Development of a performance-based design approach and related loads for facilities designated as essential during a hurricane event

Joffrey Elliott Easley

Louisiana State University and Agricultural and Mechanical College, jeasle1@lsu.edu

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DEVELOPMENT OF A PERFORMANCE-BASED DESIGN APPROACH AND RELATED LOADS FOR FACILITIES DESIGNATED AS ESSENTIAL DURING A HURRICANE EVENT

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

by

Joffrey Elliott Easley
B.S., Louisiana State University, 2000
May 2003
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ABSTRACT

Historically, shelters and other facilities designated as “essential” during hurricanes have experienced unacceptable damage during recent hurricanes, exposing the occupants to uncomfortable and dangerous conditions. One of the reasons for this is the lack of standards or design guidelines addressing the special considerations required for such facilities.

A new approach to the design of essential facilities in hurricane regions is proposed. The goal of this work is to create a tool for improving the safety and serviceability of evacuation shelters and other critical facilities utilized during hurricane events. This is achieved by developing a new philosophy based on selection of a design hurricane event of a specific intensity, corresponding to a Hurricane Category (on the Saffir-Simpson scale). This design basis provides critical information to emergency managers for making evacuation and sheltering decisions. Performance-based design criteria were then developed for five different types of “essential” facilities based on their required function before, during, and after the hurricane event. Loads and load combinations consistent with the design hurricane event were also developed. The specific factors addressed include; design wind speed, directionality factor, site exposure, enclosure classification, importance factor, rain load, flood load, load factors and load combinations, and debris impact. Also addressed were other special considerations, such as the flooding hazards and mass care issues. A comparison was made between the design recommendations presented in this thesis and current practice.

Several aspects of this thesis are geographically unique, including the hurricane filling rate after landfall, flooding issues, and rainfall issues. Specific recommendations for these factors were made only for the Gulf Coast region of the United States. The same methodology could, however, be applied to any region of the country exposed to hurricanes.
CHAPTER 1: INTRODUCTION

1.1 Background

Many hurricane shelters and other facilities designated as “essential” during hurricane events have experienced unacceptable damage during recent hurricanes. This has drawn the attention of both the emergency management and design communities to the design of these types of facilities. The lack of standards addressing the special considerations that must be implemented when designing essential facilities has resulted in the occupants of these facilities being exposed to unfavorable conditions during and after the hurricane event, and in some cases lives have been placed in jeopardy. Post-hurricane building performance assessments have been very beneficial for documenting the types of damage these facilities suffer.

The damage sustained during Hurricane Georges, which struck the Mississippi Gulf Coast in September of 1998, was well documented by these building performance assessments. Some of the damage discovered by post-hurricane damage assessments will be described in the following paragraphs.

Nearly 14,700 people in Mississippi chose to weather Hurricane Georges inside shelters. The structural soundness of many of these facilities was inadequate in many instances, causing danger to the occupants. After Georges ripped the roofs off two shelters, residents were required to move to new shelters. Strong winds tore the roof off the Mississippi Gulf Coast Community College gymnasium in Gautier, MS, forcing approximately 400 residents to flee. Also, some buildings on the campus experienced interior damage due to rainwater entering the buildings through damaged roofs. In Pascagoula, an apparent tornado destroyed the roof of Trent Lott Middle School, where approximately 90 people were seeking shelter. Residents had no choice but to remain in the
shelter, however (Rekenthaler, 1998; Kolker, 1998; FEMA, 1999a; Associated Press, 1998; CNN, 1998a). Also, the roof was “twisted off” of the Marathon High School cafeteria allowing water to flood the building (SRCC, 1998).

Other critical facilities experienced significant damage from Hurricane Georges, putting the residents inside these facilities at risk. The roof of Singing River Hospital, a regional medical center in Pascagoula, MS, was severely damaged, causing patient rooms, delivery rooms, and other sectors to be evacuated. Residents of the Plaza Nursing Center in Pascagoula were required to be relocated after several inches of water flooded the facility due to openings in the building’s flat roof. The residents were required to remain in the flooded building for hours until a facility was located that could handle the special needs of the 110 bedridden patients. The patients, along with their beds, medicines, and other necessary items, had to be transported to Spring River Hospital by ambulances and school buses (FEMA, 1999a; CNN, 1998b).

