pan flashing, as previously discussed in this section. If the threshold has weep holes, specify that the weep holes not be obstructed (see Figure 3-35).



The threshold should be set in butyl sealant. If a drain pan exists underneath the threshold, weep holes should not be blocked with sealant or debris.

Figure 3-35:
Interlocking threshold with drain pan



The threshold should be set in butyl sealant. If a drain pan exists underneath the threshold, weep holes should not be blocked with sealant or debris.

Figure 3-36:
Threshold with stop and seal

Adjustable jamb/head weatherstripping: This type of weatherstripping is recommended because the wide sponge neoprene offers good contact with the door (see Figure 3-37). The adjustment feature also helps to ensure good contact, provided the proper adjustment is maintained.

Meeting stile: At the meeting stile of pairs of doors, an overlapping astragal weatherstripping offers greater protection than weatherstripping that does not overlap.

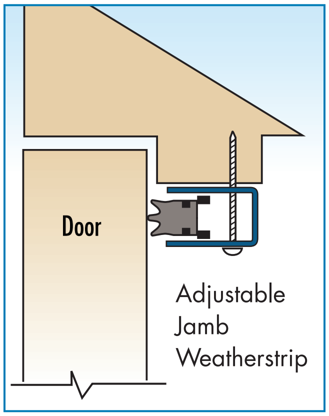


Figure 3-37: Adjustable jamb/head weatherstripping

3.3.3.2 Windows and Skylights

This section addresses general design considerations for exterior windows and skylights in critical facilities. For additional information on windows and skylights in critical facilities located in hurricane-prone regions, see Section 3.4.3.2, and for those in tornado-prone regions, see Section 3.5.

Loads and Resistance

The IBC requires that windows, curtain walls, and skylight assemblies (i.e., the glazing, frame, and frame attachment to the wall or roof) have sufficient strength to resist the positive and negative design wind pressure (see Figure 3-38). Design professionals should specify that these assemblies comply with wind load testing in accordance with ASTM E 1233. It is important to specify an adequate load path and to check its continuity during submittal review.

For further general information on windows, see the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

Water Infiltration

Heavy rain accompanied by high winds can cause wind-driven water infiltration problems. The magnitude of the problem increases with the wind speed. Leakage can occur at the glazing/frame interface, the frame itself, or between the frame and wall. When the basic wind speed is greater than 120 mph, because of the very high design wind pressures and numerous opportunities for leakage path development, some leakage should be anticipated when the design wind speed conditions are approached.

Figure 3-38:
Two complete windows, including frames, blew out as a result of an inadequate number of fasteners. Typhoon Paka (Guam, 1997)

The successful integration of windows and curtain walls into exterior walls is a challenge in protecting against water infiltration. To the extent possible when detailing the interface between the wall and the window or curtain wall units, designers should rely on sealants as the secondary line of defense against water infiltration, rather than making the sealant the primary protection. If a sealant joint is the first line of defense, a second line of defense should be designed to intercept and drain water that drives past the sealant joint.

Where corrosion is a problem, use of anodized aluminum or stainless steel frames and stainless steel frame anchors and screws are recommended.

When designing joints between walls and windows and curtain wall units, consider the shape of the sealant joint (i.e., a square joint is typically preferred) and the type of sealant to be specified. The sealant joint should be designed to enable the sealant to bond on only two opposing surfaces (i.e., a backer rod or bond-breaker tape should be specified). Butyl is recommended as a sealant for concealed joints, and polyurethane for exposed joints. During installation, cleanliness of the sealant substrate is important (particularly if polyurethane or silicone sealants are specified), as is the tooling of the sealant. ASTM

The maximum test pressure used in the current ASTM test standard for evaluating resistance of window units to wind-driven rain is well below design wind pressures. Therefore, units that demonstrate adequate wind-driven rain resistance during testing may experience leakage during actual wind events.

E 2112 provides guidance on the design of sealant joints, as well as other information pertaining to the installation of windows, including the use of sill pan flashings with end dams and rear legs (see Figure 3-39). Windows that do not have nailing flanges should typically be installed over a pan flashing. It is recommended that designers use ASTM E 2112 as a design resource.

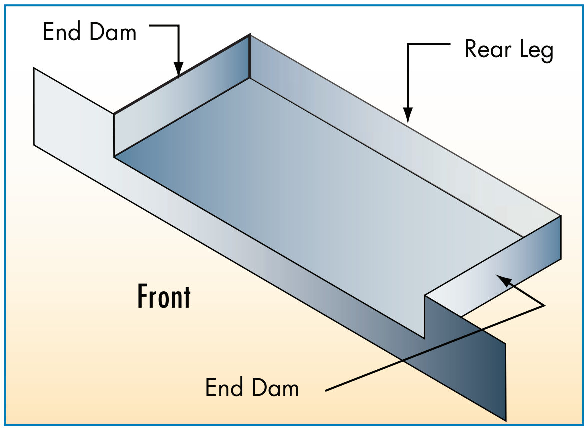


Figure 3-39:
View of a typical window sill pan flashing with end dams and rear legs

SOURCE: ASTM E 2112

Sealant joints can be protected with a removable stop, as illustrated in Figure 3-40. The stop protects the sealant from direct exposure to the weather and reduces the possibility of wind-driven rain penetration.

Where water infiltration protection is particularly demanding and important, it is recommended that onsite water infiltration testing in accordance with ASTM E 1105 be specified.

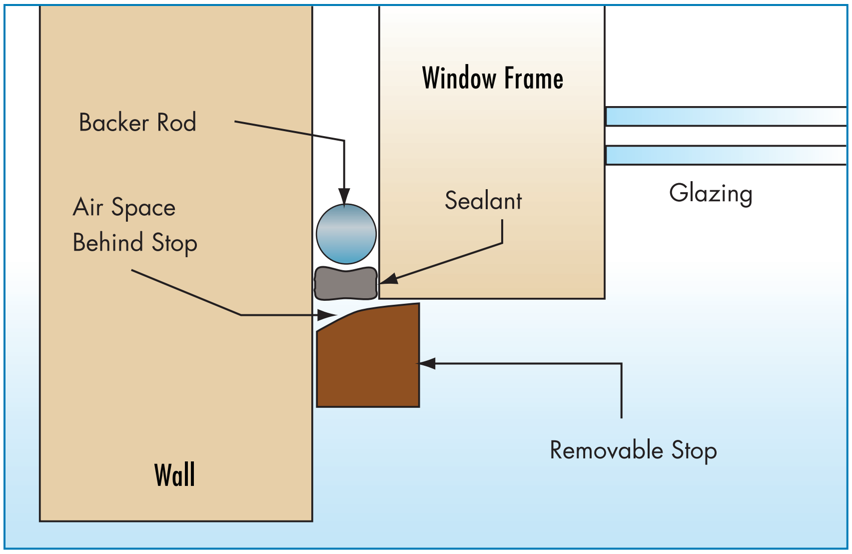


Figure 3-40:
Protecting sealant with a stop retards weathering and reduces the exposure to wind-driven rain.

3.3.3.3 Non-Load-Bearing Walls, Wall Coverings, and Soffits

This section addresses exterior non-load-bearing walls, exterior wall coverings, and soffits, as well as the underside of elevated floors, and provides guidance for interior non-load-bearing masonry walls. See Section 3.4.3.3 for additional information pertaining to critical facilities located in hurricane-prone regions, and Section 3.5 for additional information pertaining to critical facilities located in tornado-prone regions.

For further general information on non-load-bearing walls and wall coverings, see the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

Loads and Resistance

The IBC requires that soffits, exterior non-load-bearing walls, and wall coverings have sufficient strength to resist the positive and negative design wind pressures.

To ensure the continuity of elevator service, elevator penthouse walls must possess adequate wind and water resistance. If the walls blow away or water leaks through the wall system, the elevator controls and/or motors can be destroyed. Loss of elevators may critically affect facility operations because the restoration can take weeks even with expedited work (see Figure 3-41).

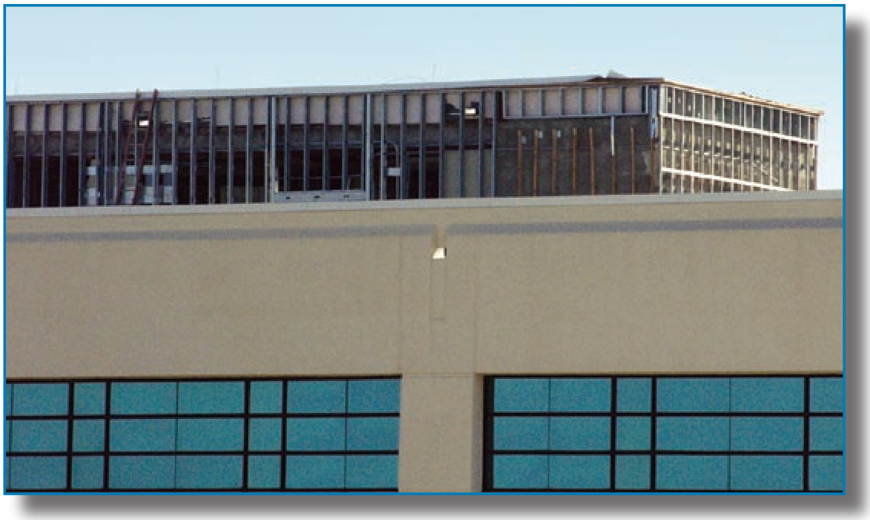


Figure 3-41:
The wall covering blew off the penthouse at this hospital complex allowing rainwater to destroy the elevator controls. Hurricane Ivan (Florida, 2004)

Soffits: Depending on the wind direction, soffits can experience either positive or negative pressure. Besides the cost of repairing the damaged soffits, wind-borne soffit debris can cause property damage and injuries (see Figure 3-42). Failed soffits may also provide a convenient path for wind-driven rain to enter the building. Storm-damage research has shown that water blown into attic spaces after the loss of soffits caused significant damage and the collapse of ceilings. At the relatively new fire station shown in Figure 3-43, essentially all of the perforated aluminum soffit was blown away. Wind-driven water entered the attic and saturated the batt insulation, which caused the ceiling boards to collapse. After the storm, the fire station was evacuated solely because of this damage. Even in instances where soffits remain in place, water can penetrate through soffit vents and cause damage. At this time, there are no known specific test standards or design guidelines to help design wind- and water-resistant soffits and soffit vents.

Where corrosion is a problem, stainless steel fasteners are recommended for wall and soffit systems. For other components (e.g., furring, blocking, struts, and hangers), nonferrous components (such as wood), stainless steel, or steel with a minimum of G-90 hot-dipped galvanized coating are recommended. Additionally, access panels are recommended so components within soffit cavities can be periodically inspected for corrosion or dry rot.

Figure 3-42:
This suspended metal soffit was not designed for upward-acting wind pressure. Typhoon Paka (Guam, 1997)

Figure 3-43:
This fire station was abandoned after Hurricane Charley because of soffit failure. (Florida, 2004)

Exterior non-load-bearing masonry walls: Particular care should be given to the design and construction of exterior non-load-bearing masonry walls. Although these walls are not intended to carry gravity loads, they should be designed to resist the external and internal loading for components and cladding in order to avoid collapse. When these types of walls collapse, they represent a severe risk to life because of their great weight (see Figure 3-15).

Interior non-load-bearing masonry walls: Special consideration should also be given to interior non-load-bearing masonry walls. Although these walls are not required by building codes to be designed to resist wind loads, if the exterior glazing is broken, or the exterior doors are blown away, the interior walls could be subjected to significant load as the building rapidly becomes fully pressurized. To avoid casualties, it is recommended that interior non-load-bearing masonry walls adjacent to occupied areas be designed to accommodate loads exerted by a design wind event, using the partially enclosed pressure coefficient (see Figure 3-44). By doing so, wall collapse may be prevented if the building envelope is breached. This recommendation is applicable to critical facilities located in areas with a basic wind speed greater than 120 mph, those used for hurricane shelters, and to critical facilities in tornado-prone regions that do not have shelter space designed in accordance with FEMA 361.

Figure 3-44:
The red arrows show the original location of a CMU wall that nearly collapsed following a rolling door failure. Hurricane Charley (Florida, 2004)

Wall Coverings

There are a variety of exterior wall coverings. Brick veneer, exterior insulation finish systems (EIFS), stucco, metal wall panels, and aluminum and vinyl siding have often exhibited poor wind performance. Veneers (such as ceramic tile and stucco) over concrete, stone veneer, and cement-fiber panels and siding have also blown off. Wood siding and panels rarely blow off. Although tilt-up precast walls have failed during wind storms, precast wall panels attached to steel or concrete framed buildings typically offer excellent wind performance.

Brick veneer:[8] Brick veneer is frequently blown off walls during high winds. When brick veneer fails, wind-driven water can enter and damage buildings, and building occupants can be vulnerable to injury from wind-borne debris (particularly if the walls are

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[8] The brick veneer discussion is from *Attachment of Brick Veneer in High-Wind Regions - Hurricane Katrina Recovery Advisory* (FEMA, December 2005).

sheathed with plastic foam insulation or wood fiberboard in lieu of wood panels). Pedestrians in the vicinity of damaged walls can also be vulnerable to injury from falling bricks (see Figure 3-45). Common failure modes include tie (anchor) fastener pull-out (see Figure 3-46), failure of masons to embed ties into the mortar (Figure 3-47), poor bonding between ties and mortar, a mortar of poor quality, and tie corrosion.

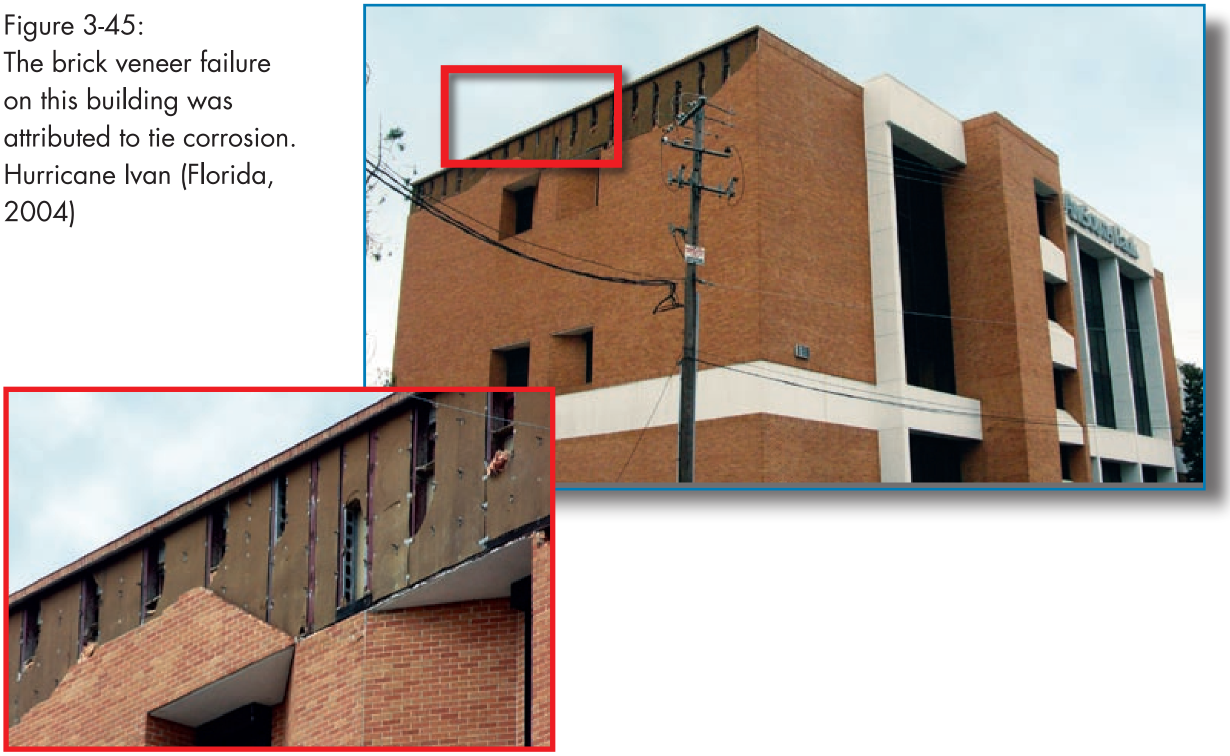


Figure 3-45:
The brick veneer failure on this building was attributed to tie corrosion. Hurricane Ivan (Florida, 2004)

Figure 3-46:
This tie remained embedded in the mortar joint while the smooth-shank nail pulled from the stud.

Figure 3-47: These four ties were never embedded into the mortar joint.

Ties are often installed before brick laying begins. When this is done, ties are often improperly placed above or below the mortar joints. When misaligned, the ties must be angled up or down to be embedded into the mortar joints (Figure 3-48). Misalignment not only reduces the embedment depth, but also reduces the effectiveness of the ties, because wind forces do not act in parallel direction to the ties.

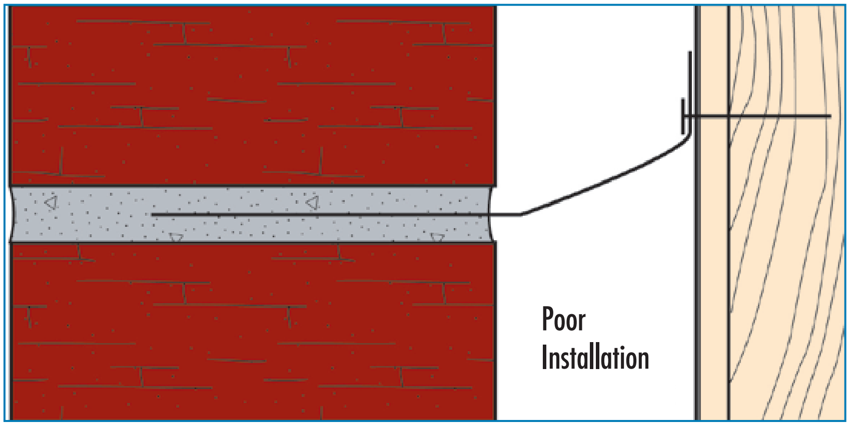


Figure 3-48: Misalignm ent of the tie reduces the embedment and promotes veneer failure.

Corrugated ties typically used in residential and nursing home veneer construction provide little resistance to compressive loads. The use of compression struts would likely be beneficial, but off-the-shelf devices do not currently exist. Two-piece adjustable ties (Figure 3-49) provide significantly greater compressive strength than corrugated ties.

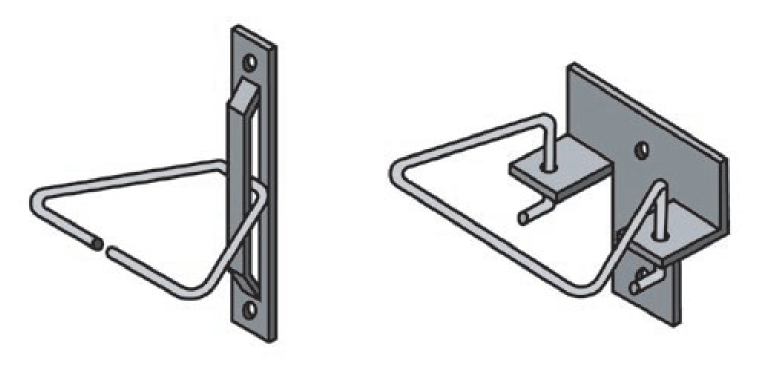


Figure 3-49: Examples of two-piece adjustable ties

The following Brick Industry Association (BIA) technical notes provide guidance on brick veneer: Technical Notes 28: *Anchored Brick Veneer, Wood Frame Construction* (2002); Technical Notes 28B: *Brick Veneer/Steel Stud Walls* (2005); and Technical Notes 44B: *Wall Ties* (2003) (available online at www.bia.org). These technical notes provide attachment recommendations; however, they are not specific for high-wind regions. To enhance wind performance of brick veneer, the following are recommended:

- ❍ Calculate wind loads and determine tie spacing in accordance with the latest edition of the *Building Code Requirements for Masonry Structures,* ACI 530/ASCE 5/TMS 402 (ACI 530, 1996)). A stud spacing of 16 inches on center is recommended so that ties can be anchored at this spacing.

- ❍ Ring-shank nails are recommended in lieu of smooth-shank nails for wood studs. A minimum embedment of 2 inches is suggested.

- ❍ For use with wood studs, two-piece adjustable ties are recommended. However, where corrugated steel ties are used, they should be 22-gauge minimum, 7/8-inch wide by 6-inch long, and comply with ASTM A 1008, with a zinc coating complying with ASTM A 153 Class B2. For ties used with steel studs, see BIA Technical Notes 28B, *Brick Veneer/Steel Stud Walls.* Stainless steel ties should be used for both wood and steel studs in areas within 3,000 feet of the coast.

- ❍ Install ties as the brick is laid so that the ties are properly aligned with the mortar joints.

- ❍ Locate ties within 8 inches of door and window openings, and within 12 inches of the top of veneer sections.

- ❍ Although corrugated ties are not recommended, if used, bend the ties at a 90-degree angle at the nail head to minimize tie flexing when the ties are loaded in tension or compression (Figure 3-50).

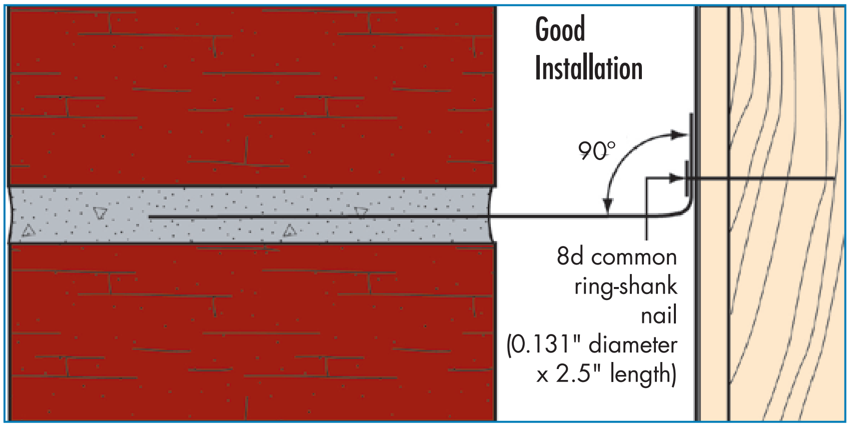


Figure 3-50:
Bend ties at nail heads

- ❍ Embed ties in joints so that the mortar completely encapsulates the ties. Embed a minimum of 1½ inches into the bed joint, with a minimum mortar cover of ⅝-inch to the outside face of the wall (see Figure 3-51).

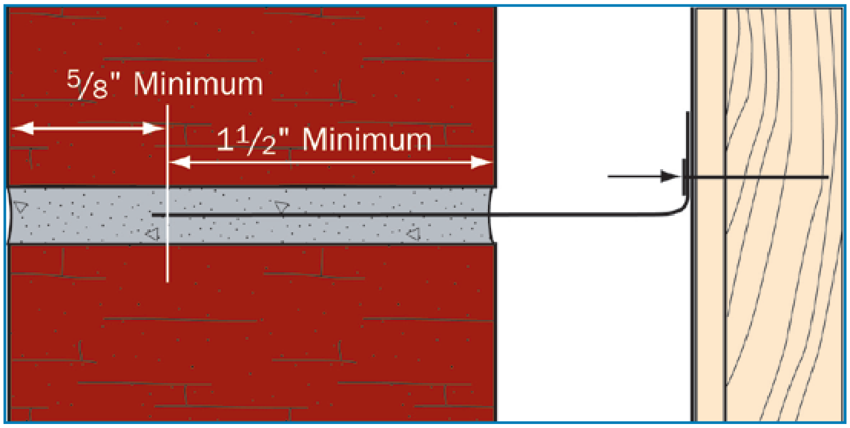


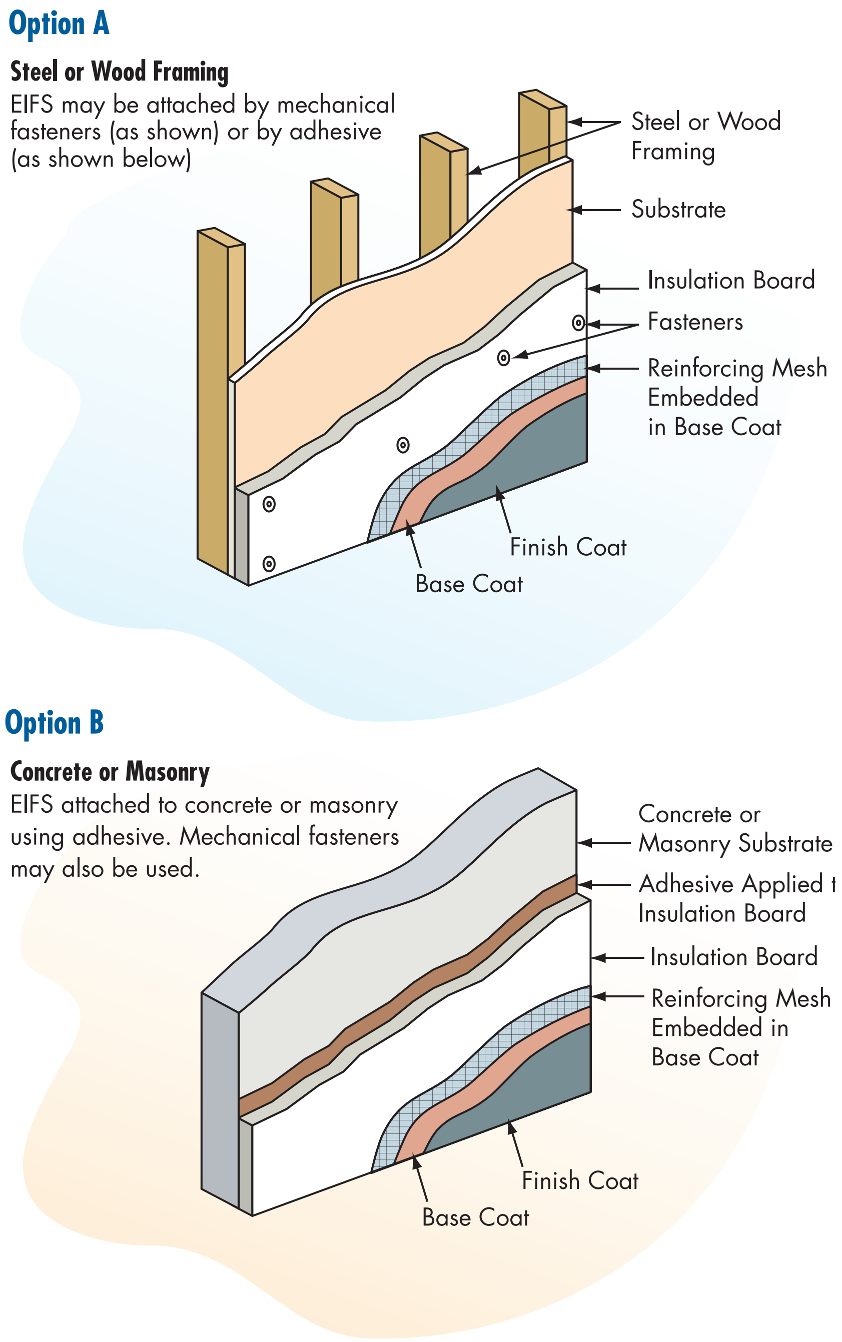
Figure 3-51:
Tie embedment

To avoid water leaking into the building, it is important that weep holes be adequately spaced and not be blocked during brick installation, and that through-wall flashings be properly designed and installed. At the hospital shown in Figure 3-52, water leaked into the building along the base of many of the brick veneer walls. When high winds accompany heavy rain, a substantial amount of water can be blown into the wall cavity.

Figure 3-52:
Water leaked inside along the base of the brick veneer walls. Hurricane Katrina (Louisiana, 2005)

EIFS: Figure 3-53 shows typical EIFS assemblies. Figures 3-41, 3-54, and 4-6 show EIFS blow-off. In these cases, the molded expanded polystyrene (MEPS) was attached to gypsum board, which in turn was attached to metal studs. The gypsum board detached from the studs, which is a common EIFS failure. When the gypsum board on the exterior side of the studs is blown away, it is common for gypsum board on the interior side to also be blown off. The opening allows the building to become fully pressurized and allows the entrance of wind-driven rain. Other common types of failure include wall framing failure, separation of the MEPS from its substrate, and separation of the synthetic stucco from the MEPS.

At the hospital shown in Figure 3-55, the EIFS was applied over a concrete wall. The MEPS debonded from the concrete. In general, a concrete substrate prevents wind and water from entering a building, but if the EIFS debonds from the concrete, EIFS debris can break unprotected glazing.



Option A

Steel or Wood Framing

EIFS may be attached by mechanical fasteners (as shown) or by adhesive (as shown below)

Option B

Concrete or Masonry

EIFS attached to concrete or masonry using adhesive. Mechanical fasteners may also be used.

Figure 3-53:
Typical EIFS assemblies

Figure 3-54:
EIFS blow-off at building corner. In places, metal fascia was also blown in. Tornado (Oklahoma, 1999)

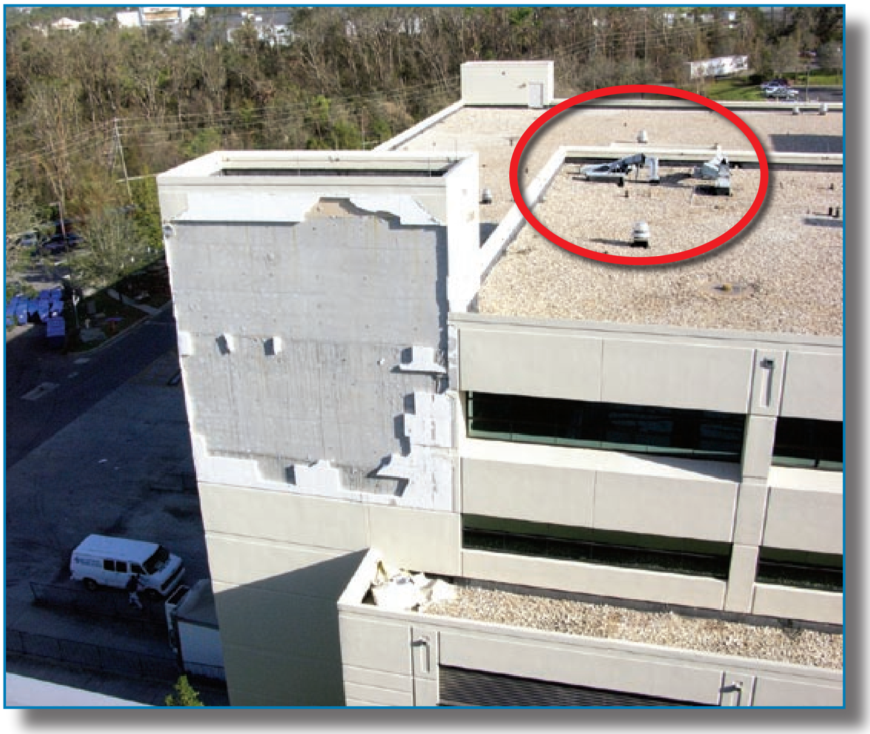


Figure 3-55:
EIFS blown off a cast-in-place concrete wall. Note the damaged rooftop ductwork. Hurricane Ivan (Florida, 2004)

Wind-borne EIFS debris can be devastating to unprotected glazing. At the hospital shown in Figure 3-56, the hospital's original concrete wall panels had been furred with metal hat channels and covered with EIFS. In a large corner area, the EIFS and gypsum board substrate blew off the hat channels and broke a large number of windows in the multi-story connecting walkway between the hospital and the medical office building (MOB). The EIFS debris also broke a large number of windows in the MOB (see Figure 3-56). Glass shards from the MOB punctured the roof membrane over the dialysis unit. The costly damage resulted in loss of several rooms in the MOB and hampered functioning of the hospital complex.