The roofing systems of essential facilities also fared poorly during Hurricane Hugo, which struck South Carolina in September of 1989. The roofs of all twenty fire stations and all five police stations in the town of Charleston, SC suffered roof damage. Of the seventy school facilities, which are commonly used as hurricane shelters, forty-nine of them had roof damage (ASCE, 1990).

1.2 Problem Statement

As shown by the previous examples, facilities designated as essential during hurricane events have experienced damage during recent hurricanes. One of the reasons for this is that, historically, essential facilities have not been designed specifically for hurricane impacts; rather existing buildings have been assessed for their ability to perform satisfactorily enough to meet the functionality requirements needed during the hurricane event. Also, until
recently, there have not been design guidelines available that address the special planning and design considerations of a facility with a secondary function as an essential facility during a hurricane event. The design guidelines that are currently available result in a building designed to resist an ultimate (tornadic) wind event, which, in many cases, is not feasible for facilities to be used in hurricanes due to economic or other considerations.

The current method of determining loads on a facility, whether it is an ordinary or an essential facility, is based on an acceptable probability of failure. For locations along the hurricane coast, the design wind speed is the wind speed corresponding to the 500 year Mean Recurrence Interval (MRI) divided by a factor of 1.225. This results in a MRI that varies depending on location, but is always in excess of 50 years. For an essential facility, the design wind speed is increased by the use of a 1.15 Importance Factor.

Once the design loads have been determined, the building is designed using the governing building code. The design recommendations given in most building codes are based on a prescriptive design approach, which bases the design on a “no damage” approach when the facility is exposed to its design event (Harris, 2002 and Hamburger, 2002). This type of design methodology is not adequate when designing facilities designated as essential during hurricane events because the special planning and design considerations specific to these types of facilities are not addressed using this method.

1.3 Goals and Objectives

A new approach to the design of facilities designated as essential during hurricane events is proposed. The overall goal of this thesis is to create a tool to help improve the safety and serviceability of hurricane evacuation shelters and other essential facilities utilized during hurricane events. This will be achieved by developing a more rational design philosophy appropriate for the design of facilities designated as essential during a hurricane
event. This new philosophy will entail defining a new design event, developing a set of performance standards, establishing a set of design criteria, and developing design guidelines to be utilized during the planning and design stages of one of these facilities. The specific objectives that will be addressed are:

1) Define a new design event. Instead of designing an essential facility based on a wind speed or flood event corresponding to a given MRI, it is proposed that these facilities be designed based upon a hurricane of a given strength (based on the Saffir-Simpson Hurricane Scale) chosen by the building owner. Considerations for selection of the design hurricane include shelter demand, the available budget, and other considerations deemed important. The associated loads for the design hurricane can then be determined and the building designed accordingly. Then, when a given hurricane is approaching, the building owner can identify which buildings have been designed to meet their intended function for the approaching hurricane and manage the emergency preparedness operations accordingly.

2) Develop a performance-based design approach appropriate for essential facilities. A set of performance standards will be developed by first identifying the different types of “essential” facilities and categorizing them according to their use before, during, and after the hurricane event. The required performance levels of each of these categories will then be established. For example, a hospital building does not need to perform to the same level as a building used to store emergency response and recovery equipment. This type of approach allows for the most efficient design. Also, the performance-based design approach allows for the use of the latest products in the design of the facility. These two concepts allow for the best, most up-to-date, and most efficient design of buildings designated as essential during a hurricane.
event. The performance standards will be developed through a detailed literature survey along with the results of a survey given to members of the emergency management community.