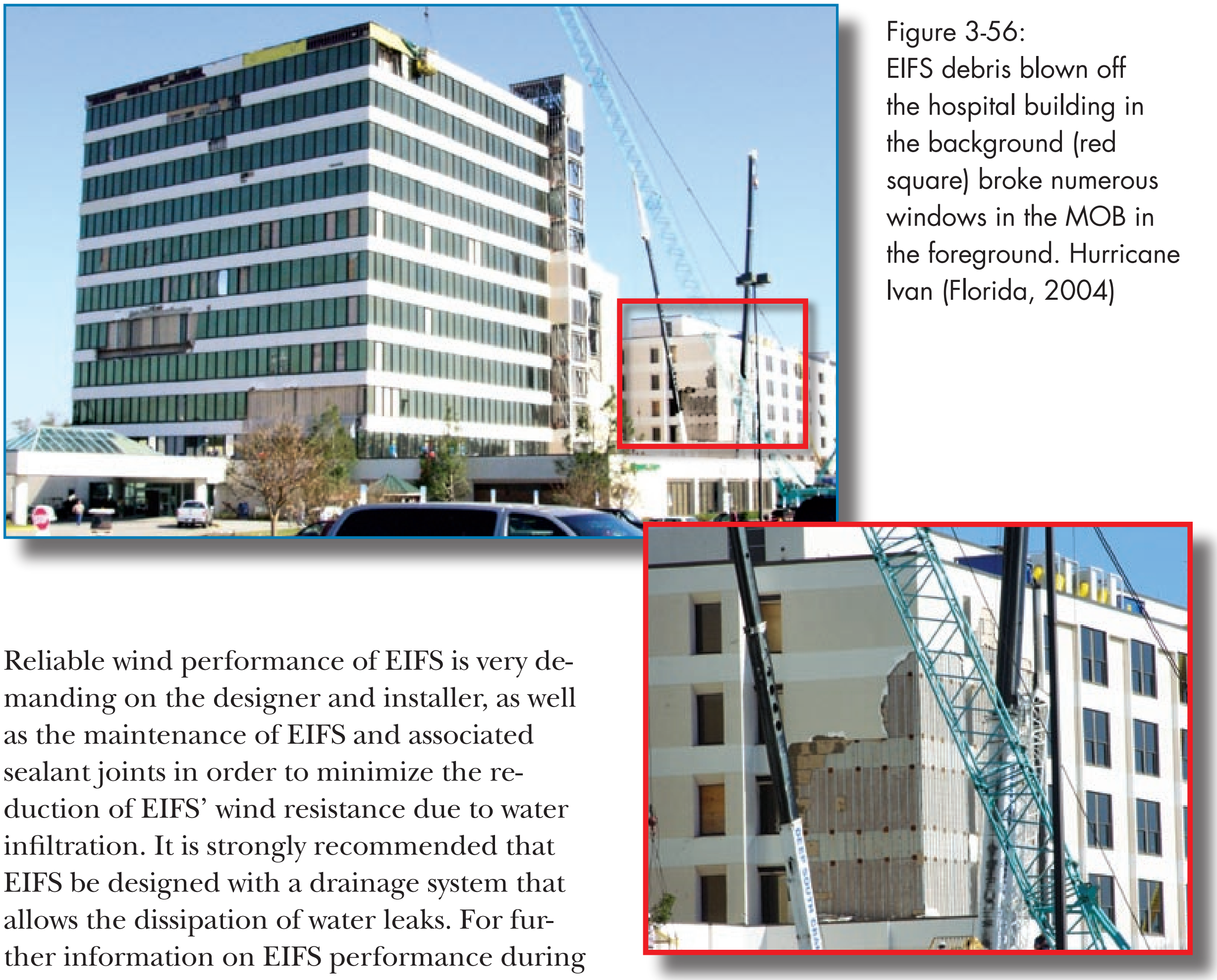


Figure 3-56:
EIFS debris blown off the hospital building in the background (red square) broke numerous windows in the MOB in the foreground. Hurricane Ivan (Florida, 2004)

Reliable wind performance of EIFS is very demanding on the designer and installer, as well as the maintenance of EIFS and associated sealant joints in order to minimize the reduction of EIFS' wind resistance due to water infiltration. It is strongly recommended that EIFS be designed with a drainage system that allows the dissipation of water leaks. For further information on EIFS performance during high winds and design guidance see FEMA 489 and 549.

Another issue associated with EIFS is the potential for judgment errors. EIFS applied over studs is sometimes mistaken for a concrete wall, which may lead people to seek shelter behind it. However, instead of being protected by several inches of concrete, only two layers of gypsum board (i.e., one layer on each side of the studs) and a layer of MEPS separate the occupants from the impact of wind-borne debris that can easily penetrate such a wall and cause injury.

Stucco: Wind performance of traditional stucco walls is similar to the performance of EIFS, as shown in Figure 3-57. In several areas the metal stud system failed; in other areas the gypsum sheathing blew off the studs; and in other areas, the metal lath blew off the gypsum sheathing. The failure shown in Figure 3-57 illustrates the importance of designing and constructing wall framing (including attachment of stud tracks to the building and attachment of the studs to the tracks) to resist the design wind loads.

Figure 3-57:
The stucco wall failure was caused by inadequate attachment between the stud tracks and the building's structure. Hurricane Ivan (Florida, 2004)

Metal wall panels: Wind performance of metal wall panels is highly variable. Performance depends on the strength of the specified panel (which is a function of material and thickness, panel profile, panel width, and whether the panel is a composite) and the adequacy of the attachment (which can either be by concealed clips or exposed fasteners). Excessive spacing between clips/fasteners is the most common problem. Clip/fastener spacing should be specified, along with the specific type and size of fastener. Figures 3-14 and 3-58 illustrate metal wall panel problems. At the school shown in Figure 3-58 (which was being used as a shelter), the metal panels were attached with concealed fasteners. The panels unlatched at the standing seams. In addition to generating windborne debris, loss of panels allowed wind-driven rain to enter the building.

Figure 3-58:
The loss of metal wall panels allowed a substantial amount of wind-driven rain to penetrate this building. Hurricane Ivan (Florida, 2004)

To minimize water infiltration at metal wall panel joints, it is recommended that sealant tape be specified at sidelaps when the basic wind speed is in excess of 90 mph. However, endlaps should be left unsealed so that moisture behind the panels can be wicked away. Endlaps should be a minimum of 3 inches (4 inches where the basic wind speed is greater than 120 mph) to avoid wind-driven rain infiltration. At the base of the wall, a 3-inch (4-inch) flashing should also be detailed, or the panels should be detailed to overlap with the slab or other components by a minimum of 3 inches (4 inches).

Vinyl siding: Vinyl siding blow-off is typically caused by nails spaced too far apart and/or the use of vinyl siding that has inadequate wind resistance. Vinyl siding is available with enhanced wind resistance features, such as an enhanced nailing hem, greater interlocking area, and greater thickness.

The Vinyl Siding Institute (VSI) sponsors a Certified Installer Program that recognizes individuals with at least 1 year of experience who can demonstrate proper vinyl siding application. If vinyl siding is specified, design professionals should consider specifying that the siding contractor be a VSI-certified installer. For further information on this program, see www.vinylsiding.org.

Secondary line of protection: Almost all wall coverings permit the passage of some water past the exterior surface of the covering, particularly when the rain is wind-driven. For this reason, most wall coverings should be considered water-shedding, rather than waterproofing coverings. To avoid moisture-related problems, it is recommended that a secondary line of protection with a moisture barrier (such as housewrap or asphalt-saturated felt) and flashings around door and window openings be provided. Designers should specify that horizontal laps of the moisture barrier be installed so that water is allowed to drain from the wall (i.e., the top sheet should lap over the bottom sheet so that water running down the sheets remains on their outer surface). The bottom of the moisture barrier needs to be designed to allow drainage. Had the metal wall panels shown in Figure 3-58 been applied over a moisture barrier and sheathing, the amount of water entering the building would have likely been eliminated or greatly reduced.

In areas that experience frequent wind-driven rain, incorporating a rain screen design, by installing vertical furring strips between the moisture barrier and siding materials, will facilitate drainage of water from the space between the moisture barrier and backside of the siding. In areas that frequently experience strong winds, enhanced flashing is recommended. Enhancements include use of flashings that have extra-long flanges, and the use of sealant and tapes. Flashing design should recognize that wind-driven water could be pushed up vertically. The height to which water can be pushed increases with wind speed. Water can also migrate vertically and horizontally by capillary action between layers of materials (e.g., between a flashing flange and housewrap). Use of a rain screen design, in conjunction with enhanced flashing design, is recommended in areas that frequently experience wind-driven rain or strong winds. It is recommended that designers attempt to determine what type of flashing details have successfully been used in the area where the facility will be constructed.

Underside of Elevated Floors

If sheathing is applied to the underside of joists or trusses elevated on piles (e.g., to protect insulation installed between the joists/trusses), its attachment should be specified in order to avoid blow-off. Stainless steel or hot-dip galvanized nails or screws are recommended. Since ASCE 7 does not provide guidance for load determination, professional judgment in specifying attachment is needed.

3.3.3.4 Roof Systems

Because roof covering damage has historically been the most frequent and the costliest type of wind damage, special attention needs to be given to roof system design. See Section 3.4.3.4 for additional information pertaining to critical facilities located in hurricane-prone regions, and Section 3.5 for critical facilities located in tornado-prone regions.

For further general information on roof systems, see the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

Code Requirements

The IBC requires the load resistance of the roof assembly to be evaluated by one of the test methods listed in IBC's Chapter 15. Design professionals are cautioned that designs that deviate from the tested assembly (either with material substitutions or change in thickness or arrangement) may adversely affect the wind performance of the assembly. The IBC does not specify a minimum safety factor. However, for the roof system, a safety factor of 2 is recommended. To apply the safety factor, divide the test load by 2 to determine the allowable design load. Conversely, multiply the design load by 2 to determine the minimum required test resistance.

For structural metal panel systems, the IBC requires test methods UL 580 or ASTM E 1592. It is recommended that design professionals specify use of E 1592, because it gives a better representation of the system's uplift performance capability.

The roof of the elevator penthouse must possess adequate wind and water resistance to ensure continuity of elevator service. It is recommended that a secondary roof membrane, as discussed in Section 3.3.3.3, be specified over the elevator penthouse roof deck.

Load Resistance

Specifying the load resistance is commonly done by specifying a Factory Mutual Research (FMR) rating, such as FM 1-75. The first number (1) indicates that the roof assembly passed the FMR tests for a Class 1 fire rating. The second number (75) indicates the uplift resistance in pounds per square foot (psf) that the assembly achieved during testing. With a safety factor of two this assembly would be suitable for a maximum design uplift load of 37.5 psf.

The highest uplift load occurs at the roof corners because of building aerodynamics as discussed in Section 3.1.3. The perimeter has a somewhat lower load, while the field of the roof has the lowest load. FMG Property Loss Prevention Data Sheets are formatted so that a roof assembly can be selected for the field of the roof. For the perimeter and corner areas, FMG Data Sheet 1-29 provides three options: 1) use the FMG Approval Guide listing if it includes a perimeter and corner fastening method; 2) use a roof system with the appropriate FMG Approval rating in the field, perimeter, and corner, in accordance with Table 1 in FMG Data Sheet 1-29; or 3) use prescriptive recommendations given in FMG Data Sheet 1-29.

FM Global (FMG) is the name of the Factory Mutual Insurance Company and its affiliates. One of FMG's affiliates, Factory Mutual Research (FMR) provides testing services, produces documents that can be used by designers and contractors, and develops test standards for construction products and systems. FMR evaluates roofing materials and systems for resistance to fire, wind, hail, water, foot traffic and corrosion. Roof assemblies and components are evaluated to establish acceptable levels of performance. Some documents and activities are under the auspices of FMG and others are under FMR.

When perimeter and corner uplift resistance values are based on a prescriptive method rather than testing, the field assembly is adjusted to meet the higher loads in the perimeter and corners by increasing the number of fasteners or decreasing the spacing of adhesive ribbons by a required amount. However, this assumes that the failure is the result of the fastener pulling out from the deck, or that the failure is in the vicinity of the fastener plate, which may not be the case. Also, the increased number of fasteners required by FMG may not be sufficient to comply with the perimeter and corner loads derived from the building code. Therefore, if FMG resistance data are specified, it is prudent for the design professional to specify the resistance for each zone of the roof separately. Using the example cited above, if the field of the roof is specified as 1-75, the perimeter would be specified as 1-130 and the corner would be specified as 1-190.

If the roof system is fully adhered, it is not possible to increase the uplift resistance in the perimeter and corners. Therefore, for fully adhered systems, the uplift resistance requirement should be based on the corner load rather than the field load.

Roof System Performance

Storm-damage research has shown that sprayed polyurethane foam (SPF) and liquid-applied roof systems are very reliable high-wind performers. If the substrate to which the SPF or liquid-applied membrane is applied does not lift, it is highly unlikely that these systems will blow off. Both systems are also more resistant to leakage after missile impact damage than most other systems. Built-up roofs (BURs) and modified bitumen systems have also demonstrated good wind performance provided the edge flashing/coping does not fail (which happens frequently). The exception is aggregate surfacing, which is prone to blow-off (see Figures 3-12 and 3-13). Modified bitumen applied to a concrete deck has demonstrated excellent resistance to progressive peeling after blow-off of the metal edge flashing. Metal panel performance is highly variable. Some systems are very wind-resistant, while others are quite vulnerable.

Of the single-ply attachment methods, the paver-ballasted and fully adhered methods are the least problematic. Systems with aggregate ballast are prone to blow-off, unless care is taken in specifying the size of aggregate and the parapet height (see Figure 3-9). The performance of protected membrane roofs (PMRs) with a factory-applied cementitious coating over insulation boards is highly variable. When these boards are installed over a loose-laid membrane, it is critical that an air retarder be incorporated to prevent the membrane from ballooning and disengaging the boards. ANSI/SPRI RP-4 (which is referenced in the IBC) provides wind guidance for ballasted systems using aggregate, pavers, and cementitious-coated boards.

The National Research Council of Canada, Institute for Research in Construction's Wind Design Guide for Mechanically Attached Flexible Membrane Roofs (B1049, 2005) provides recommendations related to mechanically attached single-ply and modified bituminous systems. B1049 is a comprehensive wind design guide that includes discussion on air retarders. Air retarders can be effective in reducing membrane flutter, in addition to being beneficial for use in ballasted single-ply systems. When a mechanically attached system is specified, careful coordination with the structural engineer in selecting deck type and thickness is important.

If a steel deck is selected, it is critical to specify that the membrane fasteners be attached in rows perpendicular to the steel flanges to avoid overstressing the attachment of the deck to the deck support structure. At the school shown in Figure 3-59, the fastener rows of the mechanically attached single-ply membrane ran parallel to the top flange of the steel deck. The deck fasteners were overstressed and a portion of the deck blew off and the membrane progressively tore. At another building, shown in Figure 3-60, the membrane fastener rows also ran parallel to the top flange of the steel deck. When membrane fasteners run parallel to the flange, the flange with membrane fasteners essentially carries all the uplift load because of the deck's inability to transfer any significant load to adjacent flanges. Hence, at the joists shown in Figure 3-60, the deck fasteners on either side of the flange with the membrane fasteners are the only connections to the joist that are carrying substantial uplift load.

Figure 3-59:
The orientation of the membrane fastener rows led to blow-off of the steel deck. Hurricane Marilyn (U.S. Virgin Islands, 1995)

Figure 3-60:
View of the underside of a steel deck showing the mechanically attached single-ply membrane fastener rows running parallel to, instead of across, the top flange of the deck.

For metal panel roof systems, the following are recommended:

- ❍ When clip or panel fasteners are attached to nailers, detail the connection of the nailer to the nailer support (including the detail of where nailers are spliced over a support).
- ❍ When clip or panel fasteners are loaded in withdrawal (tension), screws are recommended in lieu of nails.
- ❍ For concealed clips over a solid substrate, it is recommended that chalk lines be specified so that the clips are correctly spaced.
- ❍ When the basic wind speed is 110 mph or greater, it is recommended that two clips be used along the eaves, ridges, and hips.
- ❍ For copper panel roofs in areas with a basic wind speed greater than 90 mph, it is recommended that Type 316 stainless steel clips and stainless steel screws be used in lieu of copper clips.
- ❍ Close spacing of fasteners is recommended at hip and ridge flashings (e.g., spacing in the range of 3 to 6 inches on center, commensurate with the design wind loads.)

Edge Flashings and Copings

Roof membrane blow-off is almost always a result of lifting and peeling of the metal edge flashing or coping, which serves to clamp down the membrane at the roof edge. Therefore, it is important for the design professional to carefully consider the design of metal edge flashings, copings, and the nailers to which they are attached. The metal edge flashing on the modified bitumen membrane roof shown in Figure 3-61 was installed underneath the membrane, rather than on top of it, and then stripped in. In this location, the edge flashing was unable to clamp the membrane down. At one area, the membrane was not sealed to the flashing. An ink pen was inserted into the opening prior to photographing to demonstrate how wind could catch the opening and lift and peel the membrane.

Figure 3-61:
The ink pen shows an opening that the wind can catch, and cause lifting and peeling of the membrane.

ANSI/SPRI ES-1, *Wind Design Standard for Edge Systems Used in Low Slope Roofing Systems* (2003) provides general design guidance including a methodology for determining the outward-acting load on the vertical flange of the flashing/coping (ASCE 7 does not provide this guidance). ANSI/SPRI ES-1 is referenced in the IBC. ANSI/SPRI ES-1 also includes test methods for assessing flashing/coping resistance. This manual recommends a minimum safety factor of 3 for edge flashings, copings, and nailers for critical facilities. For FMG-insured facilities, FMR-approved flashing should be used and FM Data Sheet 1-49 should also be consulted.

The traditional edge flashing/coping attachment method relies on concealed cleats that can deform under wind load and lead to disengagement of the flashing/coping (see Figure 3-62) and subsequent lifting and peeling of the roof membrane (as shown in Figure 3-12). When a vertical flange disengages and lifts up, the edge flashing and membrane are very susceptible to failure. Normally, when a flange lifts such as shown in Figure 3-62, the failure continues to propagate and the metal edge flashing and roof membrane blows off.

Storm-damage research has revealed that, in lieu of cleat attachment, the use of exposed fasteners to attach the vertical flanges of copings and edge flashings has been found to be a very effective and reliable attachment method. The coping shown in Figure 3-63 was attached with ¼-inch diameter stainless steel concrete spikes at 12 inches on center. When the fastener is placed in wood, #12 stainless steel screws with stainless steel washers are recommended. The fasteners should be more closely spaced in the corner areas (the spacing will depend upon the design wind loads). ANSI/SPRI ES-1 provides guidance on fastener spacing and thickness of the coping and edge flashing.

Figure 3-62:
The metal edge flashing disengaged from the continuous cleat and the vertical flange lifted. Hurricane Hugo (South Carolina, 1989)

Figure 3-63:
Both vertical faces of the coping were attached with exposed fasteners instead of concealed cleats. Typhoon Paka (Guam, 1997)

Gutters

Storm-damage research has shown that gutters are seldom constructed to resist wind loads (see Figure 3-64). When a gutter lifts, it typically causes the edge flashing that laps into the gutter to lift as well. Frequently, this results in a progressive lifting and peeling of the roof membrane. The membrane blow-off shown in Figure 3-65 was initiated by gutter uplift. The gutter was similar to that shown in Figure 3-64. The building, housing the county Sheriff's office, suffered water leakage that shut down the county 911 call center, destroyed the crime lab equipment, and caused significant interior water damage.

Figure 3-64:
This gutter, supported by a type of bracket that provides no significant uplift resistance, failed when wind lifted it together with the metal edge flashing that lapped into the gutter. Hurricane Francis (Florida, 2004)

Figure 3-65:
The original modified bitumen membrane was blown away after the gutter lifted in the area shown by the red arrow (the black membrane is a temporary roof). Hurricane Francis (Florida, 2004)

Special design attention needs to be given to attaching gutters to prevent uplift, particularly for those in excess of 6 inches in width. Currently, there are no standards pertaining to gutter wind resistance. It is recommended that the designer calculate the uplift load on gutters using the overhang coefficient from ASCE 7. There are two approaches to resist gutter uplift.

- ❍ Gravity-support brackets can be designed to resist uplift loads. In these cases, in addition to being attached at its top, the bracket should also be attached at its low end to the wall. The gutter also needs to be designed so it is attached securely to the bracket in a way that will effectively transfer the gutter uplift load to the bracket. Bracket spacing will depend on the gravity and uplift load, the bracket's strength, and the strength of connections between the gutter/bracket and the bracket/wall. With this option, the bracket's top will typically be attached to a wood nailer, and that fastener will be designed to carry the gravity load. The bracket's lower connection will resist the rotational force induced by gutter uplift. Because brackets are usually spaced close together to carry the gravity load, developing adequate connection strength at the lower fastener is generally not difficult.

- ❍ The other option is to use gravity-support brackets only to resist gravity loads, and use separate sheet-metal straps at 45-degree angles to the wall to resist uplift loads. Strap spacing will depend on the gutter uplift load and strength of the connections between the gutter/strap and the strap/wall. Note that FMG Data Sheet 1-49 recommends placing straps 10 feet apart. However, at that spacing with wide gutters, fastener loads induced by uplift are quite high. When straps are spaced at 10 feet, it can be difficult to achieve sufficiently strong uplift connections.

When designing a bracket's lower connection to a wall or a strap's connection to a wall, designers should determine appropriate screw pull-out values. With this option, a minimum of two screws at each end of a strap is recommended. At a wall, screws should be placed side by side, rather than vertically aligned, so the strap load is carried equally by the two fasteners. When fasteners are vertically aligned, most of the load is carried by the top fastener.

Since the uplift load in the corners is much higher than the load between the corners, enhanced attachment is needed in corner areas regardless of the option chosen. ASCE 7 provides guidance about determining a corner area's length.

Parapet Base Flashings

Information on loads for parapet base flashings was first introduced in the 2002 edition of ASCE 7. The loads on base flashings are greater than the loads on the roof covering if the parapet's exterior side is air-permeable. When base flashing is fully adhered, it has sufficient wind resistance in most cases. However, when base flashing is mechanically fastened, typical fastening patterns may be inadequate, depending on design wind conditions (see Figure 3-66). Therefore, it is imperative that the base flashing loads be calculated, and attachments be designed to accommodate these loads. It is also important for designers to specify the attachment spacing in parapet corner regions to differentiate them from the regions between corners.

Figure 3-66:
If mechanically attached base flashings have an insufficient number of fasteners, the base flashing can be blown away. Hurricane Andrew (Florida, 1992)

Steep-Slope Roof Coverings

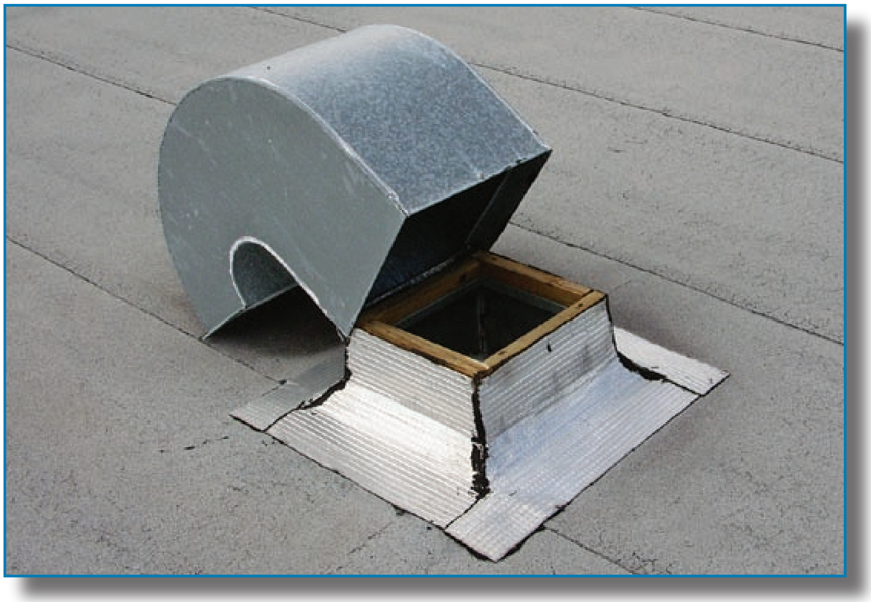
For a discussion of wind performance of asphalt shingle and tile roof coverings, see FEMA 488 (2005), 489 (2005), and 549 (2006). For recommendations pertaining to asphalt shingles and tiles, see Fact Sheets 19, 20, and 21 in FEMA 499 (2005).

3.3.4 NONSTRUCTURAL SYSTEMS AND EQUIPMENT

Nonstructural systems and equipment include all components that are not part of the structural system or building envelope. Exterior-mounted mechanical equipment (e.g., exhaust fans, HVAC units, relief air hoods, rooftop ductwork, and boiler stacks), electrical equipment (e.g., light fixtures and lightning protection systems), and communications equipment (e.g., antennae and satellite dishes) are often damaged during high winds. Damaged equipment can impair the operation of the facility, the equipment can detach and become wind-borne missiles, and water can enter the facility where equipment was displaced (see Figures 3-20, 3-67, 3-68, 3-72, 3-76, and 3-78). The most common problems typically relate to inadequate equipment anchorage, inadequate strength of the equipment itself, and corrosion.

Figure 3-67:
Toppled rooftop mechanical equipment. Hurricane Andrew (Florida, 1992)

Figure 3-68:
This gooseneck was attached with only two small screws. A substantial amount of water was able to enter the building during Hurricane Francis. (Florida, 2004)



See Section 3.4.4 for additional information pertaining to critical facilities located in hurricane-prone regions.

3.3.4.1 Exterior-Mounted Mechanical Equipment

This section discusses loads and attachment methods, as well as the problems of corrosion and water infiltration.

Loads and Attachment Methods[9]

Information on loads on rooftop equipment was first introduced in the 2002 edition of ASCE 7. For guidance on load calculations, see “Calculating Wind Loads and Anchorage Requirements for Rooftop Equipment” (ASHRAE, 2006). A minimum safety factor of 3 is recommended for critical facilities. Loads and resistance should also be calculated for heavy pieces of equipment since the dead load of the equipment is often inadequate to resist the design wind load. The 30’ x 10’ x 8’ 18,000-pound HVAC unit shown in Figure 3-69 was attached to its curb with 16 straps (one screw per strap). Although the wind speeds were estimated to be only 85 to 95 miles per hour (peak gust), the HVAC unit blew off the medical office building.

To anchor fans, small HVAC units, and relief air hoods, the minimum attachment schedule provided in Table 3-2 is recommended. The attachment of the curb to the roof deck also needs to be designed and constructed to resist the design loads.

Mechanical penetrations through the elevator penthouse roof and walls must possess adequate wind and water resistance to ensure continuity of elevator service (see Section 3.3.3.3). In addition to paying special attention to equipment attachment, air intakes and exhausts should be designed and constructed to prevent wind-driven water from entering the penthouse.

Figure 3-69: Although this 18,000-pound HVAC unit was attached to its curb with 16 straps, it blew off during Hurricane Ivan. (Florida, 2004)

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[9] Discussion is based on: *Attachment of Rooftop Equipment in High-wind Regions—Hurricane Katrina Recovery Advisory* (May 2006, revised July 2006)

Table 3-2: Number of #12 Screws for Base Case Attachment of Rooftop Equipment

Case No	Curb Size and Equipment Type	Equipment Attachment	Fastener Factor for Each Side of Curb or Flange
1	12″ x 12″ Curb with Gooseneck Relief Air Hood	Hood Screwed to Curb	1.6
2	12″ x 12″ Gooseneck Relief Air Hood with Flange	Flange Screwed to 22 Gauge Steel Roof Deck	2.8
3	12″ x 12″ Gooseneck Relief Air Hood with Flange	Flange Screwed to 15/32″ OSB Roof Deck	2.9
4	24″ x 24″ Curb with Gooseneck Relief Air Hood	Hood Screwed to Curb	4.6
5	24″ x 24″ Gooseneck Relief Air Hood with Flange	Flange Screwed to 22 Gauge Steel Roof Deck	8.1
6	24″ x 24″ Gooseneck Relief Air Hood with Flange	Flange Screwed to 15/32″ OSB Roof Deck	8.2
7	24″ x 24″ Curb with Exhaust Fan	Fan Screwed to Curb	2.5
8	36″ x 36″ Curb with Exhaust Fan	Fan Screwed to Curb	3.3
9	5′-9″ x 3′- 8″ Curb with 2′- 8″ high HVAC Unit	HVAC Unit Screwed to Curb	4.5*
10	5′-9 ″x 3′- 8″ Curb with 2′- 8″ high Relief Air Hood	Hood Screwed to Curb	35.6*

Notes to Table 3-2:

1. The loads are based on ASCE 7-05. The resistance includes equipment weight.
2. The Base Case for the tabulated numbers of #12 screws (or ¼ pan-head screws for flange-attachment) is a 90-mph basic wind speed, 1.15 importance factor, 30′ building height, Exposure C, using a safety factor of 3.
3. For other basic wind speeds, multiply the tabulated number of #12 screws by $\left(\frac{V_D^2}{90^2}\right)$ to determine the required number of #12 screws (or ¼ pan-head screws) required for the desired basic wind speed, V_D (mph).
4. For other roof heights up to 200′, multiply the tabulated number of #12 screws by (1.00 + 0.003 [h - 30]) to determine the required number of #12 screws or ¼ pan-head screws for buildings between 30′ and 200′.

   Example A: 24″ x 24″ exhaust fan screwed to curb (table row 7), Base Case conditions (see Note 1): 2.5 screws per side; therefore, round up and specify 3 screws per side.

   Example B: 24″ x 24″ exhaust fan screwed to curb (table row 7), Base Case conditions, except 120 mph: 120^2 x 1 ÷ 90^2 = 1.78 x 2.5 screws per side = 4.44 screws per side; therefore, round down and specify 4 screws per side.

   Example C: 24″ x 24″ exhaust fan screwed to curb (table row 7), Base Case conditions, except 150′ roof height: 1.00 + 0.003 (150′ - 30′) = 1.00 + 0.36 = 1.36 x 2.5 screws per side = 3.4 screws per side; therefore, round down and specify 3 screws per side.

* This factor only applies to the long sides. At the short sides, use the fastener spacing used at the long sides.

Fan cowling attachment: Fans are frequently blown off their curbs because they are poorly attached. When fans are well attached, the cowlings frequently blow off (see Figure 3-70). Blown off cowlings can tear roof membranes and break glazing. Unless the fan manufacturer specifically engineered the cowling attachment to resist the design wind load, cable tie-downs (see Figure 3-71) are recommended to avoid cowling blow-off. For fan cowlings less than 4 feet in diameter, 1/8-inch diameter stainless steel cables are recommended. For larger cowlings, use 3/16-inch diameter cables. When the basic wind speed is 120 mph or less, specify two cables. Where the basic wind speed is greater than 120 mph, specify four cables. To minimize leakage potential at the anchor point, it is recommended that the cables be adequately anchored to the equipment curb (rather than anchored to the roof deck). The attachment of the curb itself also needs to be designed and specified.

To avoid corrosion-induced failure (see Figure 3-78), it is recommended that exterior-mounted mechanical, electrical, and communications equipment be made of nonferrous metals, stainless steel, or steel with minimum G-90 hot-dip galvanized coating for the equipment body, stands, anchors, and fasteners. When equipment with enhanced corrosion protection is not available, the designer should advise the building owner that periodic equipment maintenance and inspection is particularly important to avoid advanced corrosion and subsequent equipment damage during a windstorm.

Figure 3-70:
Cowlings blew off two of the fans on a police building that housed the county's EOC. Hurricane Ivan (Florida, 2004)

Figure 3-71:
Cables were attached to prevent the cowling from blowing off. Typhoon Paka (Guam, 1997)

Ductwork: To avoid wind and wind-borne debris damage to rooftop ductwork, it is recommended that ductwork not be installed on the roof (see Figure 3-72). If ductwork is installed on the roof, it is recommended that the ducts' gauge and the method of attachment be able to resist the design wind loads.

Figure 3-72:
Two large openings remained (circled area and inset to the left) after the ductwork on this roof blew away. Hurricane Katrina (Mississippi, 2005)

Condenser attachment: In lieu of placing rooftop-mounted condensers on wood sleepers resting on the roof (see Figure 3-73), it is recommended that condensers be anchored to equipment stands. The attachment of the stand to the roof deck also needs to be designed to resist the design loads. In addition to anchoring the base of the condenser to the stand, two metal straps with two side-by-side #12 screws or bolts with proper end and edge distances at each strap end are recommended when the basic wind speed is greater than 90 mph (see Figure 3-74).

Three publications pertaining to seismic restraint of equipment provide general information on fasteners and edge distances:

- *Installing Seismic Restraints for Mechanical Equipment* (FEMA 412, 2002)
- *Installing Seismic Restraints for Electrical Equipment* (FEMA 413, 2004)
- *Installing Seismic Restraints for Duct and Pipe* (FEMA 414, 2004)

Figure 3-73: Sleeper-mounted condensers displaced by high winds. Hurricane Katrina (Mississippi, 2005)

Vibration isolators: If vibration isolators are used to mount equipment, only those able to resist design uplift loads should be specified and installed, or an alternative means to accommodate uplift resistance should be provided (see Figure 3-75).