3) Develop appropriate design loads and load combinations consistent with objectives one and two. The specific topics that will be addressed are:

a. Formulate a method for determining the design wind speed to use for the design of the Main Wind Force Resisting System (MWFRS) and the Components and Cladding (C&C). This will be based on the design hurricane event and distance inland.

b. Determine the appropriate directionality factor.

c. Provide guidelines on the correct site exposure.

d. Determine the appropriate enclosure classification for use in selection of the internal pressure coefficient.

e. Determine the appropriate Importance Factor.

f. Determine the appropriate rain load.

g. Determine the appropriate load factors and load combinations to be used for design.

4) Provide guidance on appropriate debris loads and impact resistance.

5) Provide guidance on other special considerations that must be addressed when designing essential facilities, such as the flooding hazards associated with a hurricane event and mass care issues.

6) Compare design recommendations with current practice.

This thesis presents a general methodology for the design of facilities designated as essential during a hurricane event. Several aspects are geographically unique, including the
filling rate, flooding issues, and rainfall issues. Specific recommendations for these factors will be made only for the Gulf Coast region of the United States. The same methodology could, however, be applied to any region of the country where the design wind speed is controlled by hurricane events.
CHAPTER 2: LITERATURE REVIEW

2.1 The Hurricane Event

2.1.1 Life Cycle

- **Formation**

  The hurricane is the same meteorological event as a severe tropical cyclone and a typhoon. The only real difference between these storms is the body of water over which they are formed. Most hurricanes are formed in the warm waters of the Atlantic Ocean, between the Tropic of Capricorn and the Tropic of Cancer, which are located 23 degrees, 27 minutes south and north of the equator, respectively (Pielke, Jr., et al., 1997). Many hurricanes begin in low-pressure regions of the atmosphere assembled with a group of thunderstorms.

- **Growth**

  Air has a tendency to move towards the center of the low-pressure region (and away from the high pressure). The rotation of the Earth tends to deflect the air such that it rotates around the low-pressure system counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. This is known as the Coriolis Effect. In order for the system to develop into a tropical storm or hurricane, Pielke, Jr., et al. (1997) gives several criteria that must be met:

  - The surface temperature of the ocean must be greater than approximately 79° F so that ample moisture and heat can be supplied into the low-pressure system. This is needed to sustain thunderstorm development.

  - The vertical wind shear must be less than approximately 17 mph between the upper and lower troposphere (the region of the atmosphere that extends outward about 7 to 10 miles from the Earth’s surface, where, generally, temperature decreases rapidly with altitude, clouds form, and convection is active). This keeps the developing thunderstorms over the low-pressure region.

  - The storm’s position must be greater than approximately 5° latitude from the equator. Near the equator, low and high-pressure systems tend not to rotate.
High-pressure must develop in the upper troposphere above the surface low. This high-pressure ensures that air is evacuated from the cyclone, allowing surface pressures to continue to drop.

- **Stages of Life**

The stages of life of a tropical cyclone, the term given to all circulating weather systems that form over water, are shown in Table 2.1. The definitions given in Table 2.1 are for tropical systems that strike the mainland of the United States. The names given in parentheses are the names for the same event located in different parts of the world. The term “surface winds” in Table 2.1 and in all other places in this thesis are measured at a height of 33’ (10 m). The wind speeds given in Table 2.1 are over open water.

Table 2.1 – Stages of Life of a Tropical System (for storms that strike the mainland of the United States)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Low (Tropical Wave)</td>
<td>A surface low-pressure system in the tropical latitudes</td>
</tr>
<tr>
<td>Tropical Disturbance</td>
<td>A tropical low along with a cluster of thunderstorms that have, at most, only a weak surface wind circulation and one closed isobar.</td>
</tr>
<tr>
<td>Tropical Depression</td>
<td>A tropical low with maximum sustained 1-minute surface winds of less than 39 mph circulating around the center of the low</td>
</tr>
<tr>
<td>Tropical Storm</td>
<td>A tropical cyclone with maximum sustained surface winds between 39 and 74 mph.</td>
</tr>
<tr>
<td>Hurricane</td>
<td>A tropical cyclone with sustained surface winds 74 mph or greater.</td>
</tr>
</tbody>
</table>