Figure 3-74:
This condenser had supplemental attachment straps (see red arrows). Typhoon Paka (Guam, 1997)

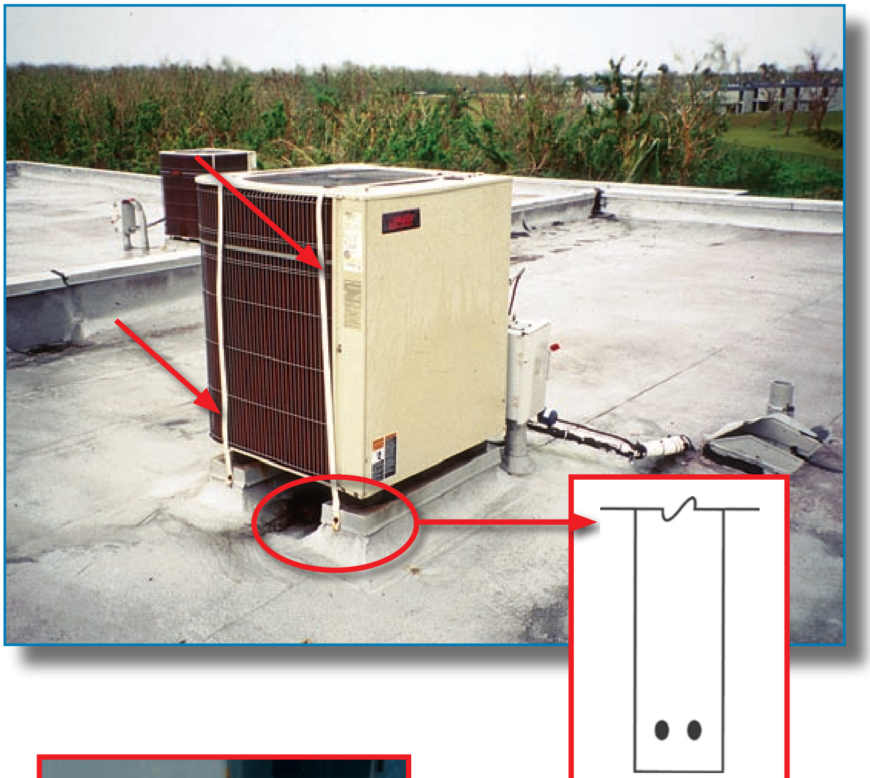
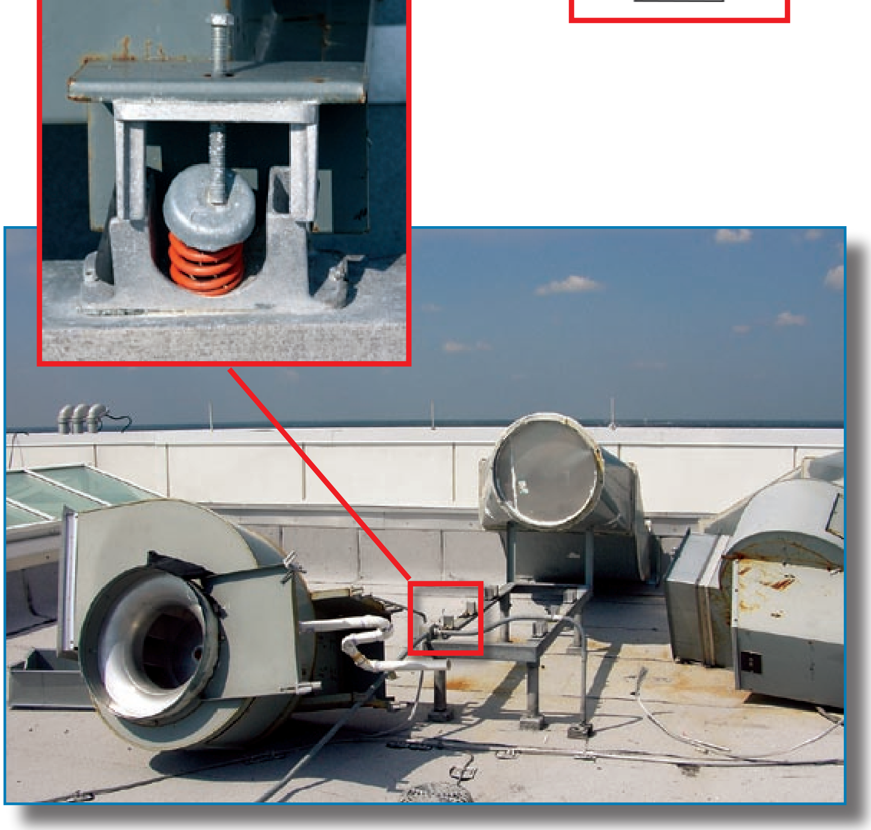


Figure 3-75:
Failure of vibration isolators that provided lateral resistance but no uplift resistance caused equipment damage. A damaged vibration isolator is shown in the inset. Hurricane Katrina (Mississippi, 2005)



Boiler and exhaust stack attachment: To avoid wind damage to boiler and exhaust stacks, wind loads on stacks should be calculated and guy-wires should be designed and constructed to resist the loads. Toppled stacks, as shown at the hospital in Figure 3-76, can allow water to enter the building at the stack penetration, damage the roof membrane, and become wind-borne debris. The designer should advise the building owner that guy-wires should be inspected annually to ensure they are taut.

Figure 3-76:
Three of the five stacks that did not have guy-wires were blown down. Hurricane Marilyn (U.S. Virgin Islands, 1995)

Access panel attachment: Equipment access panels frequently blow off. To minimize this, job-site modifications, such as attaching hasps and locking devices like carabiners, are recommended. The modification details need to be customized. Detailed design may be needed after the equipment has been delivered to the job site. Modification details should be approved by the equipment manufacturer.

Equipment screens: Screens around rooftop equipment are frequently blown away (see Figure 3-77). Screens should be designed to resist the wind load derived from ASCE 7. Since the effect of screens on equipment wind loads is unknown, the equipment attachment behind the screens should be designed to resist the design load.

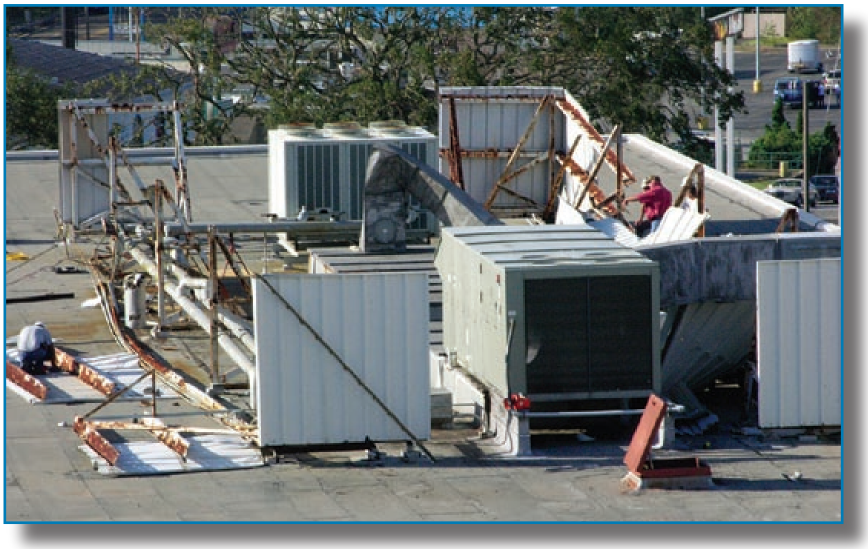


Figure 3-77:
Equipment screen panels, such as these blown away at a hospital, can break glazing, puncture roof membranes, and cause injury. Hurricane Ivan (Florida, 2004)

Water Infiltration

During high winds, wind-driven rain can be driven through air intakes and exhausts unless special measures are taken. Louvers should be designed and constructed to prevent leakage between the louver and wall. The louver itself should be designed to avoid water being driven past the louver. However, it is difficult to prevent infiltration during very high winds. Designing sumps with drains that will intercept water driving past louvers or air intakes should be considered. ASHRAE 62.1 (2004) provides some information on rain and snow intrusion. The *Standard 62.1 User's Manual* provides additional information, including examples and illustrations of various designs.

3.3.4.2 Exterior-Mounted Electrical and Communications Equipment

Damage to exterior-mounted electrical equipment is infrequent, mostly because of its small size (e.g., disconnect switches). Exceptions include communication towers, surveillance cameras, electrical service masts, satellite dishes, and lightning protection systems. The damage is typically caused by inadequate mounting as a result of failure to perform wind load calculations and anchorage design. Damage is also sometimes caused by corrosion (see Figure 3-78 and the text box on corrosion in Section 3.3.4.1).

Figure 3-78: Collapsed hospital light fixtures caused by severe corrosion (see inset). Hurricane Ivan (Florida, 2004)

Communication towers and poles: ANSI/C2 provides guidance for determining wind loads on power distribution and transmission poles and towers. AASHTO LTS-4-M (amended by LTS-4-12, 2001 and 2003, respectively) provides guidance for determining wind loads on light fixture poles (standards).

Both ASCE 7 and ANSI/TIA-222-G contain wind load provisions for communication towers (structures). The IBC allows the use of either approach. The ASCE wind load provisions are generally consistent with those contained in ANSI/TIA-222-G. ASCE 7, however, contains provisions for dynamically sensitive towers that are not present in the ANSI/TIA standard. ANSI/TIA classifies towers according to their use (Class I, Class II, and Class III). This manual recommends that towers (including antennae) that are mounted on, located near, or serve critical facilities be designed as Class III structures.

Collapse of both large and small communication towers at emergency operation centers, fire and police stations, and hospitals is quite common during high-wind events (see Figures 3-79 and 3-80). These failures often result in complete loss of communication capabilities. In addition to the disruption of communications, collapsed towers can puncture roof membranes and allow water leakage into the facilities, unless the roof system incorporated a secondary membrane (as discussed in Section 3.4.3.4). At the tower shown in Figure 3-79 the anchor bolts were pulled out of the deck, which resulted in a progressive peeling of the fully adhered single-ply roof membrane. Tower collapse can also injure or kill people.

See Section 3.3.1.1 regarding site considerations for light fixture poles, power poles, and electrical and communications towers.

Figure 3-79:
The collapse of the antenna tower caused progressive peeling of the roof membrane. Also note that the exhaust fan blew off the curb, but the high parapet kept it from blowing off the roof. Hurricane Andrew (Florida, 1992)

Figure 3-80:
The antenna tower at this fire station buckled.
Hurricane Katrina (Mississippi, 2005)

Electrical service masts: Service mast failure is typically caused by collapse of overhead power lines, which can be avoided by using underground service. Where overhead service is provided, it is recommended that the service mast not penetrate the roof. Otherwise, a downed service line could pull on the mast and rupture the roof membrane.

Satellite dishes: For the satellite dish shown in Figure 3-81, the dish mast was anchored to a large metal pan that rested on the roof membrane. CMU was placed on the pan to provide overturning resistance. This anchorage method should only be used where calculations demonstrate that it provides sufficient resistance. In this case the wind approached the satellite dish in such a way that it experienced very little wind pressure. In hurricane-prone regions, use of this anchorage method is not recommended (see Figure 3-82).

Lightning protection systems: For attachment of lightning protection systems on buildings higher than 100 feet above grade, and for buildings located where the basic wind speed is in excess of 90 mph, see Section 3.4.4.3.

Figure 3-81: Common anchoring method for satellite dish. Hurricane Ivan (Florida, 2004)

Figure 3-82: A satellite dish anchored similarly to that shown in Figure 3-81 was blown off of this five-story building. Hurricane Charley (Florida, 2004)

The recommendations given in Section 3.3 are summarized in Table 3-3.

Table 3-3: Risk Reduction Design Methods

Site and General Design	See Section 3.3.1
Exposure	Locate in Exposure B if possible. Avoid escarpments and upper half of hills.
Presence of trees or poles	Locate to avoid blow-down on facility.
Site access	Minimum of two roads.
General design issues	See recommendations in Section 3.3.1.2.
Wind loads on MWFRS, building envelope and rooftop equipment	Use ASCE 7 or local building code, whichever procedure results in highest loads.
Load resistance	Determine via calculations and/or text data. Give load resistance criteria in contract documents, and clearly indicate load path continuity.
Durability	Give special attention to material selection and detailing to avoid problems of corrosion, wood decay, and termite attack.
Rain penetration	Detail to minimize wind-driven rain penetration into the building.
Structural Systems (MWFRS)	**See Section 3.3.2**
Pre-engineered metal buildings	Take special steps to ensure structure is not vulnerable to progressive collapse.
Exterior load-bearing walls	Design as MWFRS and C&C. Reinforce CMU. Sufficiently connect precast concrete panels.
Roof decks	Concrete, steel, or wood sheathing is recommended. Attach steel decks with screws. Use special fasteners for wood sheathing. Anchor precast concrete to resist wind loads. If FMG-rated assembly, deck must comply with FMG criteria.
Walkways and canopies	Use pressure coefficients from ASCE 7.
Exterior Doors	**See Section 3.3.3.1**
Door, frame, and frame fasteners	Must be able to resist positive and negative design load, verified by ASTM E 1233 testing. Specify type, size, and spacing of frame fasteners.
Water infiltration	Consider vestibules, door swing, and weatherstripping. Refer to ASTM E 2112 (2001) for design guidance.

Table 3-3: Risk Reduction Design Methods (continued)

Windows and Skylights	**See Section 3.3.3.2**
Glazing, frame, and frame fasteners	Must be able to resist positive and negative design load, verified by ASTM E 1233 (2000) testing. Specify type, size, and spacing of frame fasteners.
Water infiltration	Carefully design junctures between walls and windows/ curtain walls. Avoid relying on sealant as the first or only line of defense. Refer to ASTM E 2112 for design guidance. Where infiltration protection is demanding, conduct onsite water infiltration testing per ASTM E 1105 (2000).
Non-Load-Bearing Walls, Wall Coverings, and Soffits	**See Section 3.3.3.3**
Exterior non-load-bearing walls, wall coverings, soffits, and elevated floors	See recommendations in Section 3.3.3.3
Load resistance	Must be able to resist positive and negative design load. Design as C&C.
Elevator penthouses	Design to prevent water infiltration at walls, roof, and mechanical penetrations.
Soffits	Design to resist wind and wind-driven water infiltration.
Interior non-load-bearing masonry walls	Design for wind load per Section 3.3.3.3.
Brick veneer	See recommendations in Section 3.3.3.3.
Secondary protection	Provide moisture barrier underneath wall coverings that are water-shedding.
Roof Systems	**See Section 3.3.3.4**
Testing	Avoid designs that deviate from a tested assembly. If deviation is evident, perform rational analysis. For structural metal panel systems, test per ASTM E 1592 (2000).
Load resistance for field, perimeter, and corner areas	Specify requirements. See recommendations in Section 3.3.3.4.
Edge flashings and copings	Follow ANSI/SPRI ES-1 (2003). Use a safety factor of three.
Gutters	Calculate loads and design attachment to resist uplift.
System selection	Select systems that offer high reliability, commensurate with the wind-regime at facility location.

Table 3-3: Risk Reduction Design Methods (continued)

Roof Systems (continued)	**See Section 3.3.3.4**
Mechanically attached modified bitumen and single-ply membrane systems	Refer to *Wind Design Guide for Mechanically Attached Flexible Membrane Roofs,* B1049 (NRCC, 2005).
Metal panel systems	See recommendations in Section 3.3.3.4.
Parapet base flashing	Calculate loads and resistance. This is particularly important if base flashing is mechanically attached.
Asphalt shingles and tile coverings	See Fact Sheets 19, 20, or 21 in FEMA 499.
Exterior-mounted Mechanical, Electrical, and Communications Equipment	**See Section 3.3.4**
Load resistance	Specify anchorage of all rooftop and wall-mounted equipment. Use a safety factor of three for equipment anchorage. See recommendations in Section 3.3.4.1.
Equipment strength	Specify cable tie-downs for fan cowlings. Specify hasps and locking devises for equipment access panels. See recommendations in Section 3.3.4.1.
Rooftop satellite dishes	Design the attachment to resist the design wind loads.
Antennae towers	See recommendations in Section 3.3.4.2.
After Completing Contract Documents	**See Section 3.3.1**
Peer review	Consider peer review of contract documents. See Section 3.3.1.2.
Submittals	Ensure required documents are submitted, including all necessary information. Verify that each submittal demonstrates the load path through the system and into its supporting element. See Section 3.3.1.3.
Field observations	Analyze design to determine which elements are critical to ensuring high-wind performance. Determine observation frequency of critical elements. See Section 3.3.1.3.
Post-occupancy inspections, maintenance, and repair	Advise the building owner of the importance of periodic inspections, special inspections after unusually high winds, maintenance, and timely repair. See Section 3.3.1.4.

3.4 BEST PRACTICES IN HURRICANE-PRONE REGIONS

This section presents the general design and construction practice recommendations for critical facilities located in hurricane-prone regions. These recommendations are additional to the ones presented in Section 3.3 and in many cases supersede those recommendations. Critical facilities located in hurricane-prone regions require special design and construction attention because of the unique characteristics of this type of windstorm. Hurricanes can bring very high winds that last for many hours, which can lead to material fatigue failures. The variability of wind direction increases the probability that the wind will approach the building at the most critical angle. Hurricanes also generate a large amount of wind-borne debris, which can damage various building components and cause injury and death.

Although all critical facilities in hurricane-prone regions require special attention, three types of facilities are particularly important because of their function or occupancy: EOCs, healthcare facilities, and shelters. EOCs serve as centralized management hubs for emergency operations. The loss of an EOC can severely affect the overall response and recovery in the area. Healthcare facilities normally have vulnerable occupants (patients) at the time of a hurricane, and afterwards, many injured people seek medical care. Significant damage to a facility can put patients at risk and jeopardize delivery of care to those seeking treatment. Shelters often have a large number of occupants. The collapse of a shelter building or entrance of wind-borne debris into a shelter has the potential to injure or kill many people. See

Chapter 4 for information on the performance of some EOCs, healthcare facilities, shelters, and other types of critical facilities that were affected by Hurricane Katrina.

In order to ensure continuity of service during and after hurricanes, the design, construction, and maintenance of the following critical facilities should be very robust to provide sufficient resiliency to withstand the effects of hurricanes.

EOCs: Communications are important for most types of critical facilities, but for EOCs they are vital. To inhibit disruption of operations, water infiltration that could damage electrical equipment must be prevented, antenna towers need to be strong enough to resist the wind, and the emergency and standby power system needs to remain operational.

Healthcare facilities: Full or partial evacuation of a hospital prior to, during, or after a hurricane, is time consuming, expensive, and for some patients, potentially life-threatening. Water infiltration that could damage electrical equipment or medical supplies, or inhibit the use of critical areas (such as operating rooms and nursing floors) needs to be prevented. The emergency and standby power systems need to remain operational and be adequately sized to power all needed circuits, including the HVAC system. Provisions are needed for water and sewer service in the event of loss of municipal services, and antenna towers need to be strong enough to resist the wind.

Nursing homes are often no more hurricane-resistant than residential buildings. Evacuating these facilities (particularly skilled nursing homes and facilities caring for patients with Alzheimer's disease) can be difficult. Except for antenna towers, the issues identified for hospitals are applicable to nursing homes.

Shelters: During and after hurricanes, these facilities are often occupied by more than 1,000 people. The primary purpose of shelters is to protect occupants from injury or death as a result of building collapse or entrance of wind-borne debris. However, beyond meeting this basic requirement, providing a degree of occupant comfort during a stressful time is important. The building's design and construction should avoid significant water infiltration and provide at least a minimum level of lighting and mechanical ventilation using emergency generators. Shelters should also have provisions for sewage service (such as portable toilets) in the event of loss of municipal water or sewer service.

FEMA recommends that shelters be designed in accordance with FEMA 361, *Design and Construction Guidance for Community Shelters (2000).*

3.4.1 SITE AND GENERAL DESIGN CONSIDERATIONS

Via ASCE 7, the 2006 edition of the IBC has only one special wind-related provision pertaining to Category III and IV buildings in hurricane-prone regions. It pertains to glazing protection within wind-borne debris regions (as defined in ASCE 7). This single additional requirement does not provide adequate protection for occupants of a facility during a hurricane, nor does it ensure a critical facility will remain functional during and after a hurricane. A critical facility may comply with IBC but still remain vulnerable to water and missile penetration through the roof or walls. To provide occupant protection, the exterior walls and the roof must be designed and constructed to resist wind-borne debris as discussed in Sections 3.4.2 and 3.4.3.

The following recommendations are made regarding siting:

- Locate poles, towers, and trees with trunks larger than 6 inches in diameter away from primary site access roads so that they do not block access to, or hit, the facility if toppled.

- Determine if existing buildings within 1,500 feet of the new facility have aggregate surfaced roofs. If roofs with aggregate surfacing are present, it is recommended that the aggregate be removed to prevent it from impacting the new facility. Aggregate removal may necessitate reroofing or other remedial work in order to maintain the roof's fire or wind resistance.

- In cases where multiple buildings, such as hospitals or school campuses, are occupied during a storm, it is recommended that enclosed walkways be designed to connect the buildings. The enclosed walkways (above- or below-grade) are particularly important for protecting people moving between buildings during a hurricane (e.g., to retrieve equipment or supplies) or for situations when it is necessary to evacuate occupants from one building to another during a hurricane.

Figure 3-83:
Open walkways do not provide protection from wind-borne debris. Hurricane Katrina (Mississippi, 2005)

3.4.2 STRUCTURAL SYSTEMS

Because of the exceptionally good wind performance and wind-borne debris resistance that reinforced cast-in-place concrete structures offer, a reinforced concrete roof deck and reinforced concrete or reinforced and fully grouted CMU exterior walls are recommended as follows:

Roof deck: A minimum 4-inch thick cast-in-place reinforced concrete deck is the preferred deck. Other recommended decks are minimum 4-inch thick structural concrete topping over steel decking, and precast concrete with an additional minimum 4-inch structural concrete topping.

If these recommendations are not followed for critical facilities located in areas where the basic wind speed is 100 mph or greater, it is recommended that the roof assembly be able to resist complete penetration of the deck by the "D" missile specified in ASTM E 1996 (2005, see text box in Section 3.4.3.1).

If precast concrete is used for the roof or wall structure, the connections should be carefully designed, detailed, and constructed.

Exterior load-bearing walls: A minimum 6-inch thick cast-in-place concrete wall reinforced with #4 rebars at 12 inches on center each way is the preferred wall. Other recommended walls are a minimum 8-inch thick fully grouted CMU reinforced with #4 rebars in each cell, and precast concrete that is a minimum 6 inches thick and reinforced equivalent to the recommendations for cast-in-place walls.

3.4.3 BUILDING ENVELOPE

The design considerations for building envelope components of critical facilities in hurricane-prone regions include a number of additional recommendations. The principal concern that must be addressed is the additional risk from wind-borne debris and water leakage, as discussed below.

3.4.3.1 Exterior Doors

Although the ASCE-7 wind-borne debris provisions only apply to glazing within a portion of hurricane-prone regions, it is recommended that all critical facilities located where the basic wind speed is 100 mph or greater comply with the following recommendations:

- To minimize the potential for missiles penetrating exterior doors and striking people inside the facility, it is recommended that doors (with and without glazing) be designed to resist the "E" missile load specified in ASTM E 1996. The doors should be tested in accordance with ASTM E 1886 (2005). The test assembly should include the door, door frame, and hardware.

- It is recommended that the doors on shelters meet the wind pressure and missile resistance criteria found in FEMA 361. Information on door assemblies that meet these criteria is included in FEMA 361.

ASTM E 1996 specifies five missile categories, A through E. The missiles are of various weights and fired at various velocities during testing. Building type (critical or non-critical) and basic wind speed determine the missiles required for testing. Of the five missiles, the E missile has the greatest momentum. Missile E is required for critical facilities located where the basic wind speed is greater than or equal to 130 mph. Missile D is permitted where the basic wind speed is less than130 mph. FEMA 361 also specifies a missile for shelters. The shelter missile has much greater momentum than the D and E missiles, as shown below:

Missile	Missile Weight	Impact Speed	Momentum
ASTM E 1996—D	9 pound 2x4 lumber	50 feet per second (34 mph)	14 lb_f -s*
ASTM E 1996—E	9 pound 2x4 lumber	80 feet per second (55 mph)	22 lb_f -s*
FEMA 361 (Shelter Missile)	15 pound 2x4 lumber	147 feet per second (100 mph)	68 lb_f -s*

*lb_f -s = pounds force per second

3.4.3.2 Windows and Skylights

Exterior glazing that is not impact-resistant (such as laminated glass or polycarbonate) or protected by shutters is extremely susceptible to breaking if struck by wind-borne debris. Even small, low-momentum missiles can easily break glazing that is not protected (see Figures 3-84 and 3-85). At the hospital shown in Figure 3-84, approximately 400 windows were broken. Most of the breakage was caused by wind-blown aggregate from the hospital's aggregate ballasted single-ply membrane roofs, and aggregate from built-up roofs. With broken windows, a substantial amount of water can be blown into a building, and the internal air pressure can be greatly increased (as discussed in Section 3.1.3) which may damage the interior partitions and ceilings.

Figure 3-84:
Plywood panels (black continuous bands) installed after the glass spandrel panels were broken by roof aggregate. Hurricane Katrina (Mississippi, 2005)

Figure 3-85:
A small piece of asphalt shingle (red arrow) broke the window at this nursing home. Hurricane Katrina (Mississippi, 2005)

In order to minimize interior damage, the IBC, through ASCE 7, prescribes that exterior glazing in wind-borne debris regions be impact-resistant, or be protected with an impact-resistant covering (shutters). For Category III and IV buildings in areas with a basic wind speed of 130 mph or greater, the glazing is required to resist a larger momentum test missile than would Category II buildings and Category III and IV buildings in areas with wind speeds of less than 130 mph.

ASCE 7 refers to ASTM E 1996 for missile loads and to ASTM E 1886 for the test method to be used to demonstrate compliance with the E 1996 load criteria. In addition to testing impact resistance, the window unit is subjected to pressure cycling after test missile impact to evaluate whether the window can still resist wind loads. If wind-borne debris glazing protection is provided by shutters, the glazing is still required by ASCE 7 to meet the positive and negative design air pressures.

Although the ASCE 7 wind-borne debris provisions only apply to glazing within a portion of hurricane-prone regions, it is recommended that all critical facilities located where the basic wind speed is 100 mph or greater comply with the following recommendations:

❍ To minimize the potential for missiles penetrating exterior glazing and injuring people, it is recommended that exterior glazing up to 60 feet above grade be designed to resist the test Missile E load specified in ASTM E 1996 (see text box in Section 3.4.3.1). In addition, if roofs with aggregate surfacing are present within 1,500 feet of the facility, glazing above 60 feet should be designed to resist the test Missile A load specified in ASTM E 1996. The height of the protected glazing should extend a minimum of 30 feet above the aggregate surfaced roof per ASCE 7.

  Because large missiles are generally flying at lower elevations, glazing that is more than 60 feet above grade and meets the test Missile A load should be sufficient. However, if the facility is within a few hundred feet of another building that may create debris such as EIFS, tiles, or rooftop equipment, it is recommended that the test Missile E load be specified instead of the Missile A for the upper-level glazing.

❍ For those facilities where glazing resistant to bomb blasts is desired, the windows and glazed doors can be designed to accommodate wind pressure, missile loads, and blast pressure. However, the window and door units need to be tested for missile loads and cyclic air pressure, as well as for blast. A unit that meets blast criteria will not necessarily meet the E 1996 and E 1886 criteria, and vice versa.

For further information on designing glazing to resist blast, see the "Blast Safety" resource pages of the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/enve-lope.php).

With the advent of building codes requiring glazing protection in wind-borne debris regions, a variety of shutter designs have entered the market. Shutters typically have a lower initial cost than laminated glass. However, unless the shutter is permanently anchored to the building (e.g., an accordion shutter), storage space will be needed. Also, when a hurricane is forecast, costs will be incurred each time shutters are installed and removed. The cost and difficulty of shutter deployment and demobilization on upper-level glazing may be avoided by using motorized shutters, although laminated glass may be a more economical solution. For further information on shutters, see Section 3.6.2.2.

3.4.3.3 Non-Load-Bearing Walls, Wall Coverings, and Soffits

For buildings not constructed using concrete roof decks and concrete or CMU walls (as recommended), shelters can be constructed within buildings for occupant protection. FEMA 320—*Taking Shelter From the Storm: Building a Safe Room Inside Your Home (2004)* describes how restrooms and storage rooms can be designed for sheltering inside new and existing buildings.

It is recommended that wood-framed and pre-engineered metal buildings in areas with a basic wind speed of 100 mph or greater, that will be occupied during a hurricane, have a designated storage room(s), office(s), or small conference room(s) designed in accordance with FEMA 320 to protect the occupants. Although FEMA 320 is intended for residential construction, the guidance is suitable for small shelters inside critical facilities such as fire and police stations. For large shelters, FEMA 361 criteria are recommended.

In order to achieve enhanced missile resistance of non-load-bearing exterior walls, the wall types discussed in Section 3.4.2 (i.e., reinforced concrete, or reinforced and fully grouted CMU) are recommended.

To minimize long-term problems with exterior wall coverings and soffits, it is recommended that they be avoided to the maximum extent possible. Exposed or painted reinforced concrete or CMU offers greater reliability (i.e., they have no coverings that can blow off and become wind-borne debris).

For all critical facilities located where the basic wind speed is 100 mph or greater that are not constructed using reinforced concrete or reinforced and fully grouted CMU (as is recommended in this manual), it is recommended that the wall system selected be sufficient to resist complete penetration of the wall by the "E" missile specified in ASTM E 1996.

For interior non-load-bearing masonry walls in critical facilities located where the basic wind speed is greater than 120 mph, see the recommendations given in Section 3.3.3.3.

3.4.3.4 Roof Systems

The following types of roof systems are recommended for critical facilities in hurricane-prone regions, because they are more likely to avoid water infiltration if the roof is hit by wind-borne debris, and also because these systems are less likely to become sources of wind-borne debris:

❍ In tropical climates where insulation is not needed above the roof deck, specify either liquid-applied membrane over cast-in-place concrete deck, or modified bitumen membrane torched directly to primed cast-in-place concrete deck.

❍ Install a secondary membrane over a concrete deck (if another type of deck is specified, a cover board may be needed over the deck). Seal the secondary membrane at perimeters and penetrations. Specify rigid insulation over the secondary membrane. Where the basic wind speed is up to 110 mph, a minimum 2-inch thick layer of insulation is recommended. Where the speed is between 110 and 130 mph, a total minimum thickness of 3 inches is recommended (installed in two layers). Where the speed is greater than 130 mph, a total minimum thickness of 4 inches is recommended (installed in two layers). A layer of ⅝-inch thick glass mat gypsum roof board is recommended over the insulation, followed by a modified bitumen membrane. A modified bitumen membrane is recommended for the primary membrane because of its somewhat enhanced resistance to puncture by small missiles compared with other types of roof membranes.

  The purpose of the insulation and gypsum roof board is to absorb missile energy. If the primary membrane is punctured or blown off during a storm, the secondary membrane should provide watertight protection unless the roof is hit with missiles of very high momentum that penetrate the insulation and secondary membrane. Figure 3-86 illustrates the merit of specifying a secondary membrane. The copper roof blew off the hospital's intensive care unit (ICU). Patients and staff were frightened by the loud noise generated by the metal panels as they banged around during the hurricane. Fortunately there was a very robust underlayment (a built-up membrane) that remained in place. Since only minor leakage occurred, the ICU continued to function.

Figure 3-86: Because this roof system incorporated a secondary membrane, the ICU was not evacuated after the copper roof blew off. Hurricane Andrew (Florida, 1992)

- For an SPF roof system over a concrete deck, where the basic wind speed is less than 130 mph, it is recommended that the foam be a minimum of 3 inches thick to avoid missile penetration through the entire layer of foam. Where the speed is greater than 130 mph, a 4-inch minimum thickness is recommended. It is also recommended that the SPF be coated, rather than protected with an aggregate surfacing.
- For a PMR, it is recommended that pavers weighing a minimum of 22 psf be specified. In addition, base flashings should be protected with metal (such as shown in Figure 3-93) to provide debris protection. Parapets with a 3 foot minimum height (or higher if so indicated by ANSI/SPRI RP-4, 2002) are recommended at roof edges. This manual recommends that PMRs not be used for critical facilities in hurricane-prone regions where the basic wind speed exceeds 130 mph.

- For structural metal roofs, it is recommended that a roof deck be specified, rather than attaching the panels directly to purlins as is commonly done with pre-engineered metal buildings. If panels blow off buildings without roof decking, as shown in Figure 3-17, wind-borne debris and rain are free to enter the building.