- **Hurricane Classification**

Hurricanes are classified by their intensity. The scale currently used in the United States is the Saffir/Simpson Hurricane Scale, which was developed in the 1970’s by Robert Simpson, a meteorologist and director of the National Hurricane Center, and Herbert Saffir, a consulting engineer in Dade County Florida (Pielke Jr., et al., 1997). The Saffir/Simpson Hurricane Scale has five categories, Category 1 through 5, with a Category 1 hurricane being the least intense and a Category 5 hurricane being the most intense. The Saffir/Simpson
Hurricane Scale is shown in Table 2.2. Hurricane categories are assigned based on maximum wind speeds. The values of central pressure and storm surge are typical values associated with each storm category. The wind speed shown in Table 2.2 is a one-minute sustained wind speed at 33 ft (10 m) height over open water. The magnitude of damage expected for a hurricane of a given intensity is given in Table 2.3.

Table 2.2 – Saffir/Simpson Hurricane Scale

<table>
<thead>
<tr>
<th>Category</th>
<th>Wind Speed (mph)</th>
<th>Wind Speed (m/s)</th>
<th>Central Pressure (inches Hg)</th>
<th>Central Pressure (millibars)</th>
<th>Surge (feet)</th>
<th>Surge (meters)</th>
<th>Damage Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74-94</td>
<td>33.1-42.0</td>
<td>≥28.94</td>
<td>≥980</td>
<td>4-5</td>
<td>1.2-1.5</td>
<td>Minimal</td>
</tr>
<tr>
<td>2</td>
<td>94-110</td>
<td>42.0-49.6</td>
<td>28.50-28.94</td>
<td>965-979</td>
<td>6-8</td>
<td>1.8-2.4</td>
<td>Moderate</td>
</tr>
<tr>
<td>3</td>
<td>110-130</td>
<td>49.6-58.1</td>
<td>27.91-28.49</td>
<td>945-964</td>
<td>9-12</td>
<td>2.7-3.7</td>
<td>Extensive</td>
</tr>
<tr>
<td>4</td>
<td>130-155</td>
<td>58.1-69.3</td>
<td>27.17-27.90</td>
<td>920-944</td>
<td>13-18</td>
<td>3.9-5.5</td>
<td>Extreme</td>
</tr>
<tr>
<td>5</td>
<td>&gt;155</td>
<td>&gt;69.3</td>
<td>&lt;27.17</td>
<td>&lt;920</td>
<td>&gt;18</td>
<td>&gt;5.5</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

- **Decay**

While a large number of atmospheric conditions must be met for a storm to develop into a hurricane, once it reaches hurricane intensity it becomes a very persistent weather feature. Pielke Jr., et al. (1997) state that once a tropical cyclone has reached hurricane intensity it will not weaken unless:

- The vertical wind shear grows too large.

- The hurricane passes over land or relatively cold water, at which time the hurricane’s source of heat and moisture is reduced.

- Dry, cool air, which retards thunderstorm development, is transported into the hurricane.

- The high-pressure in the upper troposphere is replaced by a cyclonic circulation, which, instead of evacuating air, adds air to the hurricane system.
<table>
<thead>
<tr>
<th>Category</th>
<th>Wind</th>
<th>Storm surge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Damage primarily to shrubbery, trees, poorly constructed signs, and unanchored mobile homes. No significant damage to other structures.</td>
<td>Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorages torn from moorings.</td>
</tr>
<tr>
<td>2</td>
<td>Considerable damage to shrubbery and tree foliage; some trees blown down. Extensive damage to poorly constructed signs. Major damage to exposed mobile homes. Some damage to roofing materials of buildings; some window and door damage. No major damage to buildings.</td>
<td>Coastal roads and low-lying escape routes made impassable by rising water 2 to 4 hours before arrival of hurricane center. Considerable damage to piers. Marinas flooded. Small craft in unprotected anchorage torn from moorings. Evacuations of some shoreline residences and low-lying island areas required.</td>
</tr>
<tr>
<td>3</td>
<td>Foliage torn from trees; large trees blown down. Practically all poorly constructed signs blown down. Some damage to roofing materials of buildings; some window and door damage. Some structural damage to small buildings. Mobile homes destroyed.</td>
<td>Serious flooding at coast and many small structures near coast destroyed; large structures near coast damaged by battering waves and floating debris. Low-lying escape routes made impassable by rising water 3 to 5 hours before hurricane center arrives. Flat terrain 5 ft or less above sea level flooded inland 8 miles or more. Evacuation of low-lying residences within several blocks of shoreline possibly required.</td>
</tr>
<tr>
<td>4</td>
<td>Shrubs and trees blown down; all signs down. Extensive damage to roofing materials, windows and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes.</td>
<td>Flat terrain 10 ft or less above sea level flooded inland as far as 6 miles. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Low-lying escape routes made impassable by rising waters 3 to 5 hours before hurricane center arrives. Major erosion of beaches. Massive evacuation of all residences within 500 yards of shore possibly required, and of single-story residences on low ground within 2 miles of shore.</td>
</tr>
<tr>
<td>5</td>
<td>Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Very severe and extensive damage to windows and doors with extensive shattering of glass components. Complete failure of roofs on many residences and industrial buildings. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes.</td>
<td>Major damage to lower floors of all structures less than 15 ft above sea level within 500 yards of shore. Low-lying escape routes made impassable by rising water 3 to 5 hours before hurricane center arrives. Massive evacuation of residential areas on low ground within 5 to 10 miles of shore possibly required.</td>
</tr>
</tbody>
</table>
2.1.2 The Mature Hurricane

- Wind Field

As shown in Figure 2.1, the mature hurricane can be a very large force of nature. It consists of a large vortex that can be hundreds of miles in diameter, with winds that spiral inward toward the eye at approximately 15° - 20°, as shown in Figure 2.2. As the wind speed increases inside a hurricane, it becomes more difficult for the wind to reach the center of the storm. This happens because the centrifugal force (the force that tends to impel an object outward from the center of rotation) becomes too large as the stronger winds spiral towards the center of the storm (Pielke Jr., et al., 1997). This leads to the formation of an eye, as shown in Figure 2.1. A typical diameter of the eye of a mature hurricane is 20 miles, but can be much smaller or larger. A hurricane with a smaller eye is generally more intense than a hurricane with a larger eye. The winds are very calm inside the eye of a mature hurricane. The highest winds in a hurricane are found at the edge of the eye, called the eye wall. The winds generally diminish with increasing distance extending outward from the eye wall, except for the strong winds generally found in rain bands. The wind field of a typical hurricane is shown in Figure 2.2. The highest wind speeds relative to the ground are almost invariably found on the right side of a hurricane, relative to the direction of movement. This is due to the additive effect of the forward movement of the storm and the counterclockwise circulation of the wind.

- Variation of Wind Speed with Height

In general, the wind speeds increase with height above the earth’s surface. This is because obstructions (trees, buildings, waves, etc.) retard the movement of air close to the earth’s surface, which causes a reduction of the wind speed. This is true over both land and water. At some height above the surface, the movement of air is no longer affected by
Figure 2.1 – Hurricane Structure (NOAA, 2002a)

Figure 2.2 – Wind Field of Hurricane Andrew (NOAA, 2002b)
obstructions. This height, which is a function of the surface roughness, is called the gradient height. Above the gradient height, the wind speed is relatively constant. This unobstructed wind speed is called the gradient wind speed.