Roofs over rooms used to store important records (such as police station evidence rooms) should incorporate secondary membranes to avoid water leakage damage. To preclude water infiltration damage from exterior walls, avoid locating important storage rooms adjacent to exterior walls.

Structural standing seam metal roof panels with concealed clips and mechanically seamed ribs spaced at 12 inches on center are recommended. If the panels are installed over a concrete deck, a modified bitumen secondary membrane is recommended if the deck has a slope less than ½:12. If the panels are installed over a steel deck or wood sheathing, a modified bitumen secondary membrane (over a suitable cover board when over steel decking) is recommend, followed by rigid insulation and metal panels. Where the basic wind speed is up to 110 mph, a minimum 2-inch thick layer of insulation is recommended. Where the speed is between 110 and 130 mph, a total minimum thickness of 3 inches is recommended. Where the speed is greater than 130 mph, a total minimum thickness of 4 inches is recommended. Although some clips are designed to bear on insulation, it is recommended that the panels be attached to wood nailers attached to the deck, because nailers provide a more stable foundation for the clips.

If the metal panels are blown off or punctured during a hurricane, the secondary membrane should provide watertight protection unless the roof is hit with missiles of very high momentum. At the roof shown in Figure 3-87, the structural standing seam panel clips bore on rigid insulation over a steel deck. Had a secondary membrane been installed over the steel deck, the membrane would have likely prevented significant interior water damage and facility disruption.

- Based on field performance of architectural metal panels in hurricane-prone regions, exposed fastener panels are recommended in lieu of architectural panels with concealed clips. For panel fasteners, stainless steel screws are recommended. A secondary membrane protected with insulation is recommended, as discussed above for structural standing seam systems.

Figure 3-87:
Significant interior water damage and facility interruption occurred after the standing seam roof blew off. Hurricane Marilyn (U.S. Virgin Islands, 1995)

In order to avoid the possibility of roofing components blowing off and striking people arriving at a critical facility during a storm, the following roof systems are not recommended: aggregate surfacings either on BUR (shown in Figure 3-12), single-plies (shown in Figure 3-9), or SPF; lightweight concrete pavers; cementitious-coated insulation boards; slate; and tile (see Figure 3-88). Even when slates and tiles are properly attached to resist wind loads, their brittleness makes them vulnerable to breakage as a result of wind-borne debris impact. The tile and slate fragments can be blown off the roof, and fragments can damage other parts of the roof causing a cascading failure.

Figure 3-88:
Brittle roof coverings, like slate and tile, can be broken by missiles, and tile debris can break other tiles. Hurricane Charley (Florida, 2004)

Mechanically attached and air-pressure equalized single-ply membrane systems are susceptible to massive progressive failure after missile impact, and are therefore not recommended for critical facilities in hurricane-prone regions. At the building shown in Figure 3-89, a missile struck the fully adhered low-sloped roof and slid into the steep-sloped reinforced mechanically attached single-ply membrane in the vicinity of the red arrow. A large area of the mechanically attached membrane was blown away as a result of progressive membrane tearing. Fully adhered single-ply membranes are very vulnerable to missiles (see Figure 3-90) and are not recommended unless they are ballasted with pavers.

Figure 3-89:
Mechanically attached single-ply membrane progressively tore after being cut by wind-borne debris. Hurricane Andrew (Florida, 1992)

Figure 3-90:
Fully adhered single-ply roof membrane struck by a large number of missiles. Hurricane Marilyn (U.S. Virgin Islands, 1995)

Edge flashings and copings: If cleats are used for attachment, it is recommended that a "peel-stop" bar be placed over the roof membrane near the edge flashing/coping, as illustrated in Figure 3-91. The purpose of the bar is to provide secondary protection against membrane lifting and peeling in the event that edge flashing/coping fails. A robust bar specifically made for bar-over mechanically attached single-ply systems is recommended. The bar needs to be very well anchored to the parapet or the deck. Depending on design wind loads, spacing between 4 and 12 inches on center is recommended. A gap of a few inches should be left between each bar to allow for water flow across the membrane. After the bar is attached, it is stripped over with a stripping ply.

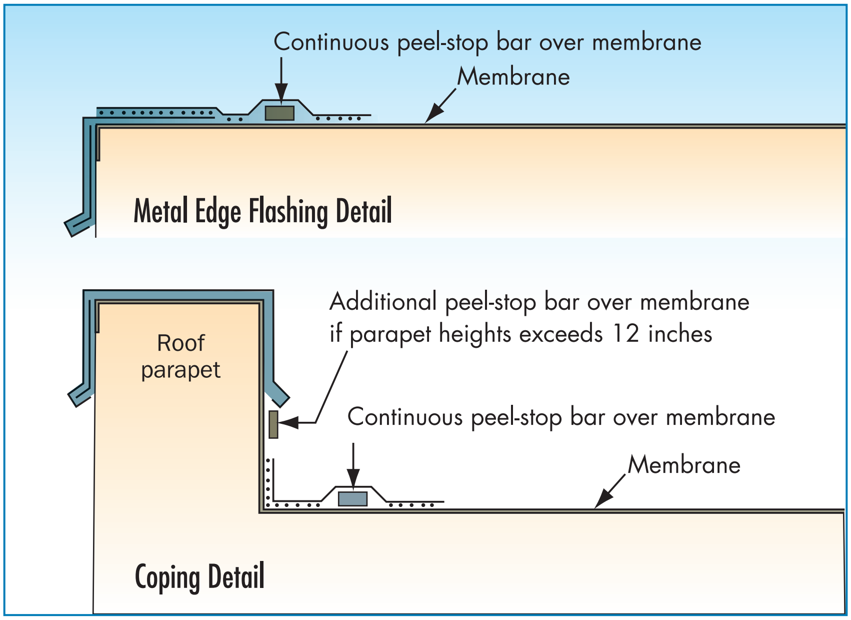


Figure 3-91:
A continuous peel-stop bar over the membrane may prevent a catastrophic progressive failure if the edge flashing or coping is blown off. (Modified from FEMA 55, 2000)

Walkway pads: Roof walkway pads are frequently blown off during hurricanes (Figure 3-92). Pad blow-off does not usually damage the roof membrane. However, wind-borne pad debris can damage other building components and injure people. Walkway pads are therefore not recommended in hurricane-prone regions.

Figure 3-92:
To avoid walkway pad blow off, as occurred on this hospital roof, walkway pads are not recommended. Hurricane Charley (Florida, 2004)

Parapets: For low-sloped roofs, minimum 3-foot high parapets are recommended. With parapets of this height or greater, the uplift load in the corner region is substantially reduced (ASCE 7 permits treating the corner zone as a perimeter zone). Also, a high parapet (as shown in Figures 3-78 and 3-118) may intercept wind-borne debris and keep it from blowing off the roof and damaging other building components or injuring people. To protect base flashings from wind-borne debris damage and subsequent water leakage, it is recommended that metal panels on furring strips be installed over the base flashing (Figure 3-93). Exposed stainless steel screws are recommended for attaching the panels to the furring strips because using exposed fasteners is more reliable than using concealed fasteners or clips (as were used for the failed panels shown in Figure 3-58).

Figure 3-93:
Base flashing protected by metal panels attached with exposed screws. Hurricane Katrina (Mississippi, 2005)

3.4.4 NONSTRUCTURAL SYSTEMS AND EQUIPMENT

Nonstructural systems and equipment include all components that are not part of the structural system or building envelope. Exterior-mounted equipment is especially vulnerable to hurricane-induced damage, and special attention should be paid to positioning and mounting of these components in hurricane-prone regions.

3.4.4.1 Elevators

Where interruption of elevator service would significantly disrupt facility operations, it is recommended that elevators be placed in separate locations within the building and be served by separate elevator penthouses. This is recommended, irrespective of the elevator penthouse enhancements recommended in Sections 3.3.3 and 3.3.4, because of the greater likelihood that at least one of the elevators will remain operational and therefore allow the facility to function as intended.

3.4.4.2 Mechanical Penthouses

By placing equipment in mechanical penthouses rather than leaving them exposed on the roof, equipment can be shielded from high-wind loads and wind-borne debris. Although screens (such as shown in Figure 3-77) could be designed and constructed to protect equipment from horizontally-flying debris, they are not effective in protecting equipment from missiles that have an angular trajectory. It is therefore recommended that mechanical equipment be placed inside mechanical penthouses. The penthouse itself should be designed and constructed in accordance with the recommendations given in Sections 3.4.2 and 3.4.3.

3.4.4.3 Lightning Protection Systems (LPS)

Lightning protection systems frequently become disconnected from rooftops during hurricanes. Displaced LPS components can puncture and tear roof coverings, thus allowing water to leak into buildings (see Figures 3-94 and 3-95). Prolonged and repeated slashing of the roof membrane by loose conductors (“cables”) and puncturing by air terminals (“lightning rods”) can result in lifting and peeling of the membrane. Also, when displaced, the LPS is no longer capable of providing lightning protection in the vicinity of the displaced conductors and air terminals.

Figure 3-94:
A displaced air terminal that punctured the membrane in several locations. Hurricane Marilyn (U.S. Virgin Islands, 1995)

Figure 3-95:
View of an end of a conductor that became disconnected. Hurricane Katrina (Mississippi, 2005)

Lightning protection standards such as NFPA 780 and UL 96A provide inadequate guidance for attaching LPS to rooftops in hurricane-prone regions, as are those recommendations typically provided by LPS and roofing material manufacturers. LPS conductors are typically attached to the roof at 3-foot intervals. The conductors are flexible, and when they are exposed to high winds, the conductors exert dynamic loads on the conductor connectors ("clips"). Guidance for calculating the dynamic loads does not exist. LPS conductor connectors typically have prongs to anchor the conductor. When the connector is well-attached to the roof surface, during high winds the conductor frequently bends back the malleable connector prongs (see Figure 3-96). Conductor connectors have also debonded from roof surfaces during high winds. Based on observations after Hurricane Katrina and other hurricanes, it is apparent that pronged conductor connectors typically have not provided reliable attachment.

Figure 3-96:
The conductor deformed the prongs under wind pressure, and pulled away from the connector. Hurricane Katrina (Mississippi, 2005)

To enhance the wind performance of LPS, the following are recommended:[10]

Parapet attachment: When the parapet is 12 inches high or greater, it is recommended that the air terminal base plates and conductor connectors be mechanically attached with #12 screws that have minimum 1¼-inch embedment into the inside face of the parapet nailer and are properly sealed for watertight protection. Instead of conductor connectors that have prongs, it is recommended that mechanically attached looped connectors be installed (see Figure 3-97).

Figure 3-97: This conductor was attached to the coping with a looped connector. Hurricane Katrina (Mississippi, 2005)

Attachment to built-up, modified bitumen, and single-ply membranes: For built-up and modified bitumen membranes, attach the air terminal base plates with asphalt roof cement. For single-ply membranes, attach the air terminal base plates with pourable sealer (of the type recommended by the membrane manufacturer).

In lieu of attaching conductors with conductor connectors, it is recommended that conductors be attached with strips of membrane installed by the roofing contractor. For built-up and modified bitumen membranes, use strips of modified bitumen cap sheet, approximately 9 inches wide at a minimum. If strips

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[10] Discussion is based on *Rooftop Attachment of Lightning Protection Systems in High-Wind Regions—Hurricane Katrina Recover Advisory* (May 2006, Revised July 2006).

are torch-applied, avoid overheating the conductors. For single-ply membranes, use self-adhering flashing strips, approximately 9 inches wide at a minimum. Start the strips approximately 3 inches from either side of the air terminal base plates. Use strips that are approximately 3 feet long, separated by a gap of approximately 3 inches (see Figure 3-98).

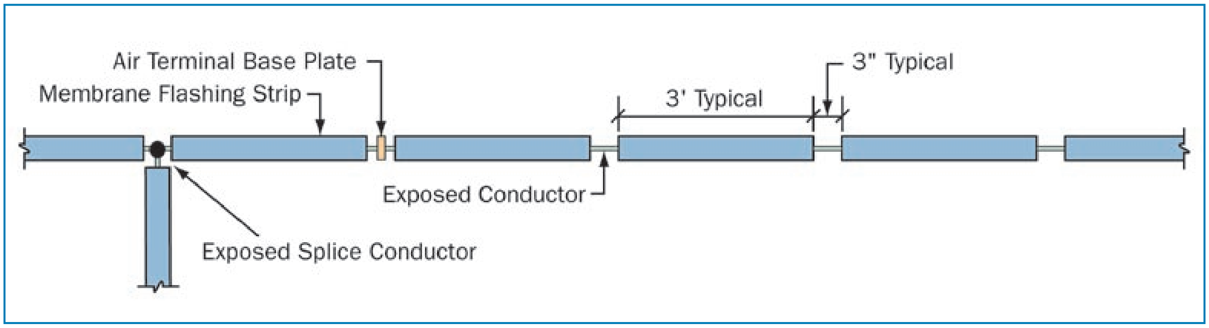


Figure 3-98: Plan showing conductor attachment

As an option to securing the conductors with stripping plies, conductor connectors that do not rely on prongs could be used (such as the one shown in Figure 3-99). However, the magnitude of the dynamic loads induced by the conductor is unknown, and there is a lack of data on the resistance provided by adhesively-attached connectors. For this reason, attachment with stripping plies is the preferred option, because the plies shield the conductor from the wind. If adhesive-applied conductor connectors are used, it is recommended that they be spaced more closely than the 3-foot spacing required by NFPA 780 and UL 96A. Depending on wind loads, a spacing of 6 to 12 inches on center may be needed in the corner regions of the roof, with a spacing of 12 to 18 inches on center at roof perimeters (see ASCE 7 for the size of corner regions).

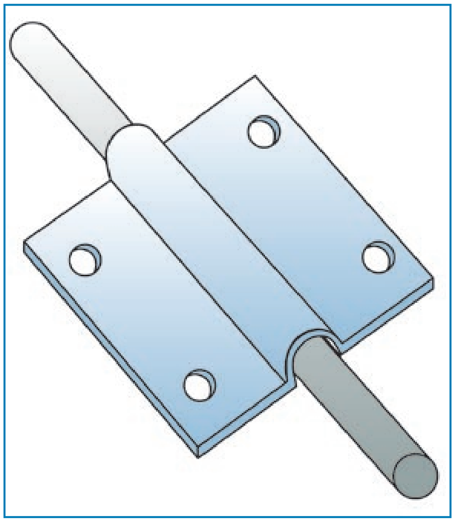


Figure 3-99:
Adhesively-attached conductor connector that does not use prongs

Mechanically attached single-ply membranes: It is recommended that conductors be placed parallel to, and within 8 inches of, membrane fastener rows. Where the conductor falls between or is perpendicular to membrane fastener rows, install an additional row of membrane fasteners where the conductor will be located, and install a membrane cover-strip over the membrane fasteners. Place the conductor over the cover-strip and secure the conductor as recommended above.

By following the above recommendations, additional rows of membrane fasteners (beyond those needed to attach the membrane) may be needed to accommodate the layout of the conductors. The additional membrane fasteners and cover-strip should be coordinated with, and installed by, the roofing contractor.

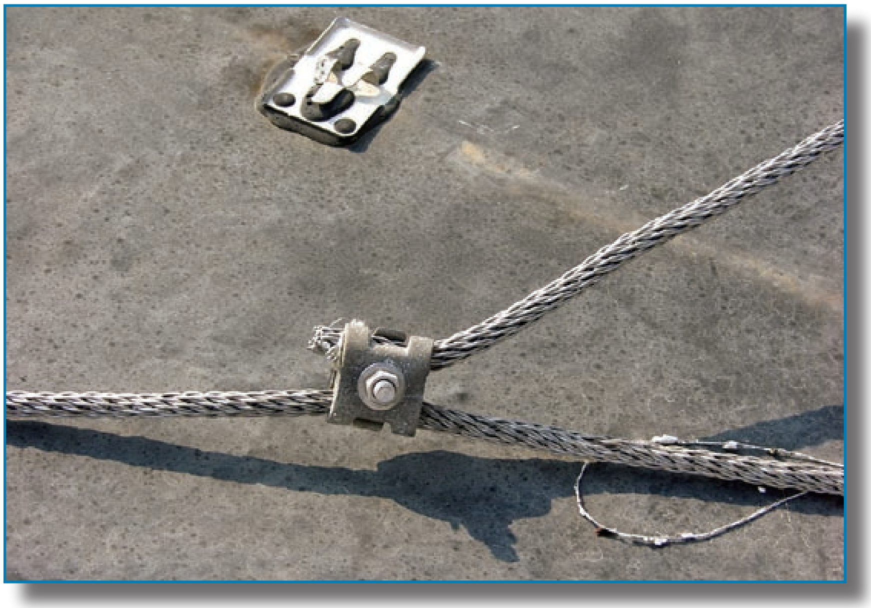
Standing seam metal roofs: It is recommended that pre-manufactured, mechanically attached clips that are commonly used to attach various items to roof panels be used. After anchoring the clips to the panel ribs, the air terminal base plates and conductor connectors are anchored to the panel clips. In lieu of conductor connectors that have prongs, it is recommended that mechanically attached looped connectors be installed (see Figure 3-97).

Conductor splice connectors: In lieu of pronged splice connectors (see Figure 3-100), bolted splice connectors are recommended because they provide a more reliable connection (see Figure 3-101). It is recommended that strips of flashing membrane (as recommended above) be placed approximately 3 inches from either side of the splice connector to minimize conductor movement and to avoid the possibility of the conductors becoming disconnected. To allow for observation during maintenance inspections, do not cover the connectors.

It is recommended that the building designer advise the building owner to have the LPS inspected each spring, to verify that connectors are still attached to the roof surface, that they still engage the conductors, and that the splice connectors are still secure. Inspections are also recommended after high-wind events.

Figure 3-100:
If conductors detach from the roof, they are likely to pull out from pronged splice connectors. Hurricane Charley (Florida, 2004)

Figure 3-101:
Bolted splice connectors are recommended to prevent free ends of connectors from being whipped around by wind. Hurricane Katrina (Mississippi, 2005)



3.4.5 MUNICIPAL UTILITIES

Hurricanes typically disrupt municipal electrical service, and often they disrupt telephone (both cellular and land-line), water, and sewer services. These disruptions may last from several days to several weeks. Electrical power disruptions can be caused by damage to power generation stations and by damaged lines, such as major transmission lines and secondary feeders. Water disruptions can be caused by damage to water treatment or well facilities, lack of power for pumps or treatment facilities, or by broken water lines caused by uprooted trees. Sewer disruptions can be caused by damage to treatment facilities, lack of power for treatment facilities or lift stations, or broken sewer lines. Phone disruptions can be caused by damage at switching facilities and collapse of towers. Critical facilities should be designed to prevent the disruption of operations arising from prolonged loss of municipal services.

3.4.5.1 Electrical Power

It is recommended that critical facilities that will be occupied during a hurricane, or will be needed within the first few weeks afterwards, be equipped with one or more emergency generators. In addition to providing emergency generators, it is recommended that one or more additional standby generators be considered, particularly for facilities such as EOCs, hospitals and nursing homes, shelters, and fire and police stations, where continued availability of electrical power is vital. The purpose of providing the standby generators is to power those circuits that are not powered by the emergency generators. With both emergency and standby generators, the entire facility will be completely backed up. It is recommended that the emergency generator and standby generator systems be electrically connected via manual transfer switches to allow for interconnectivity in the event of emergency generator failure. The standby circuits can be disconnected from the standby generators, and the emergency circuits can be manually added. The emergency generators should be rated for prime power (continuous operation).

Running generators for extended time periods frequently results in equipment failure. Thus, provisions for back-up generation capacity are important, because the municipal power system may be out of service for many days or even weeks. Therefore, it is recommended that an exterior box for single pole cable cam locking connectors be provided so that a portable generator can be connected to the facility. With a cam locking box, if one or more of the emergency or standby generators malfunction, a portable generator can be brought to the facility and quickly connected.

It is recommended that shelters be provided with an emergency generator to supply power for lighting, exit signs, fire alarm system, public address system, and for mechanical ventilation. A standby generator is also recommended in the event that the emergency generator malfunctions. A cam locking box is also recommended to facilitate connection of a back-up portable generator.

Back-up portable generators should be viewed as a third source of power (i.e., they should not replace standby generators), because it may take several days to get a back-up portable generator to the site.

Generators should be placed inside wind-borne debris resistant buildings (see recommendations in Sections 3.4.2 and 3.4.3) so that they are not susceptible to damage from debris or tree fall. Locating generators outdoors (see Figure 4-44) or inside weak enclosures is not recommended. It is recommended that wall louvers for generators be capable of resisting the test Missile E load specified in ASTM E 1996. Alternatively, wall louvers can be protected with a debris-resistant screen wall so that wind-borne debris is unable to penetrate the louvers and damage the generators.

It is recommended that sufficient onsite fuel storage be provided to allow all of the facility's emergency and standby generators to operate at full capacity for a minimum of 96 hours (4 days).[11] If at any time it appears that refueling won't occur within 96 hours, provision should be made to shut off part or all the standby circuits in order to provide longer operation of the emergency circuits. For remote facilities or situations where it is believed that refueling may not occur within 96 hours, the onsite fuel storage capacity should be increased as deemed appropriate. It is recommended that fuel storage tanks, piping, and pumps be placed inside wind-borne debris resistant buildings, or underground. If the site is susceptible to flooding, refer to Chapter 2 recommendations.

3.4.5.2 Water Service

It is recommended that critical facilities that rely on water for continuity of service (especially hospitals and nursing homes) be provided with an independent water supply—a well or on-site water storage. Facilities that only need drinking water for

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[11] The 96-hour fuel supply is based in part on the Department of Veterans Affairs criteria.

occupants can have bottled water provided instead.

If water is needed for cooling towers, the independent water supply should be sized to accommodate the system. It is recommended that the well or onsite storage be capable of providing an adequate water supply for fire sprinklers. Alternatively, it is recommended that the building designer should advise the building owner to implement a continual fire-watch and provide additional fire extinguishers until the municipal water service is restored. For hospitals, it is recommended that the well or onsite water storage be capable of providing a minimum of 100 gallons of potable water per day per patient bed for four days (the 100 gallons includes water for cooling towers).[12]

For critical facilities with boilers, it is recommended to store fuel onsite for a minimum of 96 hours (4 days). Storage tanks, piping, and pumps should be inside wind-borne debris resistant buildings or be placed underground (if site is susceptible to flooding, refer to Chapter 2).

It is recommended that pumps for wells or onsite storage be connected to an emergency power circuit, that a valve be provided on the municipal service line, and that onsite water treatment capability be provided where appropriate.

For hospitals and nursing homes, it is recommended that onsite storage of medical gases be sized to provide a minimum of 96 hours (4 days) of service.

3.4.5.3 Sewer Service

It is recommended that critical facilities that rely on sewer service for continuity of operations (especially hospitals and nursing homes) be provided with an alternative means of waste disposal, such as a temporary storage tank which can be pumped out by a local contractor. For facilities such as EOCs, fire and police stations, and shelters, portable toilets can be placed inside the facility before the onset of a hurricane. It is recommended that all critical facilities be provided with back-flow preventors.

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[12] This recommendation is based on the Department of Veterans Affairs criteria.

3.4.6 POST-DESIGN CONSIDERATIONS

In addition to adequate design, proper attention must be given to construction, post-occupancy inspection, and maintenance.

3.4.6.1 Construction Contract Administration

It is important for owners of critical facilities in hurricane-prone regions to obtain the services of a professional contractor who will execute the work described in the contract documents in a diligent and technically proficient manner. The frequency of field observations and extent of special inspections and testing should be greater than those employed on critical facilities that are not in hurricane-prone regions.

3.4.6.2 Periodic Inspections, Maintenance, and Repair

The recommendations given in Section 3.3.1.4 for post-occupancy and post-storm inspections, maintenance, and repair are crucial for critical facilities in hurricane-prone regions. Failure of a building component that was not maintained properly, repaired or replaced, can present a considerable risk of injury or death to occupants, and the continued operation of the facility can be jeopardized.

The recommendations given in Section 3.4 are summarized in Table 3-4.

Table 3-4: Recommendations for Design of Critical Facilities

EOCs, healthcare facilities, and shelters	Design very robustly.
Shelters	Refer to FEMA 361, *Design and Construction Guidance for Community Shelters*.
Walkways between campus buildings	If buildings will be occupied during a hurricane, provide enclosed walkways.
Structural systems	Use reinforced cast-in-place concrete. If the roof deck is not cast-in-place, use precast concrete or concrete topping over steel decking.
Exterior walls	Use reinforced concrete or fully grouted and reinforced CMU without wall coverings, other than paint.
Exterior doors	Use doors designed and tested to resist test missiles.
Exterior windows and skylights	Use laminated glass or shutters designed and tested to resist test missiles. If equipped with shutters, glazing is still required to resist wind pressure loads.
Roof covering	Design a roof system that can accommodate missiles as recommended in Section 3.4.3.4. Avoid aggregate surfacings, lightweight concrete pavers, cementitious-coated insulation boards, slate, and tile. Avoid single-ply membranes unless ballasted with heavy pavers.
Parapets	Use minimum 3-foot high parapets for low-sloped roofs.
Elevators	Place elevators in separate locations served by separate penthouses.
Mechanical penthouses	Place rooftop equipment in penthouses rather than exposed on the roof.
Lightning protection systems	Attach LPS to the roof as recommended in Section 3.4.4.3.
Emergency power	Provide emergency power as recommended in Section 3.4.5.1.
Water service	Provide a water supply independent of municipal supplies.
Sewer service	Provide a means of waste disposal independent of municipal service.
Construction contract administration	Construction executed by a professional contractor and subcontractors. Conduct more frequent field observations, special inspections and testing.
Periodic inspections, maintenance, and repair	After construction, conduct diligent periodic inspections and special inspections after storms. Ensure diligent maintenance and prompt repairs.

3.5 BEST PRACTICES IN TORNADO-PRONE REGIONS

Strong and violent tornadoes may reach wind speeds substantially greater than those recorded in the strongest hurricanes. The wind pressures that these tornadoes can exert on a building are tremendous, and far exceed the minimum pressures derived from building codes. Figure 3-102 shows a classroom wing in a school in Illinois. All of the exterior windows were broken, and virtually all of the cementitious wood-fiber deck panels were blown away. Much of the metal roof decking over the band and chorus area also blew off. The gymnasium collapsed, as did a portion of the multi-purpose room. The school was not in session at the time the tornado struck.

Figure 3-102:
A Northern Illinois school heavily damaged by a strong tornado in 1990

Strong and violent tornadoes can generate very powerful missiles. Experience shows that large and heavy objects, including vehicles, can be hurled into buildings at high speeds. The missile sticking out of the roof in the foreground of Figure 3-103 is a double 2-inch by 6-inch wood member. The portion sticking out of the roof is 13 feet long. It penetrated a ballasted ethylene propylene diene monomer (EPDM) membrane, approximately 3 inches of polyisocyanurate roof insulation, and the steel roof deck. The missile lying on the roof just beyond is a 2-inch by 10-inch by 16-foot long wood member.

Figure 3-103:
A violent tornado showered the roof of this school with missiles. (Oklahoma, 1999)

There is little documentation regarding tornado-induced damage to critical facilities. Most of the damage reports available pertain to schools because schools are the most prevalent type of critical facilities and, therefore, are more likely to be struck. A 1978 report prepared for the Veterans Administration[13] identified four hospitals that were struck by tornadoes between 1973 and 1976. Table 3-5 (taken from that report) further illustrates the effects tornados can have on critical facilities.

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[13] *A Study of Building Damage Caused by Wind Forces*, McDonald, J.R. and Lea, P.A, Institute for Disaster Research, Texas Tech University, 1978.

Table 3-5: Examples of Ramifications of Tornado Damage at Four Hospitals

Location and Building Characteristics	Tornado Characteristics	Damage	Ramifications of Damage
Mountain View, Missouri (St. Francis Hospital). One-story steel frame with non-load bearing masonry exterior walls.	The tornado crossed over one end of the hospital.	Metal roof decking was blown off, some windows were broken, and rooftop mechanical equipment was displaced.	Patients were moved to undamaged areas of the hospital.
Omaha, Nebraska (Bishop Bergen Mercy Hospital). Five-story reinforced concrete frame.	Maximum wind speed estimated at 200 mph. Proximity to hospital not documented.	Windows were broken, and rooftop mechanical equipment was damaged and displaced. Communications and electrical power were lost (emergency generators provided power).	A few minor cuts; "double walled corridors" provided protection for patients and staff. Some incoming emergency room patients (injured elsewhere in the city) were rerouted to other hospitals. Loss of communications hampered the rerouting.
Omaha, Nebraska (Bishop Bergen Mercy Hospital – Ambulatory Care Unit). One-story load bearing CMU walls with steel joists.	See above.	The building was a total loss due to wall and roof collapse.	Patients were evacuated to the first floor of the main hospital when the tornado watch was issued.
Corsicana, Texas (Navarro County Memorial Hospital). Five-story reinforced concrete frame with masonry non-load bearing walls in some areas and glass curtain walls.	The tornado was very weak.	Many windows were broken by aggregate from the hospital's built-up roofs. Intake duct work in the penthouse collapsed.	Two people in the parking lot received minor injuries from roof aggregate. Electrical power was lost for 2 hours (emergency generators provided power).
Monahans, Texas (Ward Memorial Hospital). One-story load bearing CMU walls with steel joists. Some areas had metal roof deck and others had gypsum deck.	The tornado passed directly over the hospital, with maximum wind speed estimated at 150 mph.	The roof structure was blown away on a portion of the building (the bond beam pulled away from the wall). Many windows were broken. Rooftop mechanical equipment was damaged.	

For critical facilities located in tornado-prone regions (as defined in Section 3.2.2), the following are recommended:

- Incorporate a shelter within the facility to provide occupant protection. For shelter design, FEMA 361 criteria are recommended.

- For interior non-load-bearing masonry walls, see the recommendations given in Section 3.3.3.3.

- Brick veneer, aggregate roof surfacing, roof pavers, slate, and tile cannot be effectively anchored to prevent them from becoming missiles if a strong or violent tornado passes near a building with these components. To reduce the potential number of missiles, and hence reduce the potential for building damage and injury to people, it is recommended that these materials not be specified for critical facilities in tornado prone regions.

- For hospitals, nursing homes, and other critical facilities where it is desired to minimize disruption of operations from nearby weak tornadoes and from strong and violent tornados that are on the periphery of the facility, the following are recommended:

  1) For the roof deck, exterior walls, and doors, follow the recommendations given in Sections 3.4.2 and 3.4.3.

  2) For exterior glazing, specify laminated glass window assemblies that are designed to resist the test Missile E load specified in ASTM E 1996, and are tested in accordance with ASTM E 1886. Note that missile loads used for designing tornado shelters significantly exceed the missile loads used for designing glazing protection in hurricane-prone regions. Missiles from a strong or violent tornado passing near the facility could penetrate the laminated glazing and result in injury or interior damage. Therefore, to increase occupant safety, even when laminated glass is specified, the facility should also incorporate a shelter as recommended above.

Existing Facilities without Tornado Shelters

Where the number of recorded F3, F4, and F5 tornadoes per 3,700 square miles is one or greater (see Figure 3-2 and discussion of Fujita Scale in Section 3.1.1), the best available refuge areas should be identified if the facility does not have a tornado shelter. FEMA 431, T*ornado Protection, Selecting Refuge Areas in Buildings* provides useful information for building owners, architects, and engineers who perform evaluations of existing facilities.

To minimize casualties in critical facilities, it is very important that the best available refuge areas be identified by a qualified architect or engineer.[14] Once identified, those areas need to be clearly marked so that occupants can reach the refuge areas without delay. Building occupants should not wait for the arrival of a tornado to try to find the best available refuge area in a particular facility; by that time, it will be too late. If refuge areas have not been identified beforehand, occupants will take cover wherever they can, frequently in very dangerous places. Corridors, as shown in Figure 3-104, sometimes provide protection, but they can also be death traps.

Figure 3-104:
View of school corridor after passage of a violent tornado (Oklahoma, 1999)

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[14] It should be understood that the occupants of a "best available refuge area" are still vulnerable to death and injury if the refuge area was not specifically designed as a tornado shelter.

For small shelters within facilities such as fire and police stations, a designated storage room(s), office(s), or small conference room(s) can be economically retrofitted in accordance with FEMA 320 to protect the occupants. Where it is desired to provide a large shelter area, FEMA 361 criteria are recommended.

Retrofitting a shelter space inside an existing building can be very expensive. An economical alternative is an addition that can function as a shelter as well as serve another purpose. This approach works well for smaller facilities. For very large facilities, constructing two or more shelter additions should be considered in order to reduce the time it takes to reach the shelter (often there is ample warning time, but sometimes an approaching tornado is not noticed until a few minutes before it strikes). This is particularly important for hospitals and nursing homes because of the difficulty of accommodating patients with different medical needs.