- **Variation of Wind Speed with Surface Roughness**

  The roughness of the surface the hurricane is passing over has an enormous effect on the wind speed. The rougher the surface, the more it retards the movement of air below the gradient height. Figure 2.3 shows how the wind speed in extratropical events differs with both height above the ground and surface roughness. Currently, hurricanes are assumed to have the same wind profile. Recent research, however, has shown that this might not be correct. Franklin, et al. (2000) showed that the unique wind structure of hurricanes may create a wind profile that is quite different from that of extratropical wind events. The researchers also determined that the wind profile of hurricane events may differ depending on the radial distance from the center of the storm. Using the results of dropsonde data from seventeen hurricanes from 1997 to 1999, the researchers established mean wind speed profiles for eyewall and outer vortex locations of hurricanes. The findings (normalized by the flight-level wind speed) are shown in Figure 2.4.

- **Gustiness of the Wind**

  The flow of air is an inherently turbulent phenomenon. Wind speed can be thought of as having two components, the mean wind speed and the fluctuating component of wind speed. This fluctuating component is called turbulence, and is caused by two things, the convective movement of the air (meteorological turbulence) and the ground roughness (mechanical turbulence). The mechanical turbulence increases in rougher terrain and decreases with increasing height above the ground. It is assumed that above the gradient
Figure 2.3 – Variation of Wind Speed with Height and Surface Roughness (Texas Tech University, 2002)

Figure 2.4 – Mean Wind Speed Profiles of Hurricanes (Franklin, et al., 2000)
height the mechanical component can be neglected. Figure 2.5 shows the gustiness of hurricane winds. During extreme wind events, it is generally assumed that mechanical turbulence dominates.

Figure 2.5 – Gustiness of the Wind (NWS, 1999)

- **Pressure Field**

  Central pressure is a good measure of the intensity of a hurricane. In general, the lower the central pressure, the higher the wind speed of the hurricane. The average relation between wind speed and central pressure for Atlantic hurricanes is shown in Figure 2.6. Of course, this relationship does not hold true in all hurricanes; individual storms will vary from this relationship. For example, for two hurricanes with the same central pressure, a smaller storm will have higher winds than a large one because the horizontal pressure difference (which drives the winds) is more compact (Pielke, et al., 1997).
• Distribution

The lowest pressure is found in the eye of a hurricane and increases radially from the eye until atmospheric pressure is reached. In a severe hurricane, such as a Category 5 storm, the central pressure can be as low as approximately 900 millibars (mb), or about 10% lower than typical atmospheric pressure of approximately 1000 mb.

Figure 2.6 – Variation of Central Pressure with Wind Speed in the Atlantic Ocean, reproduced from Pielke, et al. (1997)

2.2 Performance-Based Design

2.2.1 Background

Performance-Based Design is a relatively new methodology that was developed initially for the design of structures in earthquake prone areas. The idea behind Performance-Based Design is to design a structure such that it meets a certain predetermined performance level when exposed to the “design event.” Also, some publications specify a certain
performance level when the building is subjected to an “ultimate event.” The ultimate event is the maximum event that can reasonably be expected to be experienced by the building, whether it is an earthquake, a hurricane, or any other type of event. The performance level used for the design of a given structure is based on a number of factors, including the danger to individuals inside the building during the design event, the function of the facility, the importance of the structure to society as a whole, along with any other relevant considerations. By contrast, prescriptive design, which is the design approach used in most current codes and standards, deems a design to be acceptable as long as it meets certain criteria that have been shown to work in the past (Harris, 2002 and Hamburger, 2002). One of the advantages of a performance-based design approach over a prescriptive design approach is that it more easily allows for the use of the latest technology and innovative products and methods in order to solve a design problem. It also allows for the design of structures using different desired performance levels based on the functional classification of the building, which results in a much more efficient and in many cases economical design.