The recommendations given in Section 3.5 are summarized in Table 3-6.

Table 3-6: Critical Facilities Located in Tornado-Prone Regions

Proposed Facility	
Occupant protection	Refer to FEMA 361 for design guidance.
Interior non-load-bearing masonry walls	See recommendations in Section 3.3.3.3.
Wind-borne missiles	Avoid use of brick veneer, aggregate surfacing, roof pavers, slate, and tile.
Healthcare and other critical facilities where it is desired to minimize disruption of operations from nearby weak tornadoes	See recommendations in Section 3.5.
Existing facilities without specifically designed tornado shelters	
If one or more F3-F5 tornadoes per 3,700 square miles	Identify best available refuge areas. See Figure 3-2 for historical data on frequency, and refer to FEMA 431 (2003) for identification guidance.
If six or more F3-F5 tornadoes per 3,700 square miles	Consider incorporating a shelter within the building or inside a new building addition. Refer to FEMA 320 and FEMA 361 for design guidance.

3.6 REMEDIAL WORK ON EXISTING FACILITIES

Many existing critical facilities need to strengthen their structural or building envelope components. The reasons for this are the deterioration that has occurred over time, or inadequate facility strength to resist current design level winds. It is recommended that building owners have a vulnerability assessment performed by a qualified architectural and engineering team. A vulnerability assessment should be performed for all facilities older than 5 years. However, as illustrated by Figure 3-30 and the case of Garden Park Medical Center discussed in Section 4.2, an assessment is recommended for all facilities located in areas where the basic wind speed is greater than 90 mph (even if the facility is younger than five years). It is particularly important to perform vulnerability assessments on critical facilities located in hurricane-prone and tornado-prone regions.

American Red Cross (ARC) Publication 4496, *Standards for Hurricane Evacuation Shelter Selection* (2002) provides information regarding assessing existing buildings for use as hurricane shelters. Unless a facility has been specifically designed for use as a shelter, it should only be used as a shelter of last resort, and even then, only if it meets the criteria given in ARC 4496.

Components that typically make buildings constructed before the early 1990s vulnerable to high winds are weak non-load-bearing masonry walls, poorly connected precast concrete panels, long-span roof structures with limited uplift resistance (e.g., at gyms), inadequately connected roof decks, weak glass curtain walls, building envelope, and exterior-mounted equipment. Although the technical solutions to these problems are not difficult, the cost of the remedial work is typically quite high. If funds are not available for strengthening or replacement, it is important to minimize the risk of injury and death by evacuating areas adjacent to weak non-load-bearing walls, weak glass curtain walls, and areas below long-span roof structures when winds above 60 mph are forecast.

Critical facilities sometimes occupy buildings that have changed their original use (see the case of Hancock County EOC, discussed in Section 4.4). Buildings that were not designed for a critical occupancy were likely designed with a 1.0 rather than a 1.15 importance factor, and hence are not as wind-resistant as needed. It is particularly important to perform a vulnerability assessment if a facility is located in a building not originally designed for a critical occupancy, especially if the facility is located in a hurricane- or tornado-prone region.

As a result of building code changes and heightened awareness, some of the common building vulnerabilities have generally been eliminated for facilities constructed in the mid-1990s or later. Components that typically remain vulnerable to high winds are the building envelope and exterior-mounted mechanical, electrical, and communications equipment. Many failures can be averted by identifying weaknesses and correcting them.

By performing a vulnerability assessment, items that need to be strengthened or replaced can be identified and prioritized. A proactive approach in mitigating weaknesses can save significant sums of money and decrease disruption or total breakdown in critical facility operations after a storm. For example, a vulnerability assessment on a school such as that shown in Figure 3-105 can identify weakness of exterior classroom walls. Replacing walls before a hurricane is much cheaper than replacing the walls and repairing consequential damages after a storm, and proactive work avoids the loss of use while repairs are made.

Before beginning remedial work, it is necessary to understand all significant aspects of the vulnerability of a facility with respect to wind and wind-driven rain. If funds are not available to correct all identified deficiencies, the work should be systematically prioritized so that the items of greatest need are first corrected. For example, at a building such as that shown in Figure 3-105, had the windows been retrofitted with shutters, that effort would have been ineffective, because the walls themselves collapsed. Mitigation efforts can be very ineffective if they do not address all items that are likely to fail.

A comprehensive guide for remedial work on existing facilities is beyond the scope of this manual. However, the following are examples of mitigation measures that are often applicable.

Figure 3-105:
Several walls at this school collapsed. Windows were located above a non-load-bearing masonry wall. Hurricane Katrina (Mississippi, 2005)

3.6.1 STRUCTURAL SYSTEMS

As discussed in Section 3.1.4.1, roof decks on many facilities designed prior to the 1982 edition of the SBC and UBC and the 1987 edition of the NBC are very susceptible to failure. Poorly attached decks that are not upgraded are susceptible to blow-off, as shown in Figure 3-106. Decks constructed of cementitious wood-fiber, gypsum, and lightweight insulating concrete over form boards were commonly used on buildings built in the 1950s and 1960s. In that era, these types of decks typically had very limited uplift resistance due to weak connections to the support structure. Steel deck attachment is frequently not adequate because of an inadequate number of welds, or welds of poor quality. Older buildings with overhangs are particularly susceptible to blow-off, as shown in Figure 3-107, because older codes provided inadequate uplift criteria.

Figure 3-106: The school's built-up roof blew off after one of the cementitious wood-fiber deck panels detached from the joists. Hurricane Katrina (Mississippi, 2005)

Figure 3-107: The cementitious wood-fiber deck panels detached from the joists along the overhangs and caused the school's built-up membranes to lift and peel. Hurricane Katrina (Mississippi, 2005)

A vulnerability assessment of the roof deck should include evaluating the existing deck attachment, spot checking the structural integrity of the deck (including the underside, if possible), and evaluating the integrity of the beams/joists. If the deck attachment is significantly overstressed under current design wind conditions or the deck integrity is compromised, the deck should be replaced or strengthened as needed. The evaluation should be conducted by an investigator experienced with the type of deck used on the building.

If a low-slope roof is converted to a steep-slope roof, the new support structure should be engineered and constructed to resist the wind loads and avoid the kind of damage shown in Figure 3-108.

Figure 3-108:
The school's wood superstructure installed as part of a steep-slope conversion blew away because of inadequate attachment. Hurricane Katrina (Louisiana, 2005)

3.6.2 BUILDING ENVELOPE

The following recommendations apply to building envelope components of existing critical facilities.

3.6.2.1 Sectional and Rolling Doors

Sectional and rolling doors (e.g., at fire station apparatus bays and hospital loading docks), installed in older buildings before attention was given to the wind resistance of these elements, are very susceptible to being blown away. Although weak doors can be retrofitted, it is difficult to ensure that the door, door tracks, and connections between the door and tracks are sufficient. It is therefore recommended that weak doors and tracks be replaced with new assemblies that have been tested to meet the factored design wind loads. As part of the replacement work, nailers between the tracks and building structure should either be replaced, or their attachment should also be strengthened.

If a facility has more than one sectional or rolling door, all doors should be replaced, rather than just replacing one of the doors. The fire station shown in Figure 3-109 had six sectional doors. One door had been replaced before a hurricane. It performed very well, but three of the older doors were blown away and two of the older doors remained in place but had some wind damage.

Figure 3-109:
The new door in the center performed very well, but the older doors on either side of it were blown away. Hurricane Charley (Florida, 2004)

3.6.2.2 Windows and Skylights

Windows in older facilities may possess inadequate resistance to wind pressure. Window failures are typically caused by wind-borne debris, however, glazing or window frames may fail as a result of wind pressure (see Figure 3-110). Failure can be caused by inadequate resistance of the glazing, inadequate anchorage of the glazing to the frame, failure of the frame itself, or inadequate attachment of the frame to the wall. For older windows that are too weak to resist the current design pressures, window assembly replacement is recommended. Some older window assemblies have sufficient strength to resist the design pressure, but are inadequate to resist wind-driven rain. If the lack of water resistance is due to worn glazing gaskets or sealants, replacing the gaskets or sealant may be viable. In other situations, replacing the existing assemblies with new, higher-performance assemblies may be necessary.

Figure 3-110: Wind pressure caused the window frames on the upper floor to fail (red arrow). Hurricane Katrina (Mississippi, 2005)

It is recommended that all non-impact-resistant, exterior glazing located in hurricane-prone regions (with a basic wind speed of 100 mph or greater) be replaced with impact-resistant glazing or be protected with shutters, as discussed in Section 3.4.3.2.

Shutters are typically a more economical approach for existing facilities. There are a variety of shutter types, all illustrated by Figures 3-111 to 3-113. Accordion shutters are permanently attached to the wall (Figure 3-111). When a hurricane is forecast, the shutters are pulled together and latched into place. Panel shutters (Figure 3-112) are made of metal or polycarbonate. When a hurricane is forecast, the shutters are taken from storage and inserted into metal tracks that are permanently mounted to the wall above and below the window frame. The panels are locked into the frame with wing nuts or clips. Track designs that have permanently mounted studs for the nuts have been shown to be more reliable than track designs using studs that slide into the track. A disadvantage of panel shutters is the need for storage space. Roll-down shutters (Figure 3-113) can be motorized or pulled down manually. Figure 3-113 illustrates the benefits of shuttering. Two of the unprotected window units experienced glass breakage and the third window unit blew in.

Figure 3-111:
This school has accordion shutters. Hurricane Ivan (Florida, 2004)

Figure 3-112: Illustrates a metal panel shutter. Hurricane Georges (Puerto Rico, 1998)

Figure 3-113: The lower window assembly was protected with a motorized shutter. Hurricane Ivan (Florida, 2004)

Deploying accordion or panel shutters a few stories above grade is expensive. Although motorized shutters have greater initial cost, their operational cost should be lower. Other options for providing missile protection on upper levels include replacing the existing assemblies with laminated glass assemblies, or installing permanent impact resistant screens. Engineered films are also available for application to the interior of the glass. The film needs to be anchored to the frame, and the frame needs to be adequately anchored to the wall. The film degrades over time and requires replacement (approximately every decade). Use of laminated glass or shutters is recommended in lieu of engineered films.

3.6.2.3 Roof Coverings

For roofs with weak metal edge flashing or coping attachment, face-attachment of the edge flashing/coping (as shown in Figure 3-63) is a cost-effective approach to greatly improve the wind resistance of the roof system.

The vulnerability assessment of roofs ballasted with aggregate, pavers, or cementitious-coated insulation boards, should determine whether the ballast complies with ASNI/SPRI RP-4. Corrective action is recommended for non-compliant, roof coverings. It is recommended that roof coverings with aggregate surfacing, lightweight pavers, or cementitious-coated insulation boards on buildings located in hurricane-prone regions be replaced to avoid blow off (see Figure 3-114).

Figure 3-114: Aggregate from the hospital's built-up roofs broke several windows in the intensive care unit, which had to be evacuated during the hurricane. Hurricane Charley (Florida, 2004)

When planning the replacement of a roof covering, it is recommended that all existing roof covering be removed down to the deck rather than simply re-covering the roof. Tearing off the covering provides an opportunity to evaluate the structural integrity of the deck and correct deck attachment and other problems. For example, if a roof deck was deteriorated due to roof leakage (see Figure 3-115), the deterioration would likely not be identified if the roof was simply re-covered. By tearing off down to the deck, deteriorated decking like that shown in Figure 3-115 can be found and replaced. In addition, it is recommended that the attachment of the wood nailers at the top of parapets and roof edges be evaluated and strengthened where needed, to avoid blow-off and progressive lifting and peeling of the new roof membrane (see Figure 3-116).

Figure 3-115:
The built-up roof on this school was blown off after a few of the rotted wood planks detached from the joists. Hurricane Katrina (Mississippi, 2005)

Figure 3-116:
The edge nailer on top of an old brick wall at a hospital blew off because it was inadequately attached. Hurricane Ivan (Florida, 2004)

If the roof has a parapet, it is recommended that the inside of the parapet be properly prepared to receive the new base flashing. In many instances, it is prudent to re-skin the parapet with sheathing to provide a suitable substrate. Base flashing should not be applied directly to brick parapets because they have irregular surfaces that inhibit good bonding of the base flashing to the brick (see Figure 3-117). Also, if moisture drives into the wall from the exterior side of the parapet with base flashing attached directly to brick, the base flashing can inhibit drying of the wall. Therefore, rather than totally sealing the parapet with membrane base flashing, the upper portion of the brick can be protected by metal panels (as shown in Figure 3-93), which permit drying of the brick.

Figure 3-117:
Failed base flashing adhered directly to the brick parapet. Hurricane Katrina (Louisiana, 2005)

3.6.3 EXTERIOR-MOUNTED EQUIPMENT

Fastening rooftop equipment to curbs, as discussed in Section 3.3.4.1, is a cost-effective approach to minimize wind-induced problems.

Exterior-mounted equipment on existing critical facilities should be carefully examined and evaluated.

3.6.3.1 Antenna (Communications Mast)

Antenna collapse is very common. Besides loss of communications, collapsed masts can puncture roof membranes or cause other building damage as shown in Figure 3-118. This case also demonstrates the benefits of a high parapet. Although the roof still experienced high winds that blew off this penthouse door, the parapet prevented the door from blowing off the roof.

In hurricane-prone regions, it is recommended that antennae strength be evaluated as part of the vulnerability assessment. Chapter 15 of ANSI/TIA-222-G provides guidance on the structural evaluation of existing towers. Appendix J of that standard contains checklists for maintenance and condition assessments. Additional bracing, guy-wires, or tower strengthening or replacement may be needed.

Figure 3-118:
The antenna at this hospital collapsed and was whipped back and forth across the roof membrane. Hurricane Andrew (Florida, 1992)

3.6.3.2 Lightning Protection Systems

Adhesively-attached conductor connectors and pronged splice connectors typically have not provided reliable attachment during hurricanes. To provide more reliable attachment for LPS located in hurricane-prone regions where the basic wind speed is 100 mph or greater, or on critical facilities in excess of 100 feet above grade, it is recommended that attachment modifications based on the guidance given in Section 3.3.4.3 be used.

The recommendations given in Section 3.6 are summarized in Table 3-7.

Table 3-7: Recommendations for Remedial Work on Existing Critical Facilities

Weakness	Recommended remedy
Critical facilities older than 5 years, or any age if located in an area with basic wind speed greater than 90 mph.	Perform vulnerability assessment with life-safety issues as the first priority, and property damage and interruption of service as the second priority.
A building with weak non-load-bearing masonry or curtain walls, poorly connected precast concrete panels, or weak long-span roof structures.	Implement remedial work on elements with insufficient strength to resist wind loads if the facility will be occupied during high wind events (e.g., strong thunderstorms).
Sectional and rolling doors.	Replace weak doors and tracks.
Worn window gaskets and sealants.	Replace with new gaskets and sealants, or replace window assembly.
Buildings in a hurricane-prone region where the basic wind speed is 100 mph or greater, with non-impact-resistant exterior glazing.	Replace with impact-resistant glazing or protect with shutters.
Inadequately attached edge flashings or copings.	Face-attach the vertical flanges. See Figure 3-63.
Ballasted single-ply roof membranes.	Take corrective action if non-compliant with ANSI/SPRI RP-4.
Buildings in a hurricane-prone region with aggregate roof surfacing, lightweight pavers, or cementitious-coated insulation boards.	Replace roof covering to avoid blow-off.
Rooftop equipment unanchored or poorly anchored.	Add screws or bolts to anchor equipment to curbs. Add cables to secure fan cowlings. Add latches to secure equipment access panels. See Section 3.3.4.1.
Weak roof deck connections or weak roof structure.	When planning replacement of roof covering, remove roof covering and strengthen attachment of deck and/or roof structure. See Section 3.6.2.3.
Emergency generators in a hurricane-prone region not adequately protected from wind-borne debris.	Build an enclosure to provide debris protection. See Section 3.4.5.1.
Antennae (communication masts) in hurricane-prone regions.	Evaluate wind resistance and strengthen as needed. See Chapter 15 and Appendix J of ANSI/TIA-222-G.
Lightning protection systems with adhesively-attached conductor connectors or pronged splice connectors located in hurricane-prone regions where the basic wind speed is 100 mph or greater, or on critical facilities in excess of 100 feet above grade.	Modify attachment according to recommendations in Section 3.4.4.3.

3.7 CHECKLIST FOR BUILDING VULNERABILITY OF CRITICAL FACILITIES EXPOSED TO HIGH WINDS

The Building Vulnerability Assessment Checklist (Table 3-8) is a tool that can help in assessing the vulnerability of various building components during the preliminary design of a new building, or the rehabilitation of an existing building. In addition to examining design issues that affect vulnerability to high winds, the checklist also examines the potential adverse effects on the functionality of the critical and emergency systems upon which most critical facilities depend. The checklist is organized into separate sections, so that each section can be assigned to a subject expert for greater accuracy of the examination. The results should be integrated into a master vulnerability assessment to guide the design process and the choice of appropriate mitigation measures.

Table 3-8: Checklist for Building Vulnerability of Critical Facilities Exposed to High Winds

Vulnerability Sections	Guidance	Observations
General		
What is the age of the facility, and what building code and edition was used for the design of the building?	Substantial wind load improvements were made to the model building codes in the 1980s. Many buildings constructed prior to these improvements have structural vulnerabilities. Since the 1990s, several additional changes have been made, the majority of which pertain to the building envelope. Older buildings, not designed and constructed in accordance with the practices developed since the early 1990s, are generally more susceptible to damage than newer buildings.	

Table 3-8: Checklist for Building Vulnerability of Critical Facilities Exposed to High Winds (continued)

Vulnerability Sections	Guidance	Observations
General (continued)		
Is the critical facility older than 5 years, or is it located in a zone with basic wind speed greater than 90 mph?	In either case, perform a vulnerability assessment with life-safety issues as the first priority, and property damage and interruption of service as the second priority.	
Site		
What is the design wind speed at the site? Are there topographic features that will result in wind speed-up?	ASCE 7 and Section 3.1.3.	
What is the wind exposure on site?	Avoid selecting sites in Exposure D, and avoid escarpments and hills (Section 3.1.3).	
Are there trees or towers on site?	Avoid trees and towers near the facility (Section 3.3.1.1). If the site is in a hurricane-prone region, avoid trees and towers near primary access roads (Section 3.4.1).	
Road access	Provide two separate means of access (Section 3.3.1.1).	
Is the site in a hurricane-prone region?	ASCE 7. If yes, follow hurricane-resistant design guidance (Section 3.4).	
If in a hurricane-prone region, are there aggregate surfaced roofs within 1,500 feet of the facility?	Remove aggregate from existing roofs (Section 3.6.2.3). If the buildings with aggregate are owned by other parties, attempt to negotiate the removal of the aggregate (e.g., consider offering to pay the reroofing costs).	
Architectural		
Will the facility be used as a shelter?	If yes, refer to FEMA 361.	
Are there interior non-load-bearing walls?	Design for wind load according to Section 3.3.3.3.	
Are there multiple buildings on site in a hurricane-prone region?	Provide enclosed walkways between buildings that will be occupied during a hurricane (Section 3.4.1).	
Are multiple elevators needed for the building?	Place elevators in separate locations served by separate penthouses (Section 3.4.4.1).	

Table 3-8: Checklist for Building Vulnerability of Critical Facilities Exposed to High Winds (continued)

Vulnerability Sections	Guidance	Observations
Structural Systems	Section 3.3.2	
Is a pre-engineered building being considered?	If yes, ensure the structure is not vulnerable to progressive collapse. If a pre-engineered building exists, evaluate to determine if it is vulnerable to progressive collapse.	
Is precast concrete being considered?	If yes, design the connections to resist wind loads. If precast concrete elements exist, verify that the connections are adequate to resist the wind loads.	
Are exterior load-bearing walls being considered?	If yes, design as MWFRS and C&C.	
Is an FM Global-rated roof assembly specified?	If yes, comply with FM Global deck criteria.	
Is there a covered walkway or canopy?	If yes, use "free roof" pressure coefficients from ASCE 7.Canopy decks and canopy framing members on older buildings often have inadequate wind resistance. Wind-borne debris from canopies can damage adjacent buildings and cause injury.	
Is the site in a hurricane-prone region?	A reinforced cast-in-place concrete structural system, and reinforced concrete or fully grouted and reinforced CMU walls, are recommended (Section 3.4.2).	
Is the site in a tornado-prone region?	If yes, provide occupant protection. See FEMA 361.	
Do portions of the existing facility have long-span roof structures (e.g., a gymnasium)?	Evaluate structural strength, since older long-span structures often have limited uplift resistance.	
Is there adequate uplift resistance of the existing roof deck and deck support structure?	The 1979 (and earlier) SBC and UBC, and 1984 (and earlier) BOCA/NBC, did not prescribe increased wind loads at roof perimeters and corners. Decks (except cast-in-place concrete) and deck support structures designed in accordance with these older codes are quite vulnerable.The strengthening of the deck attachment and deck support structure is recommended for older buildings.	

Table 3-8: Checklist for Building Vulnerability of Critical Facilities Exposed to High Winds (continued)

Vulnerability Sections	Guidance	Observations
Structural Systems	**Section 3.3.2 (continued)**	
Are there existing roof overhangs that cantilever more than 2 feet?	Overhangs on older buildings often have inadequate uplift resistance.	
Building Envelope	**Section 3.3.3**	
Exterior doors, walls, roof systems, windows, and skylights.	Select materials and systems, and detail to resist wind and wind-driven rain (Sections 3.3.3.1 to 3.3.3.4).	
Are soffits considered for the building?	Design to resist wind and wind-driven water infiltration (Section 3.3.3.3). If there are existing soffits, evaluate their wind and wind-driven rain resistance. If the soffit is the only element preventing wind-driven rain from being blown into an attic space, consider strengthening the soffit.	
Are there elevator penthouses on the roof?	Design to prevent water infiltration at walls, roof, and mechanical penetrations (Sections 3.3.3.3, 3.3.3.4, 3.3.4.1, and 3.4.4.1).	
Is a low-slope roof considered on a site in a hurricane-prone region?	A minimum 3-foot parapet is recommended on low-slope roofs (Section 3.4.3.4).	
Is an EOC, healthcare facility, shelter, or other particularly important critical facility in a hurricane-prone region?	If yes, a very robust building envelope, resistant to missile impact, is recommended (Section 3.4).	
Is the site in a tornado-prone region?	To minimize generation of wind-borne missiles, avoid the use of brick veneer, aggregate roof surfacing, roof pavers, slate, and tile (Section 3.5).	
Are there existing sectional or rolling doors?	Older doors often lack sufficient wind resistance. Either strengthen or replace. This is particularly important for fire station apparatus bay doors.	
Does the existing building have large windows or curtain walls?	If an older building, evaluate their wind resistance.	
Does the existing building have exterior glazing (windows, glazed doors, or skylights)?	If the building is in a hurricane-prone region, replace with impact-resistant glazing, or protect with shutters.	

Table 3-8: Checklist for Building Vulnerability of Critical Facilities Exposed to High Winds (continued)

Vulnerability Sections	Guidance	Observations
Building Envelope	**Section 3.3.3 (continued)**	
Does the existing building have operable windows?	If an older building, evaluate its wind-driven rain resistance.	
Are there existing exterior non-load-bearing masonry walls?	If the building is in a hurricane- or tornado-prone region, strengthen or replace.	
Are there existing brick veneer, EIFS, or stucco exterior coverings?	If the building is in a hurricane-prone region, evaluate attachments. To evaluate wind resistance of EIFS, see ASTM E 2359 (2006).	
Are existing exterior walls resistant to wind-borne debris?	If the building is in a hurricane-prone region, consider enhancing debris resistance, particularly if dealing with an important critical facility.	
Are there existing ballasted single-ply roof membranes?	Determine if they are in compliance with ANSI/SPRI RP-4. If non-compliant, take corrective action.	
Does the existing roof have aggregate surfacing, lightweight pavers, or cementitious-coated insulation boards?	If the building is in a hurricane- prone region, replace the roof covering to avoid blow-off.	
Does the existing roof have edge flashing or coping?	Evaluate the adequacy of the attachment.	
Does the existing roof system incorporate a secondary membrane?	If not, and if the building is in a hurricane-prone region, reroof and incorporate a secondary membrane into the new system.	
Does the existing building have a brittle roof covering, such as slate or tile?	If the building is in a hurricane-prone region, consider replacing with a non-brittle covering, particularly if it is an important critical facility.	
Exterior-Mounted Mechanical Equipment		
Is there mechanical equipment mounted outside at grade or the roof?	Anchor the equipment to resist wind loads (Section 3.3.4.1). If there is existing equipment, evaluate the adequacy of the attachment, including attachment of cowlings and access panels.	
Are there penetrations through the roof?	Design intakes and exhausts to avoid water leakage (Section 3.3.4.1).	
Is the site in a hurricane-prone region?	If yes, place the equipment in a penthouse, rather than exposed on the roof (Section 3.4.4.2).	

Table 3-8: Checklist for Building Vulnerability of Critical Facilities Exposed to High Winds (continued)

Vulnerability Sections	Guidance	Observations
Exterior-mounted Electrical and Communications Equipment		
Are there antennae (communication masts) or satellite dishes?	See Section 3.3.4.2. If there are existing antennae or satellite dishes and the building is located in a hurricane-prone region, evaluate wind resistance. For antennae evaluation, see Chapter 15 of ANSI/TIA-222-G-2005.	
Does the building have a lightning protection system?	See Sections 3.3.4.2 and 3.4.4.3 for lightning protection system attachment. For existing lightning protection systems, evaluate wind resistance (Section 3.6.3.1)	
Municipal Utilities		
Is the site in a hurricane-prone region?	See Section 3.4.5.1 for emergency and standby power recommendations.	
Is the emergency generator(s) housed in a wind- and debris-resistant enclosure?	If not, build an enclosure to provide debris protection in a hurricane-prone region (Section 3.4.5.1).	
Is the emergency generator's wall louver protected from wind-borne debris?	If the building is in a hurricane-prone region, install louver debris impact protection (Section 3.4.5.1).	
Is the site in a hurricane-prone region?	If yes, an independent water supply and alternative means of sewer service are recommended, independent of municipal services (Sections 3.4.5.2 and 3.4.5.3).	

3.8 REFERENCES AND SOURCES OF ADDITIONAL INFORMATION

NOTE: FEMA publications may be obtained at no cost by calling (800) 480-2520, faxing a request to (301) 497-6378, or downloading from the library/publications section online at http://www.fema.gov.

American Association of State Highway and Transportation Officials, *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals*, LTS-4-M and LTS-4-12, January 2001 and October 2003.

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American National Standards Institute/Telecommunications Industry Association, *Structural Standards for Antenna Supporting Structures and Antennas,* ANSI/TIA-222-G, August 2005.

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American Society for Testing and Materials, *Standard Practice for Installation of Exterior Windows, Doors and Skylights*, ASTM E2112, 2001.

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American Society for Testing and Materials, *Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware,* ASTM A153, April 2005.

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American Society for Testing and Materials, *Test Method for Field Pull Testing of an In-Place Exterior Insulation and Finish System Clad Wall Assembly*, ASTM E 2359, 2006.

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4.1 INTRODUCTION

This chapter presents some observations on the performance of critical facilities during Hurricane Katrina that identify the various ways in which building and equipment damage, as well as loss of municipal services, can disrupt facility operations. These observations are intended to help people who own, operate, design, and build critical facilities to adjust their building designs, construction, and facility management practices to reflect the needs of comprehensive risk reduction.

During Hurricane Katrina, surging floodwaters and high winds caused considerable and often catastrophic building damage, forcing many critical facilities to cease operations and evacuate their premises even before the storm had passed. In many instances the continued operation of hospitals, police and fire stations, schools, and EOCs was severely compromised by relatively minor damage to the building or building-mounted equipment. Although the structural components of most critical facilities survived the hurricane, other building components performed less well, causing serious disruptions.

The observations highlighted in this chapter, made by a team of building professionals (architects and engineers) experienced in hazard mitigation, document the variety and severity of the building damage, and the corresponding effects on facility operations. Field inspections and discussions with facility managers and other personnel served as the basis for analysis of the experiences of individual facilities. The descriptions of these experiences are accompanied with suggestions on possible mitigation measures that would improve hazard-resistance and protect the facility's functionality in the future. A comprehensive risk assessment of the facility's operation and building components and systems would be required before any specific mitigation measures were implemented. This chapter emphasizes the experiences and lessons learned from facility operation disruptions in particular circumstances, and may not be applicable to all situations.

4.2 HEALTH CARE FACILITIES

4.2.1 BACKGROUND

Health care facilities are at the front line of community protection, especially during and after a natural disaster event. Their capacity to continue to provide services to existing patients, and to respond to the needs of victims following a disaster, depends not only on protecting the integrity of the structure and the building envelope, but on the facilities' ability to carry out their intended functions with little or no interruption. Continued and uninterrupted operation of health care facilities, regardless of the nature of the disaster, is one of the most important elements of a natural disaster safety program.

Health care facilities, especially hospitals, are usually very complex building systems, because they accommodate diverse and highly specialized services in a strictly controlled environment. Hospital buildings must be designed to provide appropriate spatial arrangement for the flawless interaction between staff, patients, and visitors. They also require a complex network of technological infrastructure to support the hospital's functions. Even the smallest breakdown in this complex network can cascade into a serious disruption of operations.

Protecting the functionality of a hospital requires very careful facility planning and design that is in accordance with the most stringent flooding and high-wind mitigation requirements applicable to the site. The damage sustained by hospitals during

Hurricane Katrina emphasized the fact that many of the Nation's hospitals occupy old or inadequate buildings that may not be sufficiently protected against hazards. In particular, some of the hospitals were planned and built before mitigation against natural hazards became common practice.

Considering the expanding gap between the functionality of aging hospitals on the one side, and the requirements of new technologies and the needs of a growing and aging population on the other, it is expected that many of the country's hospitals will have to be replaced, upgraded, or rebuilt in the coming years. Some medical industry forecasts predict that by the end of the decade the United States will spend $20 billion annually for this purpose. Since new or rebuilt hospitals will have to last for a long time, the anticipated construction program provides an opportunity to rethink hospital planning and design, and to consider how to avoid hazard areas and reduce the vulnerability with improved hospital design.

The following observations are based on published sources at the time of Hurricane Katrina, and on the subsequent interviews with providers and regulators in both Louisiana and Mississippi. The damage assessments present a picture of common effects on the medical facilities, which are consistent across the region affected by Hurricane Katrina. Generous contributions by the following institutions and their staff are acknowledged:

- St. Tammany Parish Office of Homeland Security and Emergency Preparedness (Covington, Louisiana)
- Touro Infirmary (New Orleans, Louisiana)
- West Jefferson Medical Center (Jefferson Parish, Louisiana)
- Hancock Medical Center (Bay St. Louis, Mississippi)
- Garden Park Medical Center (Gulfport, Mississippi)
- Guest House of Slidell (Slidell, Louisiana)
- Slidell Memorial Hospital (Slidell, Louisiana)

- LSU Health Sciences Center (New Orleans, Louisiana)

- Charity Hospital (New Orleans, Louisiana)

- University Hospital (New Orleans, Louisiana)

4.2.2 EFFECTS OF FLOODING

The damage caused by Hurricane Katrina flooding was significantly more serious than the damage caused by wind. Along the Gulf Coast, the storm surge was higher than previously experienced, which caught many health care providers by surprise (see Figure 1-2). In most places, the storm surge flooding receded in several hours, but in New Orleans the floodwaters remained for more than a week. Apart from the damage and disruption caused by floodwaters that penetrated the facilities' lower levels, many hospitals in New Orleans were completely surrounded by floodwaters, which cut off all surface access.

As a result of the disrupted access, most hospitals had to manage on their own, without any assistance from the outside. Patients and visitors were stranded, along with staff that could not be relieved for days. The injured, and others in need of emergency care, could not be brought in for treatment. Family and friends of people stranded in the hospitals had no way of communicating with them. Food, water, medical, and other supplies could not be brought in except by small boats and helicopters, or in some instances, by military vehicles. The evacuation of the critically ill patients, and eventually others, was possible only by boat or by helicopter. Hospitals with dedicated or improvised elevated helipads managed the evacuation much better than others.

Hospitals and nursing homes that were inundated during Katrina experienced the greatest damage. Hospital functions located in the areas exposed to floodwaters had to be shut down. In many cases, the elevators and other mechanical and electrical services were shut down by the floodwaters.

Flooding caused considerable disruption of utility services in most hospitals in the New Orleans area. Sewers flooded or pumping stations shorted out, disabling sewage and liquid waste disposal.

The water supply was interrupted and, in many instances, onsite sources were contaminated and could not be used for drinking purposes. Emergency generators and electrical switchgear equipment, as well as underground transformers flooded and were put out of commission.

In several instances, communications panels and other controls were located on the first floor and shorted out. The heat and the buildup of humidity in New Orleans ruined the telephone connections and the fire alarm systems in some hospitals, even though floodwaters did not contact sensitive communications equipment directly.

4.2.3 EFFECTS OF HIGH WINDS

In general, three types of wind damage affected the hospitals: damaged roof coverings, rooftop equipment, and window breakage. Damaged roof coverings that were either peeled off or punctured by wind-borne debris exposed the interior to rainwater penetration and additional damage. Similarly, rooftop equipment displaced by wind left unprotected roof openings exposed to rainwater penetration. Water damage ranged from saturation of interior surfaces, like walls and ceilings, to ruined equipment and considerable mold growth.

Window breakage during the storm was particularly dangerous, because it allowed the penetration of rainwater, and wind that can cause pressurization in the interior. Hospital patient rooms, however, faced the greatest risks from window breakage, because many of their occupants could not be moved away from monitors, medical gases, and other equipment.

4.2.4 SITE DESIGN

Although most of New Orleans is located in the lowlands that are protected by a system of canals and levees, the hospitals were not built to resist the flooding caused by levee failures. As a result of Hurricane Katrina and the failure of levees, only 3 out of more than 20 of the city's hospitals remained open during the storm (see Figure 4-1). Only one of these, the Touro Infirmary, was not completely surrounded by water, retaining access on one side. Access problems affected all hospitals. West Jefferson Medical Center had planned to deploy their staff in two shifts, to allow the second shift to stay at home until the storm had passed and then come to relieve the staff locked down in the hospital. Because of impeded access, the relief staff could not get to the hospital, which put an added burden on the initial staff, already nearing exhaustion.

Figure 4-1: University Hospital surrounded by 4 feet of water

Figure 4-2: Evacuation of New Orleans by helicopter

Hancock Medical Center in Bay St. Louis, Mississippi, although located outside of the 500-year floodplain, experienced 3-foot deep flooding as a result of the storm surge (see Figure 4-3). Access to the hospital was disrupted long before Katrina made landfall because, prior to the storm arrival, there was a 33-mile traffic backup on the road leading out of town. Access was important because all the functioning hospitals needed relief supplies, medical gases, water, and fuel for their emergency generators. In many cases, the only way to resupply the facilities was by air, using large Chinook helicopters. These helicopters are too heavy for most roof structures, and to use them for emergencies in the future, a second helipad may be necessary on the site, requiring sufficient glide angles for landing and takeoff of the largest aircraft.

Access to emergency services was also blocked by the water and, in some cases, by trees and utility lines that were knocked down. Once the hospitals had access restored, they were deluged by the injured from nearby communities. Slidell Memorial Hospital administered 40,000 tetanus shots in the days after the storm. Hancock Medical Center saw 600 to 700 patients a day for up to 2 weeks after the surge water receded.

Figure 4-3:
The lobby of Hancock Medical Center was under 3 feet of water.

Perhaps the most serious consequence of the impeded access was the way it affected the evacuation of hospitals in New Orleans. Serious disruptions in hospital operations required immediate evacuation, which could not take place because the streets were not accessible for up to 5 days. There was a critical need for a helipad, either on the roof or an equivalent landing area on a parking structure, with emergency lighting for night operation. Elevated parking structures were a great asset, providing both a protection for the vehicles and a convenient helicopter landing site on the roof. They were especially useful if the parking structure had an elevated pedestrian bridge to the hospital.

4.2.5 ARCHITECTURAL DESIGN

A typical hospital configuration is based on access requirements that usually place the emergency department on the first floor in order to receive walk-in patients or those brought in by ambulances. Clinical laboratory and imaging are frequently on the first floor as well, as are surgery and intensive care units in many smaller hospitals. All of these are vital services in the event of an emergency and for providing routine patient care. Location on the first floor frequently exposes them to additional risks from natural hazards, especially flooding, as became evident during Hurricane Katrina.

Building configuration and general shape frequently contribute to high-wind damage. Protrusions and projections in walls and roofs cause additional wind turbulence that increases uplift pressures. The penthouse at West Jefferson Medical Center illustrates the vulnerability of projections and corners to high winds (see Figure 4-4). Large portions of metal cladding came loose because they were not designed or constructed to resist these loads.

Canopies, which most hospitals have over drop-off areas, are particularly susceptible to uplift and other damage, if not designed to resist the loads (see Figure 4-5). Glass-enclosed lobbies and atria, common to many hospitals, also proved to be a hazard, because of the large areas of usually unprotected glazing that could easily shatter under the impact of wind-borne debris. In many cases, these areas were closed during the storm, thereby cutting off a major point of access to the hospitals.

Figure 4-4:
Penthouse at the West Jefferson Medical Center

Figure 4-5:
Canopy soffit damage at West Jefferson Medical Center

At Louisiana State University Hospital, the emergency generators in the basement were flooded and shut down, which put the entire hospital out of commission. Similarly, all the major mechanical equipment in Charity Hospital in New Orleans was in the basement, including fifteen 5,000-watt emergency generators. The hospital had to be evacuated soon after the basement flooded and the emergency power supply failed. Touro Infirmary, however, had the emergency power generators located on the third floor. This allowed them to run most of the critical systems, including the air conditioning, without interruption until the generators broke down from prolonged use and contaminated fuel supplies.

Critical operations such as emergency and surgical departments, recovery rooms, ICUs, and other patient bed units and laboratories should not be located in areas below ground or below the elevation of possible flooding and storm surge. These critical functions should be located on upper floors or in areas where communication between floors is easily accomplished. These areas should have no windows, or should have protected glazing to prevent window breakage and rain water penetration.

4.2.6 BUILDING ENVELOPE

Building envelope damage during Hurricane Katrina was widespread and included uplifted roof coverings and flashing, roofing punctured by flying debris or overturned roof-mounted equipment that led to extensive rainwater penetration, wall cladding separation, and window and door breakage.

The building envelope on the Garden Park Medical Center in Gulfport, a relatively new building opened in 2000, sustained considerable damage from 130-mph winds during Hurricane Katrina. The estimated wind speed may appear to have been close to the current design wind speed of 135 mph for this facility, but the actual pressures were below the current design pressures as a result of the 1.15 importance factor required for hospitals. Wall cladding consisting of EIFS was blown off in several areas, allowing water to penetrate wall cavities (see Figure 4-6). Extensive use of EIFS, despite a long track record of failure during hurricanes, contributed to significant damage from water penetration. EIFS is a popular wall cladding system, but not strong enough to prevent damage from wind-borne debris in cases where EIFS is applied over studs. In addition, EIFS design or construction deficiencies frequently make it insufficiently resistant to suction pressures caused by high winds. This is especially significant for hospitals, where such damage can allow water penetration and trigger serious disruptions in the mechanical and electrical systems and damage the building interior. Hospitals in hurricane-prone regions that have EIFS should have field testing performed to evaluate its attachment.

Figure 4-6:
Repair of EIFS wall covering on Garden Park Medical Center

Hancock Medical Center suffered damage to the wall sheathing behind the exterior brick veneer. This damage resulted from standing water at significant depths in various locations around the building. The sheathing retained moisture long enough to compromise its integrity through swelling, and to support the growth of mold and bacteria. There have been numerous examples of the failure of brick veneer. The reasons for this include corroded brick metal ties, insufficient number of metal ties installed, or ties not adequately embedded in the mortar.

Many hospitals have low-slope roofs. There have been many instances of failure of this type of roof, frequently beginning at the edge flashing and progressively spreading to other parts of the roof. Roofs are also susceptible to puncture, as happened at the Hancock Medical Center and Garden Park Medical Center (see Figure 4-7). Rubber walkway pads were blown away and the roof membrane was punctured in several places by displaced equipment and other flying debris. As a result, a substantial amount of water leaked through the roof openings into the top floor, causing considerable damage to the interior. In addition, the aggregate surfacing blew off, damaging glazing on surrounding buildings.

Figure 4-7:
Roof membrane starting to peel off at Hancock Medical Center.

Hancock Medical Center lost substantial portions of its metal roofing. Patients had to be relocated from the top floor to lower floors because of roof leakage (see Figure 4-8). West Jefferson Medical Center lost portions of roofing on the Psychiatry building, when the metal roof covering partially peeled off. The leading edge began to peel back, but did not go any further than the edge flashing, so a minimal amount of water penetrated through the roof. The psychiatry building was not occupied at the time because the hospital evacuated the building before the hurricane landfall.

Figure 4-8:
Roof damage on Hancock Medical Center

The primary cause of window breakage was wind-borne debris. (see Figure 4-9). West Jefferson Medical Center had 76 windows broken, mainly by flying aggregate. Intensive care patients had to be moved to the recovery room in the interior of the building and away from windows. The Psychiatry building had rainwater penetration through windows, even though they were not broken.

Although many important hospital functions are located away from the exterior windows, wind-blown rain can damage expensive equipment even when it is located some distance from the broken window (see Figure 4-10). At West Jefferson Medical Center, the fitness center building sustained $250,000 worth of damage that resulted from water driven through the broken windows and from 30 days of high humidity, before the air-conditioning was restored.

Exterior doors were often pushed in by floodwaters and blown open and damaged by wind pressure. Breakaway doors are particularly vulnerable to opening in high-wind conditions, as wind pressure can build up through the unsecured doors. Ground floor entrance doors at Hancock Medical Center had to be blocked by sandbags and two-by-fours, both on the inside and the outside, to stay closed (see Figure 4-11). The penthouse door at Garden Park Medical Center in Gulfport was blown off its hinges by strong winds.

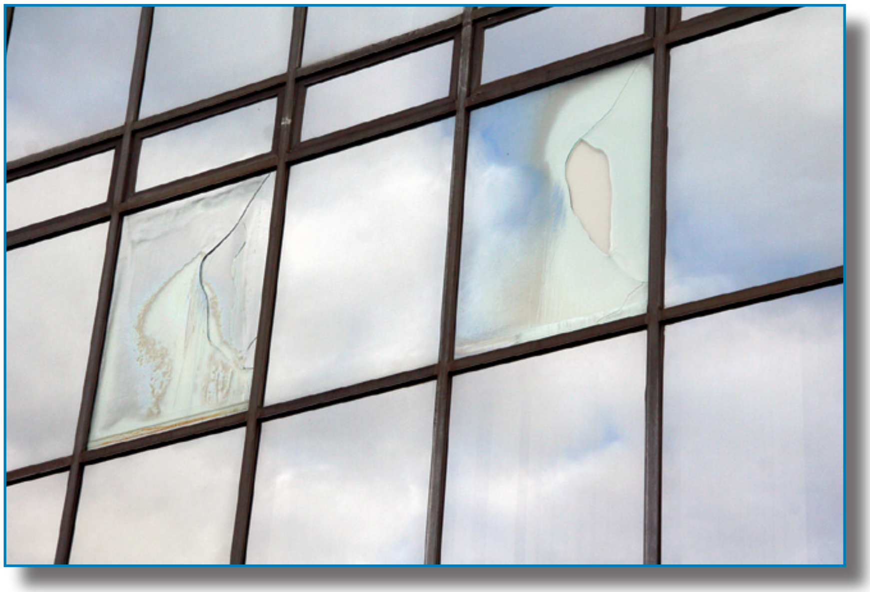

Figure 4-9:
Broken windows at Touro Infirmary

Figure 4-10:
Broken windows at West Jefferson Medical Center

Figure 4-11:
Blocked doors at Hancock Medical Center

Hancock Medical Center lost numerous fan cowlings and other rooftop equipment, which left openings in the roof. Water penetrated the building through these openings, reaching the first floor, and damaged boilers and other equipment. Vent openings in the elevator penthouse in Touro Infirmary were blown off, allowing water penetration. The water damaged the electrical and mechanical equipment and controllers, shutting down the elevators.

West Jefferson Medical Center lost a number of cowlings and other covers causing water damage to equipment in the rooms below the roof. Some motors were sealed and continued to work during the storm.

All rooftop equipment should be safely secured to the curb and stay in place during a high-wind event. Equipment that has a high failure rate in high-wind events includes air-conditioning condensers, HVAC units, exhaust fans and air intake and exhausts.

4.2.7 UTILITY PLUMBING SYSTEMS

Hospitals depend heavily on municipal services and other utilities. While it is possible to go into a minimal function mode and still maintain patient safety, certain utility systems must be operable. In many cases, Hurricane Katrina and the subsequent flooding pushed hospitals beyond the limits of even a minimal function mode. Many had to be shut down, and the patients and staff had to be evacuated. In addition to the loss of electrical power, the most common problem in maintaining the operations proved to be the failure of water supply and sewer systems.

Most hospitals lost water within a day or two following Hurricane Katrina's landfall. Even when the water service was restored, it was suspected of contamination. Drinking water was in short supply in many hospitals. West Jefferson Medical Center received three truck loads of bottled water from a local retailer in the aftermath of the storm, but other hospitals suffered from serious shortages. A running water supply is critical for boilers to produce steam for sterilizing; for the chillers for the air-conditioning system; and for sanitary uses like toilets, washing dishes and linens, bathing patients, etc. The most successful hospitals had their own wells from which they pumped water using an emergency power supply. The hospitals that stayed without water and an emergency power supply had to evacuate patients as quickly as possible. As a consequence of this experience, West Jefferson Medical Center is planning to install two wells to provide both sufficient capacity and redundancy. One well will service the central plant boilers and chillers, and the other will be dedicated to hospital operations.

Potable water service will likely be shut down during and immediately after an event because of line breakages, lack of power to run pumping stations, or repair delays because of blocked roads and access routes. Hospitals, especially those in hurricane-prone regions, need a back-up water supply system in the form of:

- Wells for exclusive hospital use should be supplied with their own emergency generator to run the well pumps.
- Water storage or water recycling systems on site should serve as a back-up to the central water supply.

In many areas, the sewer system broke down shortly after the storm arrived, either because of loss of power required to run municipal pumping stations, sewage back-up or shut down of sewage treatment plants as a result of flooding, or because uprooted trees broke the sewer lines. When the water and sanitary waste systems were disabled, patients and staff were required to use hazardous waste bags (red bags) taped to buckets or toilet bowls to manage bodily waste. At West Jefferson Medical Center, used bags were stored in the hallways for several days and then buried on the hospital site for later disposal.

Hospital design in hurricane-prone regions should also take into consideration the need to provide an onsite sewage-diversion and storage system to prevent sewer backflows from disrupting hospital sanitary system operations. Field observations indicate that in situations where the sanitary sewer system may be damaged, causing a disruption in service, functionality may be protected by:

- Installation of an onsite septic tank as a sanitary back-up system
- Installation of backflow devices in the sanitary lines to prevent sewage from backing up into the hospital
- Designating, as part of the operations plan, a limited number of sanitary systems to use in the hospital, so the onsite storage tank does not fill too quickly
- Creating holding ponds for direct pumping of sewage, if sufficient site area is available

4.2.8 MECHANICAL AND ELECTRICAL SYSTEMS

Hurricane Katrina struck at a time when the temperatures during the daytime reached 95°F. Air-conditioning systems in hospitals were generally not connected to the emergency power supply, nor was there any flexibility to switch emergency power from one system to another to provide some relief. The heat build-up was a significant factor in creating difficult conditions for patients and staff (see Figure 4-12).

Lack of air-conditioning also allowed humidity to build up, which caused problems with switchgear, computers, and other electronic equipment. In many cases dehumidifying and cooling could not resume for months after the event. The excessive humidity damaged the electronic components of mechanical and electrical equipment, such as fire alarm systems, elevator switchgear, or the telephone switchgear, as happened in Touro Infirmary. Mold growth in conditions of high temperatures and humidity caused further damage. At West Jefferson Medical Center, rainwater and high humidity caused considerable damage to the fitness center, requiring all the electrical equipment to be replaced. The ground floor at Hancock Medical Center was flooded 3 feet deep; enough to cover all electrical outlets close to the floor. The damage was irreparable.

Figure 4-12:
Toppled HVAC equipment at Charity Hospital, New Orleans

Air-conditioning systems were also disrupted by a lack of water needed for water-cooled chillers, as happened in Garden Park Medical Center in Gulfport when the municipal water service was shut down. Loss of air-conditioning resulted in interior condensation, and warm and humid air interfered with the normal functioning of electronic medical equipment.

Measures to provide sufficient HVAC capacity for patient-occupied and support areas and to protect the operation of the hospital from humidity-related damages include the following:

- Install emergency electrical generators with capacity to run the air conditioning system. This might also require water for the chillers if this is the method of delivering cold air.

- Install sufficient controls in the hospital to be able to identify the areas with mold and mildew problems, and have them cordoned off quickly.

- Install HVAC duct cleanout locations, so that any mold or mildew that begins to grow in the ductwork can be easily cleaned out.

- Create air-conditioning zones (where practical), so that crucial operations can be cooled with a minimum amount of air-conditioning.

In a storm of Katrina's magnitude, it is expected that power would be lost almost immediately and for a considerable period of time thereafter. For example, Touro Infirmary lost power within minutes of being hit with wind gusts of about 60 mph. Since power is so vital to maintaining functionality in critical facilities during normal periods, it is of paramount importance to provide an emergency power supply for all critical hospital functions.

Most hospitals store up to 72 hours of emergency fuel on site. In the case of Hurricane Katrina, emergency generators needed to run continuously for 5 days or more. Many hospitals had to obtain fuel for their generators from outside sources, usually the military. West Jefferson Medical Center got fuel from a nearby Navy ship. Hancock Medical Center had one of their underground emergency generator fuel tanks flooded, with water covering the fill cap and all vent openings. They could not use this tank, fearing that contaminated fuel would damage the power generators.

The capability to switch power to different locations at different points in time is one of the most important features of emergency power supply systems. However, most of the wiring systems in facilities affected by Hurricane Katrina were not set up with this capability. Emergency power in most cases was not available to run the air-conditioning systems. Redundancy in the emergency power systems that would have allowed maintenance and repair without disruption was lacking in most cases.

Portable generators, where they existed, were invaluable. They could be moved around as needed, but the problem of outside ventilation was difficult to overcome when the power was required away from vent openings. Use of generators indoors is extremely dangerous and should not be attempted in any circumstances.

More and more hospitals are dependent on computerized systems for patient medical records, transmission of X-ray film and other images, reporting laboratory results, patient physiological monitors, and a myriad of other uses. Once the power is lost, these systems are shut down unless they are on emergency power.

Piped oxygen and nitrous oxide supplies are essential for many patients. With electrical systems out, pumping of medical gas was not possible. Most of the hospitals maintained tanks of oxygen that could be brought to the bedside (Figure 4-13), but once the emergency supplies of medical gas ran out, the patients at serious risk had to be evacuated.

The experience of hospitals during Katrina indicates that the requirements for emergency power should have high priority. Generators should be located above the base flood elevation, be protected from flying debris, and have appropriate exhaust vent systems installed. Fuel storage tanks should be located above the flood elevation, or adequately anchored to ensure that the tank will not float off its foundation under pressure from rising floodwaters. Hospitals in hurricane-prone regions should store sufficient fuel to support running generators at full load for at least 96 hours (4 days). Emergency power distribution systems should be able to provide power to every system in the hospital, and have switching capabilities to shift loads to different parts of the hospital as needed.

Figure 4-13: Oxygen supplies at Hancock Medical Center

4.2.10 COMMUNICATIONS SYSTEMS

Hospitals have a variety of communications systems in addition to the usual telephone and e-mail systems. Many of these are for emergency communications with ambulances and other emergency support services. These include satellite telephones, government line telephones, ham radios, internal radio systems, nurses' call systems, and wireless systems of various sorts. Communications systems are critical for medical uses, but during a storm like Katrina, the ability to contact family members and friends to check on their status meant a lot to both the staff and the patients. The importance of being able to get news from outside, to request restocking of supplies, and to arrange evacuation of patients became obvious in the aftermath of Katrina.

One consistent theme in damage reports was that satellite dishes were toppled, rendering satellite phones, one of the main sources of emergency communications, inoperable. Antennae used for emergency communications frequently broke, disconnecting the hospital systems from the outside world. Hancock Medical Center lost not only the satellite dish, but also the dish for the education system and its television antennae. West Jefferson Medical Center lost only one antenna.

External communication isn't the only important link that can be broken during a hurricane. Internal communications (for example, from surgery to the nursing floor, or from the nursing floor to the supply storage areas) are critical to maintain functionality.

At Hancock Medical Center, the only means for internal communications were 5-Watt Motorola radios. These continued to work well, and were relied upon exclusively when the telephone switchgear flooded and broke down. West Jefferson Medical Center also used radio communication that continued to work throughout the storm. Cellular phones also worked, until the transmission tower was toppled. Hospitals that had ham radio operators bring their equipment in, or had a ham radio set-up in the hospital, found this system very important and useful. Several hospitals plan to have ham radios available for future emergencies.

Charity Hospital and West Jefferson Medical Center lost their computers because the computer network power supplies were not wired into the emergency power supply grid. John Hancock Medical Center also lost its computers when the ground floor flooded (see Figure 4-14).

Since many communication systems are dependent on external networks that may be out of commission, roof antennae should be well anchored, or mounted inside of penthouses. Satellite dish antennae may have to be taken down prior to a hurricane and put back after the storm had passed. Finally, redundancy of systems is important, as proven during Katrina—one system may work where others do not.

Figure 4-14: Damaged computer network equipment at Hancock Medical Center

4.2.11 NONSTRUCTURAL AND OTHER SYSTEMS

Nonstructural systems, among others, include interior non-load-bearing walls, ceilings, and floors. In hospitals flooded with storm surge, floors were destroyed and gypsum board walls were soaked. At Hancock Medical Center the water level reached 3 feet. The hospital must replace all the flooring material, rewire the outlets, and replace the wall sheathing at a level about 2 feet above the high water mark (see Figure 4-15).

In many hospitals humidity buildup damaged floor and ceiling tiles. Touro Infirmary had to replace 60,000 square feet of tile flooring and all of the ceiling tiles in the hospital because of humidity damage. The loss of air-conditioning at West Jefferson Medical Center caused the buildup of humidity in the air, leading to water condensation on terrazzo floors, making them very slippery.

Security was a major issue for most New Orleans hospitals. Members of the community naturally sought the hospital for shelter when their homes were destroyed. When the water rose, people trapped in the city followed the water's edge to the Touro Infirmary and West Jefferson Medical Center, where crowds of people congregated on the front doorsteps. Attempted break-ins and looting were reported, which prompted hospitals to barricade doors, post armed guards at entrances, and "lock down" so that no one could either enter or leave. At University Hospital, the doors were removed and the entrances sealed up.

Hospitals that allowed families to come in with the staff for the duration of the storm encountered numerous problems after a few days. Many of the family members became restless because hospitals had no appropriate accommodations for them. This became a security problem, as it was important to keep guests away from the patients and their caregivers.

Figure 4-15:
Drying of flooded ground floor at Hancock Medical Center

Fire safety should be a concern during a storm since the fire risks are usually greater than at other times. Although the fire alarms are normally connected to emergency power, other types of damage made them inoperable. At Touro Infirmary, the build-up of humidity knocked out the electronic components of the fire alarm system. After the storm, 470 points needed to be repaired before the system was fully operational again. At West Jefferson Medical Center, the fire alarm system was undamaged, but the line to the fire station was cut. Heat-activated fire suppression systems continued to function where sufficient water pressure was available, but dry standpipes might not have been supplied with water in the event of a fire. Directional signs in many hospitals were blown away. In the rush for care after the hospitals were accessible, it was necessary to put up temporary signage to route the large volume of visitors and patients to the right destination.

4.2.12 SUMMARY

The General Accounting Office (GAO) report to Congress on the evacuation of hospitals and nursing homes noted that administrators should "consider several issues when deciding to evacuate or to shelter in place, including the availability of adequate resources to shelter in place, the risks to patients in deciding when to evacuate, the availability of transportation to move patients and of receiving facilities to accept patients, and the destruction of the facility's or community's infrastructure." For new facilities, most of these issues can and should be addressed during site selection, risk assessment, and application of the appropriate planning and design recommendations described in this manual. For existing facilities, careful evaluation and consideration of the recommendations provided in this manual should help ensure greater resilience during flooding and high-wind hazard events. In this way, communities can continue to depend on these facilities both for the care of existing patients and the care of people in disaster emergencies.

4.3 EDUCATIONAL FACILITIES

4.3.1 BACKGROUND

Educational facilities are considered critical facilities because, apart from their vital role in educating children, they are frequently used during and after a storm as emergency shelters, or as staging centers by the National Guard, law enforcement personnel, or critical infrastructure repair crews for emergency operations. Educational facilities, in this case mostly K-12 school buildings, are generally equipped with food preparation facilities, well distributed sanitary facilities, and ample space for personnel and equipment.

The primary function of a place of refuge shelter is the protection of the occupants during a storm. This function is dependent on preservation of the structural integrity of the building and the building envelope. The failure of a structural component or a breach in the building envelope can lead to casualties and can make the buildings unusable as a recovery shelter after the storm.

Educational facilities planned for use as place of refuge shelters must, above all, protect the lives and well-being of evacuees. To do so, they must be constructed to withstand storm surge or inland flooding and wind impact. This means that they must be located in areas that minimize these storm effects. If they are located in the areas subject to flooding and high-wind hazards, they need to be constructed to preserve full functionality, with uninterrupted electricity, communications, water, and sanitary service. This will also allow them to serve as recovery shelters. Educational facilities that may not have served as shelters during the storm, because of their proximity to the coast or their susceptibility to inland flooding, may be useful as recovery shelters provided they are able to survive the hurricane intact.

The primary function of a recovery shelter is to provide a location for resources and manpower after the storm has passed, to centralize the command and distribution functions for recovery work in the community. Recovery shelters require that all building functions and services remain usable in the aftermath of a storm. They are often used by the American Red Cross (ARC), National Guard, or other government agencies as a distribution point of first aid, food, water, and other supplies. They also serve as management or information dissemination hubs concerning recovery efforts.

The following facilities were visited for the preparation of this manual:

- Charles P. Murphy Elementary School (Pearlington, Mississippi)
- Pass Christian Middle School (Pass Christian, Mississippi)
- St. Stanislaus High School (Bay St. Louis, Mississippi)
- Northbay Elementary School (Bay St. Louis, Mississippi)
- Hancock High School (Kiln, Mississippi)
- Pineville Elementary School (Pass Christian, Mississippi)
- D’Iberville High School (D’Iberville, Mississippi)
- D’Iberville Middle School (D’Iberville, Mississippi)
- Lyman Elementary School (Gulfport, Mississippi)
- East Hancock Elementary School (Hancock County, Mississippi)
- Saucier Elementary School (Saucier, Mississippi)
- Port Sulpher School (Port Sulpher, Louisiana)

4.3.2 EFFECTS OF FLOODING

The most devastating damage to educational facilities during Hurricane Katrina was caused by the storm surge. FEMA reported a storm surge of 20 to 30 feet above normal tide levels. In some places the flooding extended up to 6 miles inland. The effect on coastal communities was catastrophic, because most buildings within a quarter of a mile of the shore were virtually washed away, while most of the remaining buildings beyond this area were severely damaged. Virtually all of the educational facilities in Pass Christian, Mississippi, were heavily damaged as a result of their proximity to the coastline.

Inland flooding occurred in low-lying areas farther away from the coastline. D'Iberville Middle School had approximately 8 feet of water, but was not used as a shelter because the school district staff was aware of the potential for flooding from past experience. The structural integrity of the school was not compromised by the flooding, but the water damage to the interior was substantial (see Figure 4-16).

Figure 4-16:
D'Iberville Middle School was flooded to the depth of 8 feet

The experience of Hurricane Katrina shows that the damage caused by rising water generally renders shelters uninhabitable and useless, further aggravating the recovery process. In most cases the mechanical and electrical systems were disabled as a result of flooding, which allowed the internal temperatures to reach intolerable levels. Additionally, the flood-induced back-flow of plumbing systems created unsafe sanitary conditions in most of the facilities.

4.3.3 EFFECTS OF HIGH WINDS

Hurricane Katrina reached maximum gust wind speeds of 130 mph at landfall, with hurricane force winds extending outward 105 miles from the center of the storm (FEMA, 2006). Numerous tornadoes were also spawned by the hurricane, contributing to further damage as the storm moved northward. There were 11 tornadoes recorded in Mississippi, with 17 more in Georgia, and 4 in Alabama. Current model building codes in the areas affected by Hurricane Katrina generally require buildings to be designed to meet 120 to 150 mph design wind speeds. Some buildings, however, were constructed prior to the implementation and enforcement of the current model codes.

Wind damage was most evident on the building envelope, especially roofs, walls, doors, and windows, as well as other exterior elements, such as walkway canopies and exposed mechanical and electrical equipment. The extent of the damage was dependent on the force of the wind, the type of construction, and the configuration of the buildings. Once a building envelope was breached, the interior of the building sustained additional damage, both as a result of pressurization and rainwater penetration. The most severe damage in the interior was observed on the least durable finishes, such as acoustical ceilings, wood doors and trim, and building contents such as office equipment, furniture, and books.

Most of the educational facilities used as place of refuge shelters suffered wind damage to the roofs and windows. When a portion of the roof was lost or a window was broken, rainwater was able to enter the building, causing damage to the interior. In some instances, the occupants were forced to relocate to other buildings during the storm, because of the danger of progressive building failure (see Figure 4-17).

Figure 4-17:
Broken windows at
D'Iberville High School

4.3.4 SITE SELECTION

Most educational facilities that were destroyed or severely damaged by Katrina were located in the areas subject to storm surge flooding. Ideally, educational facilities used as shelters should not be located in floodplains, but since they must be located in proximity to the neighborhoods they serve, some are built on flood-prone sites. Even if buildings can be elevated to reduce the potential for damage, the surrounding area remains susceptible to flooding, which could prevent access and disrupt the delivery of emergency aid. This also underscores the need to provide multiple routes to and from a facility, in case of roadway blockage following a storm.

Pineville Elementary School near Pass Christian, Mississippi, was used as a place of refuge during the storm, but when the water rose to a depth of 2 feet, the people had to be moved by school buses to another shelter (see Figure 4-18). The buses were driven by school bus mechanics struggling to maintain control in rising water and 80 mph winds.

The schools in Pass Christian—mostly one-story buildings located in mapped flood hazard areas—sustained heavy damage from storm surge flooding. The massive storm surge devastated parts of Northbay Elementary School in Bay St. Louis, Mississippi, a single-story building located in a mapped flood zone. Exterior walls collapsed, and most of the interior and contents were destroyed (see Figure 4-19).

Figure 4-18:
Pineville Elementary School shelter had to be evacuated when the floodwaters started to rise.

Figure 4-19:
Exterior walls at Northbay Elementary School

St. Stanislaus High School in Bay St. Louis, although located right on the coast, was on naturally higher ground, and only the first floors were affected by the storm surge. Within a few months after the storm, the second floors in some of the buildings had been repaired, including restored power, water, and sanitary service, and were back in use (see Figure 4-20).

Figure 4-20:
Lower floors washed away by the storm surge at St. Stanislaus campus

Considerable damage occurred in low-lying areas that were flooded by storm surge ranging in depth from 2 to 8 feet. Such was the case at D'Iberville Middle School in D'Iberville, Mississippi, which sustained severe damage, including the destruction of many exterior walls, when water rose to nearly 8 feet above the floor. Fortunately, it was not used as a shelter, unlike the nearby D'Iberville High School, which is a designated shelter. The high school is built on higher ground and was not affected by flooding.

4.3.5 ARCHITECTURAL DESIGN

Generally, educational facilities have centrally located corridors (with classrooms or other spaces on both sides) that have ready access to sanitary facilities, are at least 8 to 10 feet wide, and are free of all obstructions. These features make them ideally suited for emergency shelter use. Although there are a few exterior openings that can be breached by a storm, the hallways are generally well protected from outside elements. It should be pointed out, however, that in situations where the roof or the exterior walls fall, interior corridor walls may collapse as well. The corridors are usually unfurnished and readily available for a variety of functions. They served well as safe areas during the storm, with only a few notable exceptions. At the D'Iberville High School, the corridors had unprotected windows at each end. These windows were broken during the storm and it was necessary to move people into another building. Unfortunately, there were no enclosed walkways or interior corridors connecting the buildings, and it was necessary to go outside into the storm to reach the other building. Similarly, when the roof structure at Lyman Elementary School shelter started to fail, it became necessary to take the refugees outside before they could reach safety in another building (see Figure 4-21).