Much of the research that has been done related to performance-based design started with work aimed at reducing the damage to structures and the danger to loss of life during an earthquake event. Much of this research was performed through the National Earthquake Hazards Reduction Program (NEHRP). The four agencies that receive funding through NEHRP are: the Federal Emergency Management Agency (FEMA), the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the United States Geological Survey (USGS).
2.2.2 Existing Performance-Based Design Manuals

- **Vision 2000 – Performance-Based Seismic Engineering of Buildings**

  The goal of Vision 2000 (SEAOC, 1995) is to assist designers in designing a building such that not only is the goal of life safety during an earthquake event met, but the building is also able to withstand the forces of the earthquake and reach the desired performance state after the earthquake.

  Four performance levels are defined:

  - Fully Operational
  - Operational
  - Life-safe
  - Near Collapse

  The definition of each of the performance levels is as follows (SEAOC, 1995):

  - Fully Operational – A performance level in which no damage has occurred. If a building responds to an earthquake within this performance level, the consequences to the building user community are negligible. The building remains safe to occupy and it is expected that post-earthquake damage inspectors utilizing the ATC-20 methodology (described in the following note) would post the building with a green placard. The building is occupiable and all equipment and services related to the building’s basic occupancy and function are available for use. In general, repair is not required.

  - Operational – A performance level in which moderate damage to nonstructural elements and contents, and light damage to structural elements has occurred. The damage is limited and does not compromise the safety of the building for occupancy. Post-earthquake damage inspectors utilizing the ATC-20 methodology would be expected to post the building with a green placard. It would be available for occupancy for its normal intended function immediately following the earthquake, however, damage to some contents, utilities and nonstructural components may partially disrupt some normal functions. Back-up systems and procedures may be required to permit continued use. Repairs may be instituted at the owners’ and tenants’ convenience.

  - Life-safe – A performance level (damage state) in which moderate damage to structural and nonstructural elements and contents has occurred. The structure’s lateral stiffness and ability to resist additional lateral loads has been reduced, possibly to a great extent, however, some margin against collapse remains. No major falling debris hazards have occurred. Egress from the building is not substantially impaired, albeit elevator and similar electrical and mechanical devices may not function. In the
worst case, post-earthquake damage inspectors, using the ATC-20 methodology, would be expected to post such a building with a yellow placard. In such cases the building would not be available for immediate post-earthquake occupancy. The building would probably be repairable, although it may not be economically practical to do so.

- Near Collapse – An extreme damage state in which the lateral and vertical load resistance of the building have been substantially compromised. Aftershocks could result in partial or total collapse of the structure. Debris hazards may have occurred and egress may be impaired, however, all significant vertical load carrying elements (beams, columns, slabs, etc.) continue to function. In the worst case, post-earthquake damage inspectors, using ATC-20 methodology, would be expected to post such a building with a red placard. The building will likely be unsafe for occupancy and repair may not be technically or economically feasible.

* Note: ATC-20 (ATC, 1989) provides post-earthquake building investigators a set of procedures and guidelines to follow in order to make an “on-the-spot” determination of the suitability of occupancy and use of a building after an earthquake. A green placard designates the building as being safe to occupy. A yellow placard designates the building as being damaged and limits the occupancy and use of the building accordingly. A red placard designates the building as being unsafe to occupy and prohibits entry into the building.

The Vision 2000 document uses three different building use classifications and four earthquake design levels. The definitions of use classifications follow and the earthquake design levels are shown in Table 2.4.

- Safety Critical Facilities – Facilities which contain large quantities of hazardous materials, which would cause an unacceptable risk to the public if they were released.

- Essential/Hazardous Facilities – Facilities that are critical to post-earthquake operations, including hospitals, police stations, fire stations, communications centers, emergency control centers and shelters for emergency response vehicles.