For hurricane shelter safety, it would be beneficial to have all of the buildings connected with enclosed corridors, to allow safer movement between buildings during a storm. Other components of the building envelope would have to be sufficiently resistant to wind and wind-borne debris impact to protect the occupants and the services they need. School corridors in particular should either have impact-resistant (or protected) windows or none at all. All exterior doors should also be designed to meet hurricane wind loads and wind-borne debris impact requirements, as described in Section 3.4.3.1).

Figure 4-21:
Collapsed portion of the Lyman Elementary School Building

4.3.6 STRUCTURAL SYSTEMS

Most of the educational facilities observed were one-story buildings with concrete slab-on-grade foundations constructed using concrete masonry load-bearing walls and steel-framed roofs. The roof joists were supported either by masonry walls or steel beams. Some facilities, like the East Hancock Elementary School, used pre-engineered systems consisting of rigid steel frames supporting a standing seam metal roof. Pass Christian Middle School and Saucier Elementary School used structural steel frames with standing seam or built up roofs. St. Stanislaus High School, located on the coast, had a concrete structural frame where the first floor was heavily damaged by the storm surge, but the foundations, concrete structure, and the upper floors survived. This was because the buildings on campus were located on higher ground than the surrounding area.

The storm surge exerted tremendous forces on the buildings in its path, first as the water rose, and again when it receded. The forces were strong enough to knock down exterior masonry walls, as happened in the Northbay, Charles B. Murphy, Pass Christian, and Plaquemines Parish schools (see Figure 4-22). In most cases, the main structural components survived with little or no damage.

Figure 4-22: Damaged exterior walls at Charles B. Murphy Elementary School

Designing the connections between structural components according to loads is critical to maintaining the load path and the structural integrity of school buildings in hurricane-prone regions.

4.3.7 BUILDING ENVELOPE

Newer educational facilities located some distance from the coast sustained mainly wind-induced damage to the building envelope, primarily to roof coverings and windows. Facilities located along the coastline were hit by the storm surge that destroyed most of the building envelope on the ground floor, including large sections of exterior walls. The walls collapsed under flood loads that exceeded all expectations.

At Charles P. Murphy Elementary School, many of the infill masonry walls were displaced, and the concrete slabs on grade were uplifted and severely cracked in several classrooms (see Figure 4-23). A similar slab failure also occurred at D'Iberville Middle School. The cause of this type of failure was an increase in upward hydrostatic pressure below the slab, causing it to burst upward.

Figure 4-23:
Cracked concrete floor slab at Charles B. Murphy Elementary School

The St. Stanislaus High School campus consists of several buildings that used different exterior wall systems, including masonry and precast concrete panels. The masonry walls on the first floor were heavily damaged by the storm surge, but it appears that the precast concrete panels withstood the force of the hurricane much better (see Figure 4-24). Large sections of the exterior masonry walls at St. Stanislaus, as well as in Northbay Elementary in Bay St Louis and Port Sulphur schools in Plaquemines Parish, collapsed under the pressure from storm surge (see Figure 4-25).

Figure 4-24:
Precast concrete paneling at St. Stanislaus High School

Figure 4-25:
Collapsed exterior masonry wall at Port Sulphur school campus

The exterior brick veneer walls at the Pass Christian Middle School and at St. Stanislaus cracked and separated from the wall framing under the impact of storm surge (see Figure 4-26). This kind of damage usually results from a failure of brick ties that did not manage to hold the brick in place. In many cases these attachments can corrode and allow the brick veneer to move under lateral pressure. Such damage allows the penetration of water into the interior, where additional damage to building contents is inevitable.

The wind-induced damage was limited primarily to the roof components at the edge, such as flashing and coping. More substantial damage occurred on a building at St. Stanislaus campus and at Harrison 9th Grade gym, where large sections of metal roof covering were blown away (see Figure 4-27). The standing seam metal roof panels peeled back and away from the roof framing, exposing the interior to rainwater and additional wind damage.

Typically, glazed doors, windows, and roof coverings are the building envelope components most susceptible to damage caused by wind-borne debris. Although glass or shutters designed to resist such wind-borne debris are available, none of the educational facilities had protection on the windows and doors. The corridor windows at D'Iberville High School were broken during the storm, which prompted the complete evacuation of the building.

Figure 4-26:
Cracked brick veneer at
St. Stanislaus High School

Figure 4-27:
Metal roof covering peeled away at a St. Stanislaus campus building

For buildings located in flood hazard areas, especially areas not subject to storm surge, elevation well above the predicted flood level is the most effective damage-reduction measure. Dry floodproofing may be used to provide some degree of protection, although if floodwaters rise higher than the designed level of protection, the damage can be catastrophic. This technique, generally feasible for flood depths of only 2 or 3 feet, is expensive and difficult to implement on existing buildings. Depending on the expected depth of water, local soil properties, and the size and location of openings, the facilities can be designed to limit water infiltration through the walls, openings, and conduits, and prevent envelope failure due to excessive hydrostatic pressure. Dry floodproofed buildings must have detailed emergency plans, with clear instructions for deployment of devices and other measures. Lack of periodic maintenance can render floodproofing measures ineffective.

Another alternative for minimizing structural damage to existing buildings is to provide wet floodproofing. This approach, which is not allowed for new construction, allows water to flood the lower floors protected with water-resistant materials and finishes that can be easily cleaned and restored.

4.3.8 UTILITY SYSTEMS

Educational facilities are typically not equipped with emergency back-up systems, but are mostly dependent on municipal water and sanitary systems. The breakdown of municipal water and sewer services, caused by power outages which shut down water treatment plants and pumping stations, adversely affected most of the facilities. Although a few of the facilities affected by Hurricane Katrina were served by onsite wells and some had septic systems, lack of power prevented their full use. The sanitary sewer system backed up under pressure from floodwaters and, together with the loss of water service, created great difficulties inside facilities used as shelters.

The sanitation problems, especially the unpleasant odors that permeated the facilities, combined with high humidity and heat, posed a serious health risk. At the D'Iberville High School, the loss of water prompted volunteers to haul buckets of water from a nearby ditch to be used for flushing the toilets. After the storm had passed, portable toilets and showers were brought in by the ARC.

4.3.9 MECHANICAL AND ELECTRICAL SYSTEMS

Most mechanical systems depend on the exterior equipment mounted on the roof or attached to the exterior walls. The exposed equipment is the most vulnerable element in the system, because it is commonly damaged by floodwaters, strong wind, and wind-borne debris. Rooftop equipment, such as air-handling units and exhaust fans, typically were not adequately anchored to meet the hurricane-force winds and were frequently damaged or toppled. Through-wall fan coil units installed below classroom windows at the Charles P. Murphy Elementary School in Pearlington were ruined by rising floodwaters (see Figure 4-28).

As a result of HVAC failures, conditions in shelters became very unpleasant because of the heat build-up and the lack of ventilation. The interior temperatures and humidity rose to unbearable levels because of the hot weather that followed Hurricane Katrina. Without the advantage of sufficient natural ventilation, the atmosphere quickly became stuffy. Undamaged mechanical equipment, especially HVAC systems, was not operational because of the power outage and the lack of emergency power supply. At D'Iberville High School, the principal reported using a generator to run a large portable box fan in the corridors to provide some relief. The same generator also provided power for night-time lighting in the corridors.

The Harrison County School District office was one of the few buildings equipped with a generator, and for that reason it was used as an EOC. It served as a command center and provided sleeping and dining facilities for emergency crews. The success of this experience reinforces the importance of having emergency power generator systems and a sufficient fuel supply. Emergency generators should be in a protected enclosure and at an elevation high enough to prevent flooding.

Figure 4-28: Damaged HVAC unit at Charles B. Murphy Elementary School

4.3.10 NONSTRUCTURAL AND OTHER SYSTEMS

It is essential to the operation of educational facilities used as place of refuge and recovery shelters that communications systems remain operational. The place of refuge shelters had a variety of communications systems at their disposal at the beginning of the storm. This included the phone system, cellular telephones, school system radios, and police and fire radios. These systems proved to be unreliable during the storm when antennae and utility lines were damaged. Immediately after the storm, all communications had to be handled through messengers, until portable antennae were brought to restore both cell phone and radio service. The Harrison County school board is now considering the purchase of satellite phones to be used during emergencies.

Nonstructural components and contents of educational facilities sustained the greatest damage from flooding. At D'Iberville Middle School, all interior wood doors, frames, trims, casework, fan coil units, and furniture typically suffered severe damage from water exposure.

The majority of interior walls were constructed of un-reinforced concrete masonry. Portions of these walls and some exterior non-load-bearing walls at Charles P. Murphy Elementary School were knocked down by the storm surge (see Figures 4-29 and 4-30). If the buildings had been occupied during the storm, people could have easily been injured by falling debris. Although many of these walls are used as partitions and are consequently not load-bearing, their mass poses a threat to life and property should they collapse.

Figure 4-29: Damaged non-load-bearing walls at Charles B. Murphy Elementary School

Figure 4-30:
Interior damage at Charles B. Murphy Elementary School

4.3.11 EQUIPMENT AND AUXILIARY INSTALLATIONS

School equipment is not necessarily important for the operation of emergency shelters, except for kitchen and dining facilities. Schools that sustained flooding damage usually had all their food preparation and refrigeration equipment ruined. The equipment stored outside consists mainly of buses and other vehicles.

In Pass Christian, many of the school buses stationed in the town were destroyed by the storm surge (see Figure 4-31), although some of them were used during the storm to move people from Pineville Elementary School to another shelter because of rising water.

The Harrison County School District moved all of its buses farther inland before the storm, which ultimately proved prudent and allowed the buses to remain available for use after Katrina. In the aftermath, Harrison County School District had no fuel supply to operate the buses or other vehicles. Several years ago, the school district opted to issue gasoline cards to the bus drivers to fill up at various gas stations rather than at a central depot. After the storm there were few gas stations operating, and it became a time-consuming process to get fuel for any vehicle. In the future, Harrison County School District intends to have its own gasoline supply available on generator power to ensure that school vehicles are kept operational.

Figure 4-31:
School bus washed away
by the storm surge

4.3.12 SUMMARY

Educational facilities intended to serve as emergency shelters, together with accompanying parking lots and access roads serving these shelters, should be located inland, away from the coast, and on high enough ground to avoid flooding. Educational facilities that are built closer to the shore because of the school district boundaries should be constructed with the first floor above the highest expected storm surge level. These educational facilities should not be used as shelters during a hurricane, but could serve as relief centers after the storm, as long as they do not sustain significant damage. No educational facilities should be constructed within the immediate area along the shore, where waves are the strongest.

Based on observations, the most resilient school buildings are built using reinforced concrete structural systems, or reinforced masonry construction. The best performing roof decks were cast-in-place concrete, precast concrete, or concrete topping over metal deck. Reinforced concrete or reinforced concrete masonry exterior and interior walls, including precast concrete panels and tilt-up concrete wall panels, seem to have sustained the least flood damage. Other observations indicate that the following measures may help reduce the damage in hurricane-prone regions:

- Doors should be designed to meet the positive and negative design wind pressure and impact resistance, as recommended in Section 3.4.3.1. Windows should use impact-resistant glazing or shutters.

- Educational facilities that will be occupied during a hurricane or needed within a few weeks afterwards should be equipped with an emergency generator.

- All shelters should have protected communications systems linked to the EOC.

- Exterior corridors should be enclosed to allow full access between buildings, so that no one is forced to go outside during a storm to get to another area of a building.

- All educational facilities intended for use as evacuation shelters should be designed according to FEMA 361 guidelines.

4.4 EMERGENCY RESPONSE FACILITIES

4.4.1 BACKGROUND

Emergency response facilities include EOCs, police stations, and fire rescue stations. All of these facilities are considered critical because they must remain functional to manage response and recovery operations during and after a hazard event. EOCs function as incident command centers for coordination and support of all emergency activities. The command and response personnel must remain on duty, in full readiness for action both during and in the aftermath of a disaster. In addition to personnel and resources, EOCs house the information and communications systems that provide feedback to the emergency managers to help them make decisions about efficient and effective deployment of resources. They also relay information to local residents, shelters, media, and other first responders, while providing Continuity of Government (COG) and Continuity of Operations (COOP).

Police and fire rescue facilities are critical to disaster response, because an interruption in their operation as a result of building or equipment failure may prevent rescue operations, evacuation, assistance delivery, or general maintenance of law and order, which can have serious consequences for the community.

While each of the three types of emergency response facilities is used for different operational purposes and their needs are different, most of them require and depend on the following facilities:

Back-Up Communications Equipment: Conventional communications that rely on radio towers with repeater systems cannot be relied upon during high-wind events, because of the high probability that the towers will lose power, as occurred in many jurisdictions in Mississippi and Louisiana. All facilities need back-up communications systems such as very high-frequency (VHF) and ham radios, and adequate back-up communications equipment.

Accommodation Space: Adequate space for all the essential personnel to work, with provisions made for continuous operations, such as sleep areas, kitchens (with supplies for all duty personnel), laundry facilities, and shower facilities for all such personnel. It should also be noted that many residents view the local fire station as a point of shelter, and will seek it as a refuge when winds and conditions become dangerous in their own homes.

Situation Rooms: "Meeting rooms" in which to conduct local government business as well as confer with community members, media, and government officials, and for press conferences and dissemination of information.

Safe Equipment Storage: Patrol and rescue vehicles and other equipment must be adequately protected from flood waters, wind-borne debris, and driving rain, and be accessible and readily available for emergency use.

The observations included in this section are based on the examination of the following facilities:

- Harrison County EOC (Gulfport, Mississippi)
- Jackson County EOC (Pascagoula, Mississippi)
- New Orleans EOC (New Orleans, Louisiana)
- Hancock County EOC (Bay Saint Louis, Mississippi)
- Orleans District Levee Board Police Department (New Orleans, Louisiana)

- New Orleans Police Department (New Orleans, Louisiana)
- Gulfport Police Department (Gulfport, Mississippi)
- Pass Christian Police Department (Pass Christian, Mississippi)
- New Orleans Fire Department (New Orleans, Louisiana)
- Gulfport Fire Department (Gulfport, Mississippi)
- Pass Christian Fire Department (Pass Christian, Mississippi)
- Cuevas Volunteer Fire Department (Pass Christian, Mississippi)
- Back Bay Fire Company #3 (Biloxi, Mississippi)

4.4.2 EFFECTS OF FLOODING

Flooding during Hurricane Katrina, especially the impact of the storm surge and levee failures, caused heavy damage that disrupted the long-term functional capabilities of the emergency response system.

The facilities damaged by rising water were generally rendered uninhabitable after the water receded. As a result, the emergency response teams were forced to relocate the operations elsewhere. Evacuation and relocation was common among damaged fire rescue and police facilities and affected their operations on many levels. Firstly, relocating farther away from their service areas meant that the response time to emergency calls increased substantially. Secondly, the response teams were forced to operate from temporary accommodations with inadequate facilities that were frequently overcrowded. Thirdly, new facilities lacked adequate supplies and services for the extra personnel, which required numerous improvisations, further hampering the operations.

4.4.3 EFFECTS OF HIGH WINDS

The highest gust wind speeds during Hurricane Katrina were typically below the design wind speeds for this area, which range from 120 to 150 mph. Despite this, many emergency response facilities sustained damage that disrupted their operations, and in a few cases shut down the facility. Most of the damage was confined to the building envelope. Portions of metal roofing were lifted and peeled off; aggregate roof surfacing was blown off, becoming wind-borne debris; and roof-mounted equipment, including communication towers and antennae, were toppled or broken. Metal wall-cladding panels detached or peeled off on a number of facilities, exposing the interior to pressurization and rainwater penetration. Doors and windows were damaged by wind-borne debris, allowing the penetration of wind-driven rain.

4.4.4 SITE SELECTION

Ideally, the emergency response facilities should not be located in a floodplain or a site exposed to other types of hazards. However, emergency response facilities, especially fire rescue and police stations, must contend with geographic limitations pertaining to size and adequate coverage of their service areas that frequently place them in hazardous locations. Many of the facilities flooded during Katrina were located in designated floodplains. However, this fact alone does not explain the catastrophic damage sustained by facilities such as the police and fire stations in Pass Christian, Mississippi (see Figure 4-32), because most of the facilities damaged by flooding were built above the minimum required elevations. The primary reason for the widespread damage is the catastrophic nature of the flooding, caused by extremely high storm surge and the failure of levees in New Orleans.

In locations where the emergency response facilities were built to a higher standard than required by local regulations, the adverse effects of Katrina were substantially reduced. The Jackson County EOC occupies the second floor of a municipal building located in Pascagoula, Mississippi. An examination of the storm surge flooding associated with different hurricane scenarios indicated that the site would be inundated during a Category 3 hurricane. Consequently, the county decided to design the building to be approximately 4.5 feet above BFE (see Figure 4-33). During Hurricane Katrina, floodwaters rose to about an inch below the level of the lowest floor. The building was not evacuated prior to the storm, because it was believed that flooding would not exceed the maximum levels recorded during Hurricane Camille. As floodwaters started to rise, the decision was made to evacuate most of the occupants to another building across the street. Despite this action, the EOC operations were not hampered significantly.

The Pass Christian police and west side fire station were less fortunate, as the storm surge flooding at these sites far exceeded the base flood elevation. It was estimated that the storm surge wave that hit the police building was at least 15 to 20 feet high, which rendered the building and the equipment stored inside totally unusable. The facility is currently looking at an alternative site on higher ground as a possible site for relocation and construction of a new station.

The headquarters of the New Orleans Police Department had approximately 2- to 3-foot deep water on the first floor, and a completely flooded basement (see Figure 4-34). The surrounding areas were also under water, isolating the facility and preventing its normal operation. All operations had to be transferred to other police facilities in the city.

Figure 4-32:
Police station in Pass Christian

Figure 4-33:
Jackson County EOC

Figure 4-34:
New Orleans Police Department Headquarters

The Hancock County EOC in Bay St. Louis, Mississippi, is located on naturally high ground outside mapped flood hazard areas. Nevertheless, the floodwaters inundated the ground level, damaging the interior finishes and practically destroying all equipment and contents (see Figure 4-35). Most of the EOC's operations were transferred to an alternate location prior to Katrina's landfall, most likely because the facility is mapped as part of an evacuation zone in case of a hurricane.

Figure 4-35:
Hancock County EOC

Site characteristics and landscaping contributed significantly to the extent and type of damage sustained by these facilities. The Gulfport Fire Station #5 in Gulfport, Mississippi, experienced significant disruption because of downed trees. One tree fell on the roof, causing minor damage, while two vehicles parked outside were severely damaged by the fallen trees. Furthermore, it took approximately 12 hours of cutting the trees before firefighters were able to open the access road and start responding to emergency calls. This experience also underscores the need to provide multiple routes into and away from a site, in order to have redundancy and minimize the possibility of isolation as a result of roadway blockage.

The experience during Hurricane Katrina proved the efficacy of preventive evacuation of equipment and personnel to a safe and secure location. It also proved wise to organize back-up facilities in other locations or in adjacent jurisdictions to serve as alternative command and operation centers. Emergency response facilities that did so were better equipped to respond to citizens' needs immediately after the storm.

4.4.5 ARCHITECTURAL DESIGN

Many buildings used as emergency response facilities were not initially designed for that purpose, or for operations under emergency conditions. During and after Hurricane Katrina, most of them experienced significant problems, irrespective of the level of damage. Some of these facilities are located in existing buildings designed as regular office space. These facilities performed poorly, and although they were able to adapt to the circumstances, they did not operate as efficiently as those designed for their particular functions.

For example, EOC facilities in New Orleans were placed into civic center offices, which were not equipped with kitchens, showers, and other facilities essential for the smooth and continuous operation of an EOC (see Figure 4-36). As a consequence, the facility had to be relocated immediately after Katrina because the available accommodations were insufficient and poorly equipped. Some of the buildings occupied by first responders were originally designed for a different purpose and subsequently converted to their current use.

Figure 4-36:
New Orleans EOC in the City Hall building

Generally, any building, whether new or old, that is used as an emergency response facility should be carefully reviewed for compliance with the requirements for uninterrupted operation of the facility. Particular attention should be paid to issues that have historically caused problems in building or operational performance, such as:

- Roof systems not designed for high winds and debris impact
- Rooftop equipment
- Unprotected exterior glazing
- Large, sectional and rolling doors not designed for high winds
- Communications towers
- Large roof overhangs
- Lack of facilities for an extended length of stay, especially emergency sanitary facilities and power supply

Basements are another design feature with a high damage potential, especially when important services and facility functions are located there. The basement at the New Orleans Police Department completely flooded, and all the essential equipment located there was severely damaged, crippling the facility for a long time. Observations indicate that essential functions and service equipment should be transferred from flood-prone basements to safer locations.

The relatively new Back Bay Fire Company #3 station in Biloxi, Mississippi, was built in 1996, and yet its design does not reflect the current needs of its occupants. The spaces are too small to accommodate the duty shifts. The kitchen is inadequate for longer stays, while the sleeping area has unprotected, large, storefront-type windows that represent a serious hazard in high-wind situations (see Figure 4-37). These minor architectural deficiencies may be amplified during the times of crisis and adversely affect the operation of the facility, especially if combined with other building component failures.

Figure 4-37:
Back Bay Fire Company #3

4.4.6 STRUCTURAL SYSTEMS

Concrete and reinforced masonry have traditionally been the most robust structural systems for hurricane-prone areas, since they have a much higher reserve structural strength than other systems. During high-wind conditions, the added weight of the concrete helps counteract the uplift forces, while the mass and depth of concrete and masonry walls provides reserve structural strength that prevents the walls from being breached during high winds and flood conditions. However, with precast concrete elements, attention to design and construction of connections is important. This was generally confirmed during Hurricane Katrina.

The Jackson County EOC, located in Pascagoula, Mississippi, was built in 1977 and is an example of a structurally well-designed facility. The structure is composed of cast-in-place concrete, and performed remarkably well (see Figure 4-38). Although the EOC is located on the second floor of the building, water only came within 1 inch of the ground floor, which is approximately 4 to 5 feet above the surrounding grade. Other structural systems proven to be resistant to flood and wind loads are steel or concrete frames that are covered with precast concrete panels. These systems have very high reserve capacities that perform extremely well during high winds and storm surges.

Figure 4-38:
Reinforced concrete building for Jackson County EOC

In contrast, pre-engineered metal buildings performed less well. Although the main structural components of most of these buildings remained standing, suffering only light damage, the rest of the building components were not able to resist the forces of storm surge. Two prime examples of these buildings are the Pass Christian Police Department Headquarters and the Gulfport Fire Department Station #7 (see Figures 4-32 and 4-39). Both of these buildings were severely damaged and all equipment stored inside was destroyed.

Based on the observations, many existing structures can be retrofitted to perform better during high winds. Although such retrofits may be expensive and generally have limited capacity to strengthen the structure, they definitely increase the overall structural resistance. For example, roof decking can be retrofitted with additional connections to provide increased uplift resistance. Furthermore, roof decks should be attached securely to make the building diaphragm work as a unit and transfer loads adequately to the walls, while simultaneously preventing the deck from being pulled from the structure during high winds.

Figure 4-39:
Gulfport Fire Station #7

4.4.7 BUILDING ENVELOPE

When the building envelope is breached, the interior is no longer protected from the outdoor environment and the whole building is exposed to additional forces that may cause its progressive collapse.

The Gulfport Police Department Headquarters and the Pass Christian Police Station are the prime examples of building envelope failure. Both buildings, located near the coast, were exposed to the storm surge that crushed the lightly built exterior walls and destroyed everything in the interior. Fire Station #7 was breached by the storm surge, and practically the entire building envelope was washed away, except for the roof deck. What remained of the building was just a shell (see Figure 4-40). The duty personnel and most of the vehicles were relocated to other facilities until a trailer was provided as a temporary place of operations.

On the other hand, the Gulfport Police Department Headquarters building, constructed with heavy concrete masonry walls, sustained no significant damage to the building envelope. The building only required restoration of flooded building components.

Figure 4-40:
Exterior walls on the Gulfport Fire Station #7 washed away by the storm surge

Longbeach Police Station sustained heavy damage to its roof trusses, metal roof, and siding that allowed wind and rainwater to saturate the interior of the building. The police officers had to scramble to evacuate the prisoners and valuable records before they abandoned the building in the middle of the storm (see Figure 4-41).

Figure 4-41:
Longbeach Police Station

Third District Fire Station in New Orleans is a newer one-story, structural steel-framed building with brick veneer walls, metal fascia panels, steel roof deck, rigid plastic foam roof insulation, and metal roof panels. The estimated maximum wind speed at this location during Hurricane Katrina was significantly lower than the design wind speed. Nevertheless, a large portion of the metal roof covering was blown off the apparatus bay (see Figure 4-42). In some areas, the architectural metal wall panels with standing seams covered by snap-on battens were still in place, but the batten covers had broken away. In other areas, the batten covers were still attached, but they had lifted—it appeared that fatigue cracks occurred along the standing seams (see Figure 4-43). Battens like these are frequently susceptible to blow-off, which allows water infiltration and may lead to panel blow-off. Both the battens and separated panels may become dangerous wind-borne debris. This station was occupied at the time of the storm, but because of the extensive damage to the interior, apparatus bay doors, and the equipment, it could not be used and was consequently evacuated.

Figure 4-42:
Metal roof and wall panels peeled off the Third District Fire Station in New Orleans

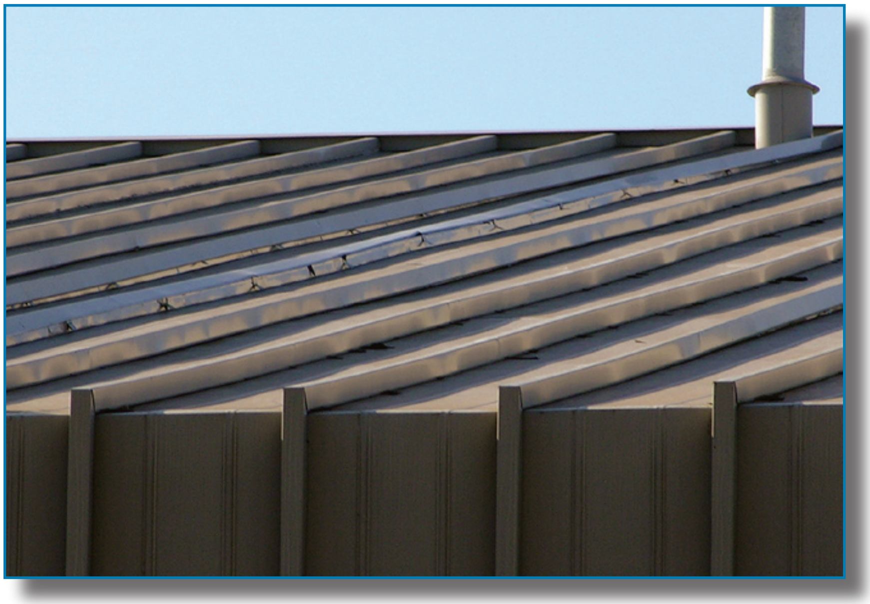

Figure 4-43:
Lifted batten covers on Third District Fire Station metal roof

Although the estimated wind speed in Bay St. Louis was slightly lower than the design wind speed, the wind blew off most of the roof membrane from the Hancock County EOC, located in the city (see Figure 4-44). The damage was initiated with the separation of metal edge flashing that had an uncleated vertical face. In addition to roof damage, the hardware on the exterior door failed and the door blew inward. As a result of rainwater penetration and flooding, most of the interior was ruined. Although most of the facility operations were moved before hurricane landfall, the remaining building occupants had to be evacuated during the event.

Jackson County EOC in Pascagoula experienced similar damage to its roofing when the metal edge flashing peeled off and lifted portions of the roof membrane. However, the roof damage did not cause water damage, because the cast-in-place reinforced concrete roof deck was capable of resisting rainwater penetration. The building's reinforced concrete walls and roof deck resisted the wind loads very well. The walls and roof deck were also extremely resistant to wind-borne debris, as was the exterior glazing retrofitted with shutters that protected the openings.

The edge flashing on low-slope roofs that usually initiates the peeling of roof membranes can be easily retrofitted with additional screws, to prevent it from uplifting and causing a progressive failure of the roofing system.

Figure 4-44:
Roof damage at Hancock County EOC

Fire stations are especially susceptible to breaches of the building envelope, because of their large sectional and rolling doors that are usually not strong enough to resist wind forces, and even less so the hydrodynamic forces of storm surge. The apparatus bay doors failed in many fire stations affected by flooding. (see Figures 4-39 and 4-45).

Water and wind from the storm were able to penetrate the buildings when the doors were breached, causing subsequent damage to other systems and equipment. Large doors should be designed to withstand wind pressures and windborne debris impact as recommended in Section 3.4.3.1.

All doors and windows can also be replaced with modern, impact-resistant systems that would reduce the chances of building pressurization and rainwater infiltration, which resulted in heavy losses to equipment and contents during Katrina. Rooftop units that were blown off and damaged the building envelope by puncturing the roof covering should be securely anchored to prevent such damage in the future.

Figure 4-45:
Damaged apparatus bay doors at Port Sulphur Volunteer Fire Department.

4.4.8 UTILITY PLUMBING SYSTEMS

Failures of public utility systems during Katrina were very common. Many first responder facilities were forced to improvise short-term solutions until public utilities were restored. The Gulfport Fire Department Headquarters was able to back-feed water into its lines by isolating the building's water supply lines from the public municipal supply system. They then fed water directly into the building's water lines in order to have water to shower and wash during the two weeks that they were without water in the facility. This capability should be considered for all emergency response facilities, as it minimizes disruption of basic sanitary functions.

In many facilities, flooding caused sewage to backflow into buildings, causing sanitary crises that directly affected their operations. Valuable time was spent cleaning up the facilities instead of helping others. To prevent this from occurring in future events the installation of backflow inhibitors (check valves) is recommended.

The Pass Christian Fire Department managed the loss of sanitary systems with plastic bags and buckets, while the staff at the Gulfport Police Department was able to acquire and use portable toilets and bottled water until public utility systems were restored. The Jackson County, Mississippi, EOC is equipped with a pressurized underground tank for toilets and washing, which supported the occupants during the 3 to 4 weeks that the facility was without water.

The Cuevas Volunteer Fire Department in Pass Christian, Mississippi, was equipped with an underground septic tank, a drain field, and a well, and did not experience significant disruptions in its plumbing and fresh water systems. These independent septic and fresh water systems do not rely on public municipal systems, and are preferred where possible as they virtually eliminate the chances of disruption during widespread outages.

4.4.9 MECHANICAL AND ELECTRICAL SYSTEMS

Hurricane Katrina also affected facilities by damaging or destroying mechanical systems. Hurricane season occurs in the warmest months of the year, and many of these facilities were not designed to allow natural ventilation. For example, the New Orleans Police Department Headquarters Building is a multi-story building where the main circuitry for the HVAC system, which was located in the basement, was severely damaged by the flood. Since the building was designed as a closed structure, natural ventilation was a problem (see Figure 4-46). All the equipment located in the basement needed to be completely rebuilt or replaced before the building could be occupied again. In the interim, the entire department was forced to relocate its operations to other facilities in the city, placing a strain on facilities not intended to house additional personnel and take on additional responsibilities.

The inability to air-condition buildings because of damaged mechanical and electrical systems allowed internal temperatures and humidity to reach intolerable levels, and in many buildings mold began to form.

Loss of electrical power during and after Hurricane Katrina affected all other essential facility systems. Examples of this were evident at all of the sites visited. Utility, mechanical, and communications systems became partially or completely unusable, either because emergency power was not available, or it had to be rationed as a result of overload or breakdown of generators.

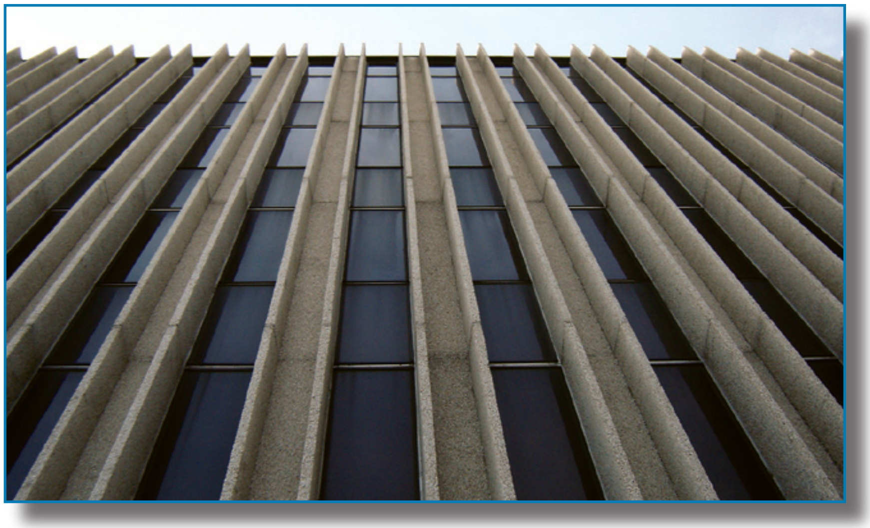

Figure 4-46: Fixed windows on New Orleans Police Department Headquarters

Cuevas Volunteer Fire Department, located inland at Pass Christian, Mississippi, was without municipal power for approximately 2 to 3 days, but, since its generator functioned properly, their operations were only slightly affected by the storm. In contrast, the indoor generator and electrical panel at the Back Bay Fire Company #3 in Biloxi, Mississippi, became submerged in the flood, even though the generator was mounted several feet above the finished floor. The water flooded the building, putting all the mechanical and electrical equipment, including the generator, out of commission. As the water continued to rise, the firefighters and the local residents that sought refuge in the station had to climb to the top of fire engines until the floodwaters receded.

The New Orleans District 3 Fire Department Headquarters lost power as a result of flooding. The generator was located outside at grade level, and was ruined when approximately 2 feet of water flooded the area (see Figure 4-47). The firefighters were forced to relocate to the nearby West Bank facility for 4 months, until power was restored at the headquarters building.

Facilities that escaped deep flooding were typically operational immediately upon restoration of power. The Gulfport Fire Department Station #1 had water barely enter the station, and was able to get by on their generator for 3 days until municipal power was restored. Although their radios worked intermittently, they were able to perform their search and rescue duties and use their newly acquired chainsaws to help clear the roads of debris.

Figure 4-47:
Generator mounted at grade level damaged by flooding

The need to provide a back-up generator at a safe and elevated location is confirmed by the experiences during Hurricane Katrina. Many facilities were without power because of the low elevation and subsequent flooding of their generators. Jackson County EOC had its emergency power station elevated and protected in a separate enclosure, which allowed the facility to operate without interruption (see Figure 4-48).

Figure 4-48:
Jackson County EOC's elevated generator enclosure

4.4.10 COMMUNICATIONS SYSTEMS

It is essential for the operation of emergency response facilities to keep their communications systems intact. Loss of communication capability prevents their primary function of responding to community needs and adversely affects their ability to coordinate their actions. If the communications system malfunctions or becomes unavailable, the coordination between command centers will be hindered, affecting management of the response and recovery operations during and after an event. Many jurisdictions in New Orleans and along the Gulf Coast were cut off from each other and could not communicate, even with their own departments. For example, one police officer from the Orleans District Levee Board Police Department was in the heart of New Orleans when the city was flooded, and had no way of communicating with the senior officials in his department. He worked for days with the officers of the New Orleans Police Department (NOPD) assisting the remaining residents in the city. For a period of days, he and his partners from NOPD were operating without communications capabilities of any sort until the military arrived and issued them new radios. It took approximately 2 to 3 weeks for communications to be re-established in a manner that resembled normalcy.

The command and communications center for the police and fire rescue departments in Pass Christian, Mississippi, was located in the police department building, and was crippled as a result of the destruction of their headquarters (see Figure 4-49). The landline communications at the Jackson County, Mississippi, EOC continued to function for a day or two, and other communications systems only experienced minor problems. The building was used during and after the storm.

Hurricane Katrina experience indicates that alternative forms of communication need to be available during and in the aftermath of a storm. High-frequency and ham radios that do not rely on repeater systems should be in place, along with detailed instructions and plans for their use in emergencies. Emergency power supply for communications systems must be available at all times. This relatively low-cost solution would reduce the loss of communications during and after future events.

Figure 4-49: Broken communications masts at Pass Christian Police Station

4.4.11 EQUIPMENT AND AUXILIARY INSTALLATIONS

Specialized equipment such as vehicles, rescue equipment, and fire pumps were the most common types of equipment lost during Hurricane Katrina. Damage to vehicles and other equipment seriously affected the operations, and frequently prevented speedy rescue and response efforts.

In many cases throughout Mississippi and Louisiana, the vehicles were stored immediately outside on facility parking lots while most of the specialized equipment was stored inside in apparatus bays. In other cases, as in Pass Christian, Mississippi, the police department stationed its vehicles in a remote location that was thought to be safe, but the entire area flooded and all vehicles were rendered useless. In Pass Christian the fire department, located approximately a quarter of a mile from the coastline, had four firefighting trucks and two rescue trucks ruined during the storm, hampering firefighters' efforts in responding to emergencies that required the use of their equipment. Gulfport Police Department and the New Orleans District Levee Board Police Department deployed their vehicles all over the area to ensure that the vehicles would be available on short notice after the storm.

For the 2006 hurricane season, Pass Christian emergency response plans include the evacuation of all vehicles to a staging site away from the coastline, and away from trees and other objects that may become wind-borne debris. This geographic distancing of vehicles from the coastline (and the area affected most by the storm and its surge) will protect key equipment and reduce the impact of a future storm by allowing the first responders to be mobile shortly after the event. It should be noted, however, that many jurisdictions in low-lying areas do not have safe staging sites at higher elevations or away from the coastline.

Based on conversations with many emergency response crews that were affected by Katrina, the protection of their equipment and vehicles was a main consideration prior to the storm. Many jurisdictions throughout Mississippi and Louisiana decided to spread their vehicles out to many locations thought to be safe, in order to be certain that at least some of them would remain operational. This practice proved prudent and enhanced their abilities to respond in the immediate aftermath of the disaster. The vehicles should be sheltered in an area that is safe from flooding hazard and easily accessible after the event.

4.4.12 SUMMARY

Emergency response services are at the backbone of a community's ability to protect and save the lives and property of its citizens in any crisis. The provision of these services depends on the uninterrupted operation of emergency response facilities during and after a hazard event. This means not only that the buildings that house the crews and equipment must survive the onslaught of flooding and high winds with minimal damage, but that all the equipment and systems necessary for emergency operations must remain fully functional.

Hurricane Katrina showed that emergency response facilities have a better chance of protecting their operations if they occupy solidly constructed buildings with sufficient reserve structural capacity that cannot be easily overwhelmed by a storm of this magnitude. It also showed that facilities with functional generators were better equipped to respond after the storm than those that were left completely without power. Since the facilities cannot operate without adequate emergency power supply, all electrical systems should be connected to power back-ups, and emergency generators should be elevated and protected against floodwaters and wind-borne debris.

Mechanical systems need to be located in a sheltered area, where they will not be damaged by wind and flooding. Plumbing systems should be equipped with backflow inhibitors to prevent sewage from entering the structure during a flood. Provisions should also be made to allow the isolation of the building's water supply, so that it is possible to feed water directly into the building's water lines until municipal water supplies are restored.

Finally, the lines of communication between community command centers and individual facilities must remain functional at all times. The basic communications systems need to be protected against the effects of flooding and high-winds as much as possible, but as this storm showed, system redundancy is still the best policy. In the event of damage, the facilities should have alternative means of communication that do not depend on local systems and networks that could be damaged in the storm.

ACRONYMS A

AASHTO	American Association of State Highway and Transportation Officials
ABFE	Advisory Base Flood Elevation
ADA	Americans with Disabilities Act
ARC	American Red Cross
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
ASCE/SEI	American Society of Civil Engineers' Structural Engineers Institute
BFE	Base Flood Elevation
BIA	Brick Industry Association
BUR	Built-Up Roof
C&C	Components and Cladding
CMU	Concrete Masonry Unit
DFE	Design Flood Elevation
EIFS	Exterior Insulation Finish Systems
EOC	Emergency Operation Center
EPDM	Ethylene Propylene Diene Monomer
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map

FIS	Flood Insurance Study
FMA	Flood Mitigation Assistance
FMG	Factory Mutual Global
FMR	Factory Mutual Research
HMGP	Hazard Mitigation Grant Program
IBC	International Building Code
ICC	International Code Council
ICU	Intensive Care Unit
LPS	Lightning Protection System
MEPS	Molded Expanded Polystyrene
MOB	Medical Office Building
MWFRS	Main Wind-Force Resisting System
NBC	National Building Code
NEHRP	National Earthquake Hazard Reduction Program
NFIP	National Flood Insurance Program
NFPA	National Fire Protection Association
NSSA	National Storm Shelter Association
OSB	Oriented Strand Board
PA	Public Assistance
PDM	Pre-Disaster Mitigation
PMR	Protected Membrane Roof
PNP	Private Non-Profit
SBC	Standard Building Code
SEAW	Structural Engineers Association of Washington
SHMO	State Hazard Mitigation Officer
SPF	Sprayed Polyurethane Foam
UBC	Uniform Building Code

100-year flood. See “base flood.”

A

Alluvial Fan. A fan-shaped deposit of alluvium formed by a stream where its velocity is abruptly decreased, as at the mouth of a ravine or at the foot of a mountain.

Astragal. The center member of a double door, which is attached to the fixed or inactive door panel.

B

Base flood. The flood having a 1-percent chance of being equaled or exceeded in any given year, commonly referred to as the “100-year flood.” The base flood is the national standard used by the NFIP and all Federal agencies for the purposes of requiring the purchase of flood insurance and regulating new development.

Base flood elevation (BFE). The height of the base (1 percent or 100-year) flood in relation to a specified datum, usually the National Geodetic Vertical Datum of 1929, or the North American Vertical Datum of 1988.

Basic wind speed. A 3-second gust speed at 33 feet above the ground in Exposure C. (Exposure C is flat open terrain with scattered obstructions having heights generally less than 30 feet.) Note: Since 1995, ASCE 7 has used a 3-second peak gust measuring time. A 3-second peak gust is the maximum instantaneous speed with a duration of approximately 3 seconds. A 3-second peak gust speed could be associated with a given windstorm (e.g., a particular storm could have a 40-mph peak gust speed), or a 3-second peak gust speed could be associated with a design-level event (e.g., the basic wind speed prescribed in ASCE 7).

Building, enclosed. A building that does not comply with the requirements for open or partially enclosed buildings.

Building, open. A building having each wall at least 80 percent open. This condition is expressed by an equation in ASCE 7.

Building, partially enclosed. A building that complies with both of the following conditions:

1. The total area of openings in a wall that receives positive external pressure exceeds the sum of the areas of openings in the balance of the building envelope (walls and roof) by more than 10 percent.
2. The total area of openings in a wall that receives positive external pressure exceeds 4 square feet, or 1 percent of the area of that wall, whichever is smaller, and the percentage of openings in the balance of the building envelope does not exceed 20 percent.

These conditions are expressed by equations in ASCE 7.

Building, regularly shaped. A building having no unusual geometrical irregularity in spatial form.

Building, simple diaphragm. An enclosed or partially enclosed building in which wind loads are transmitted through floor and roof diaphragms to the vertical main wind-force resisting system.

C

Components and cladding (C&C). Elements of the building envelope that do not qualify as part of the main wind-force resisting system.

Coping. The cover piece on top of a wall exposed to the weather, usually made of metal, masonry, or stone, and sloped to carry off water.

D

Design flood. The greater of the following two flood events: (1) the base flood, affecting those areas identified as special flood hazard areas on a community's Flood Insurance Rate Map (FIRM); or (2) the flood corresponding to the area designated as a flood hazard area on a community's flood hazard map or otherwise legally designated.

Design flood elevation (DFE). The elevation of the design flood, including wave height, relative to the datum specified on a community's flood hazard map.

Dry floodproofing. An adjustment, modification, or addition of a feature, or any combination thereof, that eliminates or reduces the potential for flood damage by sealing walls and closing openings to keep water from entering a building.

E

Erodible soil. Soil subject to wearing away due to the effects of wind, water, or other geological processes during a flood or storm or long-term exposure.

Escarpment. Also known as a scarp. With respect to topographic effects, a cliff or steep slope generally separating two levels or gently sloping areas.

Exposure. The characteristics of the ground roughness and surface irregularities in the vicinity of a building. ASCE 7 defines three exposure categories—Exposures B, C, and D.

Extratropical storm. A cyclonic storm that forms outside of the tropical zone. Extratropical storms may be large, often 1,500 miles (2,400 kilometers) in diameter, and usually contain a cold front that extends toward the equator for hundreds of miles.

F

Federal Emergency Management Agency (FEMA). The Federal Emergency Management Agency is the Federal agency which administers the National Flood Insurance Program (NFIP).

Fetch. Distance over which wind acts on the water surface to generate waves.

Flashing. Any piece of material, usually metal or plastic, installed to prevent water from penetrating a structure.

Flood Insurance Rate Map (FIRM). The official map of a community on which FEMA has delineated both the special hazard areas, and the risk premium zones applicable to the community.

Flood Insurance Study (FIS). An engineering study performed by FEMA to identify flood hazard areas, flood insurance risk zones, and other flood data in a community; used in the development of the FIRM.

Floodplain. Any land area, including the watercourse, that is susceptible to partial or complete inundation by water, from any source.

Floodplain management regulations. Zoning ordinances, subdivision regulations, building codes, or special-purpose ordinances that set flood-resistant standards for new construction, land use, and development.

Flood profile. A graph of computed flood elevations at points located along a riverine waterway. A flood profile typically is available for a waterway that has Base Flood Elevations (BFEs) shown on the Flood Insurance Rate Map (FIRM). Flood profiles are usually found in the Flood Insurance Study (FIS) report.

Floodway. The channel and that portion of the floodplain that is to be reserved to convey the base flood, without cumulatively increasing the water surface elevation more than a designated height.

Floodway fringe. The area of the floodplain outside of the floodway, where floodwaters may be shallower and slower.

Freeboard. A factor of safety, usually expressed in feet above a flood level, for purposes of floodplain management. Freeboard also compensates for the many unknown factors that could contribute to flood heights greater than the height calculated for a selected size flood and floodway conditions, such as wave action, constricting bridge openings, and the hydrological effect of urbanization of the watershed. A freeboard of 1 to 3 feet is often applied to critical facilities.

Frontal dune. Ridge or mound of unconsolidated sandy soil, extending continuously alongshore landward of the sand beach and defined by relatively steep slopes abutting markedly flatter and lower regions on each side.

G

Glazing. Glass or a transparent or translucent plastic sheet used in windows, doors, and skylights.

Glazing, impact-resistant. Glazing that has been shown, by an approved test method, to withstand the impact of wind-borne missiles likely to be generated in wind-borne debris regions during design winds.

H

Hurricane-prone regions. Areas vulnerable to hurricanes; in the United States and its territories defined as:

1. The U.S. Atlantic Ocean and Gulf of Mexico coasts, where the basic wind speed is greater than 90 miles per hour.
2. Hawaii, Puerto Rico, Guam, U.S. Virgin Islands, and American Samoa.

Human intervention. The presence and active involvement of people necessary to enact or implement floodproofing measures prior to the onset of flooding.

Hydrodynamic load. Loads imposed by water flowing against and around an object or structure, including the impacts of debris and waves.

Hydrostatic load. Load (pressure) imposed on an object or structure by a standing mass of water; the deeper the water, the greater the load or pressure against the object or structure.

I

Impact-resistant covering. A covering designed to protect glazing, which has been shown by an approved test method to withstand the impact of wind-borne missiles likely to be generated in wind-borne debris regions during design winds.

Importance factor, I. A factor that accounts for the degree of hazard to human life and damage to property. Importance factors are given in ASCE 7.

L

Lowest floor. The lowest floor of the lowest enclosed area (including basement). An unfinished or flood resistant enclosure, usable solely for parking of vehicles, building access, or storage, in an area other than a basement area, is not considered a building's lowest floor, provided that the enclosure is compliant with flood-resistant requirements.

M

Main wind-force resisting system. An assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface.

Mean roof height, (h). The average of the roof eave height and the height to the highest point on the roof surface, except that, for roof angles of less than or equal to 10 degrees, the mean roof height shall be the roof eave height.

Missiles. Debris that could become propelled into the wind stream.

N

National Flood Insurance Program (NFIP). A Federal program to identify flood-prone areas nationwide, and make flood insurance available for properties in communities that participate in the program.

Nor'easter. Nor'easters are non-tropical storms that typically occur in the eastern United States, any time between October and April, when moisture and cold air are plentiful. They are known for dumping heavy amounts of rain and snow, producing hurricane-force winds, and creating high surfs that cause severe beach erosion and coastal flooding. A nor'easter is named for the winds that blow in from the northeast and drive the storm up the east coast along the Gulf Stream, a band of warm water that lies off the Atlantic Coast.

O

Openings. Apertures or holes in the building envelope that allow air to flow through the building envelope. A door that is intended to be in the closed position during a windstorm would not be considered an opening. Glazed openings are also not typically considered openings. However, if the building is located in a wind-borne debris region and the glazing is not impact-resistant or protected with an impact-resistant covering, the glazing is considered an opening.

R

Racking. Lateral deflection of a structure resulting from external forces, such as wind or lateral ground movement in an earthquake.

Ridge. With respect to topographic effects, an elongated crest of a hill characterized by strong relief in two directions.

S

Scour. Removal of soil or fill material by the flow of floodwaters. The term is frequently used to describe storm-induced, localized erosion around pilings at building corners and other foundation supports where the obstruction of flow increases turbulence.

Seiche. A wave that oscillates in lakes, bays, or gulfs from a few minutes to a few hours as a result of seismic or atmospheric disturbances.

Sheetflow. Rainfall runoff that flows over relatively flat land without concentrating into streams or channels.

Stillwater elevation. The elevation that the surface of coastal flood waters would assume in the absence of waves, referenced to a datum.

Storm surge. Rise in the water surface above normal water level on the open coast due to the long-term action of wind and atmospheric pressure on the water surface.

Substantial damage. Damage of any origin sustained by a structure, whereby the cost of restoring the structure to its pre-damage condition equals or exceeds 50 percent of the market value of the structure before the damage occurred (or smaller percentage if established by the authority having jurisdiction). Structures that are determined to be substantially damaged are considered to be substantial improvements, regardless of the actual repair work performed.

Substantial improvement. Any reconstruction, rehabilitation, addition, or other improvement of a structure, the cost of which equals or exceeds 50 percent of the market value of the structure (or smaller percentage if established by the authority having jurisdiction) before the start of the improvement.

T

Tsunami. An unusually large sea wave produced by submarine earth movement or a volcanic eruption.

W

Wave runup. Rush of wave water up a slope or structure. The additional height reached by waves above the stillwater elevation.

Wet floodproofing. Permanent or contingent measures and construction techniques, applied to a structure or its contents, that prevent or provide resistance to damage from flooding while allowing floodwaters to enter the structure. Generally, this includes properly anchoring the structure, using flood-resistant materials below the BFE, protection of mechanical and utility equipment, and the use of openings or breakaway walls.

Wind-borne debris regions. Areas within hurricane-prone regions located:

1. Within 1 mile of the coastal mean high water line where the basic wind speed is equal to or greater than 110 mph and in Hawaii.
2. In areas where the basic wind speed is equal to or greater than 120 mph.

Federal funding for mitigation is available on a regular basis for pre-disaster mitigation activities and as federal assistance following a presidential disaster declaration. Table 1 provides a side-by-side comparison of available funding programs administered by FEMA. Although each program is constrained in a number of ways, as explained below, the following sources of federal funding may be available for mitigation projects for critical facilities:

Many other federal and state funding sources may be available to support planning and construction (or upgrades) of some critical facilities, but this manual does not identify or list such sources. Owners, planners, and community leaders are encouraged to contact appropriate state agencies to learn more.

- **Section 406 Public Assistance (PA)** is a post-disaster program established under Section 406 of the Stafford Act—it is jointly administered by FEMA and individual states. As part of the reimbursements made to restore damaged public facilities and certain private non-profit (PNP) facilities, public assistance funds may be made available for cost-effective mitigation measures undertaken as part of the recovery. The amount of Section 406 Mitigation funds made available in any given disaster is not computed by a formula, but is based on a project-by-project evaluation of the feasibility and cost-effectiveness of mitigation measures.

- **Section 404 Hazard Mitigation Grant Program (HMGP)** is a post-disaster program established under Section 404 of the Stafford Act. It offers funding to states, communities, and other eligible grant recipients to invest in long-term measures that will reduce vulnerability to future natural hazards. The states have a strong role in administering HMGP, with FEMA providing oversight. Contact the State Hazard Mitigation Officer (SHMO) for state-specific information. General guidelines and resources for this program can be found on the FEMA website (www.fema.gov/fima/hmgp).

- **Pre-Disaster Mitigation (PDM)**, established under Section 203 of the Stafford Act, is a nationally competitive grant program designed to assist states and communities to develop mitigation plans and implement mitigation projects. PDM funds are appropriated annually. FEMA convenes national panels to evaluate eligible applications. Applications are submitted by states following the state selection process. Communities should contact the SHMO for state-specific PDM procedures. PDM program guidance and other information can be found on the FEMA website (www.fema.gov/government/grant/pdm/index.shtm).

- **Flood Mitigation Assistance (FMA)** is a grant program funded by the National Flood Insurance Program (NFIP) and focused on buildings that are insured by the NFIP, with particular attention to buildings that have received multiple claim payments. As with the HMGP, FMA is state-administered, and information and assistance is available from the SHMO. General guidelines and resources for this program can be found on the FEMA website (www.fema.gov/government/grant/fma/index.shtm).

As part of the Hurricane Katrina recovery in Mississippi and Louisiana, FEMA initiated a post-disaster Partnering Mitigation Programs initiative to combine funding from Section 406 and Section 404 where possible. Section 406 mainly funds the repair and restoration of storm damage; thus, some building elements may remain exposed to future damage. The initiative fosters a cooperative approach to making decisions to use both PA and HMGP funds to accomplish recovery as well as mitigation of facilities as whole buildings in a seamless fashion.

Table 1: Side-by-Side of FEMA Programs

Item	PA (406)	HMGP (404)	PDM (203)	FMA
Eligible Applicants and Sub-applicants for Project Grants	State and local governments; PNP organizations or institutions that own or operate a PNP facility (as defined in regulation); Indian tribes or authorized tribal organizations and Alaska Native villages or organizations, but not Alaska native corporations with ownership vested in private individuals.	State and local governments; PNP organizations or institutions that own or operate a PNP facility (as defined in regulation); Indian tribes or authorized tribal organizations and Alaska Native villages or organizations, but not Alaska native corporations with ownership vested in private individuals.	State-level agencies; local governments, Indian tribes, authorized Indian tribal organizations, and Alaska Native villages; public colleges and universities; tribal colleges and universities. PNP organizations and private colleges and universities are not eligible sub-applicants, but a relevant state agency or local government may apply on their behalf.	State agencies, NFIP-participating communities (have zoning and building code jurisdiction), and local authorities designated to plan and implement projects.
Eligible Activities	Basic assistance to repair the damaged elements of public facilities and infrastructure. Eligible mitigation activities are only those that protect against direct physical damages to structures, building, and contents.	Eligible activities include structural and nonstructural mitigation measures that are feasible and cost-effective. Projects may count benefits in terms of building and contents damages, displacement costs, loss of function, and casualties and loss of life.	Eligible measures must be cost-effective and designed to reduce injuries, loss of life, and damage and destruction of property, including damage to critical services and facilities under the jurisdiction of the states or local governments.	
Cost Share	75 percent federal 25 percent non-federal	75 percent federal 25 percent non-federal	75 percent federal 25 percent non-federal Small, impoverished communities may be eligible for 90 percent federal share.	75 percent federal 25 percent non-federal

Table 1: Side-by-Side of FEMA Programs (continued)

Item	PA (406)	HMGP (404)	PDM (203)	FMA
Funding Source	The Disaster Relief Fund after a presidential disaster declaration; public assistance must be authorized specifically as part of the disaster declaration.	The Disaster Relief Fund after a presidential disaster declaration; HMGP must be authorized specifically as part of the disaster declaration.	An annual appropriation by Congress.	Annual appropriation by Congress, by transfer of income from the National Flood Insurance Fund.
Planning Requirement	For categories C-G assistance, a state must have an approved mitigation plan.	For disasters declared after 11/1/04, state and local governments must have an approved mitigation plan.	State and local mitigation plans must be adopted and approved by FEMA prior to the beginning of the selection process, as a precondition for receiving project grants.	Recipient must have adopted a mitigation plan approved by FEMA prior to receipt of grant funds.
Application Deadline	Project worksheets usually are due no later than 60 days after a formal briefing presented by FEMA and the state (extensions may be granted in unusual circumstances).	Applications must be submitted to FEMA within 12 months of the disaster declaration date (extensions may be granted in unusual circumstances).	Varies by year; contact state agency for additional information.	Usually late spring; specific date varies by year, contact state agency for additional information.

Public Assistance (Section 406)

Following a presidential disaster declaration, the PA program provides assistance for debris removal, emergency protective measures, and permanent restoration of publicly owned infrastructure. Eligible recipients of this assistance include state and local governments, Indian tribes or authorized tribal organizations, and Alaska Native villages. Certain PNP organizations may also receive assistance. Eligible PNPs include educational, utility, irrigation, emergency, medical, rehabilitation, temporary or permanent custodial care facilities (including those for the aged and disabled), and other PNP facilities that provide essential services of a governmental nature to the general public. Certain PNPs that provide "critical services" may apply directly to FEMA, including PNPs that provide power, sewer, wastewater treatment, communications, emergency medical care, and water (including water provided by an irrigation organization or facility).

As soon as practical after the declaration, the state, assisted by FEMA, conducts Applicants' Briefings for state, local, and PNP officials, to inform them of the assistance available and the application procedure. A request for public assistance must be filed with the state within 30 days after an area is designated eligible for assistance.

Following the Applicants' Briefing, a kickoff meeting is conducted with each eligible grant recipient, where specific damages are discussed, needs assessed, and a plan of action put in place. A combined federal/state/local team proceeds with project formulation—the process of documenting eligible facilities and determining the cost for fixing the identified eligible damages. The team prepares a project worksheet for each project. Eligible projects fall into the following categories:

Category A: Debris removal

Category B: Emergency protective measures

Category C: Roads and bridges

Category D: Water control facilities

Category E: Public buildings and contents

Category F: Public utilities

Category G: Parks, recreational, and other

The facility owner must pay for all costs that are not eligible for Section 406 reimbursement. The non-federal share can be a combination of cash and in-kind resources. Federal funding from other sources cannot be used as matching funds, with the exception of federal funding provided to states under the Community Development Block Grant program from the Department of Housing and Urban Development.

FEMA reviews and approves the project worksheets and obligates the federal share of the costs to the state, which, in turn, disburses the funds to local applicants. The federal share is not less than 75 percent of the eligible project costs (except in extraordinary circumstances, when some costs are eligible for 90 or 100 percent reimbursement).

Damaged buildings that are in a mapped floodplain and insured by NFIP may have access to an insurance payment to help cover the cost of mitigation, provided the damage caused by flooding is determined to be "substantial damage." A building is substantially damaged when the value of the work required to repair it to its pre-damaged condition equals or exceeds 50 percent of the market value of the building. In these cases, increased cost of compliance coverage in NFIP flood insurance policies provides to owners up to $30,000 to bring the building into compliance with floodplain management requirements. This payment may be used as part of the non-federal match of grant-funded mitigation projects designed to address flood hazards.

Section 406 provides FEMA with the authority to fund mitigation measures in conjunction with the repair of damaged facilities involving permanent restorative work (Categories C, D, E, F, and G projects). The mitigation measures must be related to the eligible disaster damages and must directly reduce the potential of future, similar damages to the eligible facility. In providing this discretionary authority, Congress recognized that the post-disaster period offers unique opportunities to prevent the recurrence of similar damage in future disasters. These measures are additional to any other measures undertaken for the purpose of compliance with applicable codes and standards, although such compliance, itself, could be considered a form of mitigation. The following are examples of the types of mitigation required for compliance with building codes that are eligible under Section 406:

- Improved building materials such as impact-resistant windows or flood-resistant materials
- Anchoring of rooftop equipment
- Improved installation methods or techniques
- New or higher elevation (for flood-prone facilities)

Owners of eligible public facilities often wish to repair and restore a damaged facility in ways that exceed the current building code requirements, in order to further reduce or eliminate future damage. Where it can be demonstrated that doing so is cost-effective, the added costs of such actions are eligible under FEMA Policy 9526.1 governing the implementation of the Section 406 program. Unfortunately, this approach rarely meets all the identified mitigation needs, because the funding can be used only for the damaged elements—mitigation of vulnerable but undamaged elements is not allowed. For example, a police station with some damaged windows can use Section 406 funds to replace the damaged windows with impact-resistant windows, but cannot replace undamaged windows. To address this limitation, facility owners should seek other sources of mitigation funding, such as the Hazard Mitigation Grant Program described below.

All mitigation activities funded with Section 406 funds must be cost-effective. To facilitate recovery, FEMA can apply one of several tests to determine cost-effectiveness:

- Measures may cost to up to 15 percent of the total eligible cost of the eligible repair work on a particular project.
- Certain pre-approved mitigation measures identified in FEMA policies will be determined to be cost-effective, as long as the cost of the mitigation measure does not exceed 100 percent of the eligible cost of the repair project.
- For measures that do not meet the first or second test, the project applicant must demonstrate cost-effectiveness using an acceptable benefit/cost analysis. FEMA developed benefit/cost models that are specific to hurricanes, coastal flooding, riverine flooding, earthquakes, and tornadoes.

Hazard Mitigation Grant Program (Section 404)

Section 404, HMGP, is FEMA's primary hazard mitigation program to help implement long-term mitigation measures following major disaster declarations. Under HMGP, each state manages its own program, and eligible participants include state and local governments, tribes, and PNP organizations. The program funds up to 75 percent of the costs of individual FEMA-approved projects. The total amount of funding made available after specific disasters depends on several variables.

HMGP funds have been used for many types of projects, including the following:

- **Wind-resistant Retrofits.** Existing facilities that were built before current code requirements may be eligible to be retrofitted to resist high winds. For any given building, applicable measures are identified by conducting an evaluation of the building.

Critical facilities have been retrofitted with shutters for windows and doors, and anchoring of architectural features and rooftop equipment.

- **Floodproof Retrofits.** Depending upon the nature of the flood risk, elevating an existing flood-prone structure or incorporating dry floodproofing techniques may be the most practical approach to meet NFIP requirements and those administered by states and local governments.

- **Code Upgrades.** Certain measures intended to provide a level of protection that exceeds the minimum requirements of the applicable building code may be eligible. This approach to mitigation is especially applicable for critical facilities that serve vital post-disaster functions.

- **Relocation.** In some cases, it may be viable to physically move a structure to a new location outside of high-risk flood hazard areas. Relocated buildings must be placed on a site located outside of the 100-year floodplain and any regulatory erosion zones, in conformance with all applicable state or local land use regulations.

- **Acquisition and Demolition.** The community purchases the flood-damaged property and demolishes the structure. The acquired property must be maintained as open space in perpetuity.

Pre-Disaster Mitigation (Section 203)

PDM provides funds to state and local governments for hazard mitigation planning and the implementation of cost-effective mitigation projects unrelated to a specific disaster. PDM is administered directly by FEMA. Eligible applicants include states, tribes, territories, and local governments (PNPs can apply if sponsored by an eligible applicant). Grants are awarded on a nationwide competitive basis and without a formula-based allocation.

Similar to HMGP, PDM has funded numerous projects that improve wind- and flood-resistance of critical facilities such as emergency operations centers, hospitals, fire stations, police stations, and wastewater treatment plants. Specific measures include strengthening exterior walls, anchoring rooftop equipment, installing shutters, and elevation of facilities or equipment above the 100-year flood elevation. Other types of projects may be eligible, provided they meet the program requirements and are cost-effective. Each year, FEMA issues PDM program guidance with specific criteria.

Cost Share for Small, Impoverished Communities

PDM grants awarded to small, impoverished communities may receive a federal cost share of up to 90 percent of eligible costs. To qualify, a community must meet several eligibility criteria related to population, average annual income, unemployment rate, and other conditions.

Flood Mitigation Assistance Program

FMA is designed to fund mitigation projects that are cost-effective and in the best interest of NFIP. Funds are provided annually from income collected from flood insurance policyholders. Each state manages its own program. Eligible grant recipients must have a FEMA-approved mitigation plan. Eligible recipients include communities that have land use authority and participate in the NFIP, certain other local authorities, and state agencies. The program funds up to 75 percent of certain eligible costs for measures that reduce or eliminate flood damage to buildings that are insured by the NFIP, including buildings and facilities owned by public agencies and PNP entities.

Eligible activities under the FMA program include acquisition, increased elevation, relocation, demolition, floodproofing, and activities that bring nonresidential structures into compliance with minimum NFIP requirements and state and local codes, and minor physical activities such as drainage improvements. As with HMGP, if an NFIP-insured building is damaged by a flood and found to be eligible for the increased cost of compliance claim payment to bring the building into compliance, the payment can be used as part of the required non-federal match for FMA grants.