- Basic Facilities – All buildings that do not fit into one of the other two categories.
Table 2.4 – Earthquake Design Levels (SEAOC, 1995)

<table>
<thead>
<tr>
<th>Earthquake Design Level</th>
<th>Recurrence Interval</th>
<th>Probability of Exceedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td>43 years</td>
<td>50% in 30 years</td>
</tr>
<tr>
<td>Occasional</td>
<td>72 years</td>
<td>50% in 50 years</td>
</tr>
<tr>
<td>Rare</td>
<td>475 years</td>
<td>10% in 50 years</td>
</tr>
<tr>
<td>Very Rare</td>
<td>970 years</td>
<td>10% in 100 years</td>
</tr>
</tbody>
</table>

The recommended performance objectives for buildings in each category are shown in Figure 2.7. Acceptable damage levels to various building systems and components to meet each performance level are also given. The items covered are: vertical and horizontal structural components, architectural elements, mechanical/electrical/plumbing systems, and building contents.

Figure 2.7 – Recommended Performance Objectives for Buildings, reproduced from SEAOC (1995)
FEMA 356 and 357 (Prestandard and Commentary for the Seismic Rehabilitation of Buildings)

FEMA 356 and 357 are the replacements to FEMA 273 and 274, which were also known as NEHRP Guidelines for Seismic Rehabilitation of Buildings. FEMA 356 (FEMA, 2000b) defines building performance as “…the safety afforded building occupants during and after the event; the cost and feasibility of restoring the building to pre-earthquake condition; the length of time the building is removed from service to effect repairs; and economic, architectural, or historic impact on the larger community.” The performance is a direct relationship to the damage sustained by the building in a design event. When designing a building using FEMA 356 as a guide, the first thing that has to be done is to decide upon a rehabilitation objective. In order to meet the rehabilitation objective, the building must perform to a certain level in an earthquake event. In order to determine the performance of the building in an earthquake, FEMA 356 separates building components into two categories, structural and nonstructural. A Target Building Performance Level, which corresponds to a combination of a Structural Performance Level and a Nonstructural Performance Level, is then decided upon.

The Structural Performance Levels are:

- S-1 – Immediate Occupancy
- S-3 – Life Safety
- S-5 – Collapse Prevention
- S-6 – Not Considered

There are also two intermediate Structural Performance Ranges. They are:

- S-2 – Damage Control Range
- S-4 – Limited Safety Range

The Nonstructural Performance Levels are:

- N-A – Operational
- N-B – Immediate Occupancy
The Structural Performance Levels and the Nonstructural Performance Levels can be combined in any number of ways to reach a desired Target Building Performance Level or Range. The Target Building Performance Levels are shown in Table 2.5. The number in the Target Performance Level denotes the Structural Performance Level and the letter denotes the Nonstructural Performance Level. For example, the Collapse Prevention Level (5-E) corresponds to Structural Performance Level S-5 and Nonstructural Performance Level N-E.

Table 2.5 – Damage Control and Building Performance Levels Recommended for Earthquake Rehabilitation (reproduced from FEMA, 2000b)

So that a designer can know the allowable damage to a building component for each performance level, a large number of structural and nonstructural building components and corresponding maximum allowed damage to satisfy each performance level are given in tables. The structural elements are separated into two categories:
The nonstructural elements are separated into three categories:

- Architectural Components
- Mechanical, Electrical, and Plumbing Systems/Components
- Contents

An example of performance levels and associated damage is shown in Table 2.6 for three types of structural elements.

### Table 2.6 – Structural Performance Levels and Associated Damage (reproduced from FEMA, 2000b)

<table>
<thead>
<tr>
<th>Elements</th>
<th>Type</th>
<th>Collapse Prevention</th>
<th>Life Safety</th>
<th>Immediate Occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Frames</td>
<td>Primary</td>
<td>Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.</td>
<td>Extensive damage to beams. Spalling of cover and shear cracking (&lt;1/8” width) for ductile columns. Minor spalling in nonductile columns. Joint cracks &lt;1/8” wide.</td>
<td>Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).</td>
</tr>
<tr>
<td></td>
<td>Secondary</td>
<td>Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.</td>
<td>Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.</td>
<td>Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints &lt;1/16” width.</td>
</tr>
<tr>
<td>Drift</td>
<td></td>
<td>4% transient or permanent</td>
<td>2% transient; 1% permanent</td>
<td>1% transient; negligible permanent</td>
</tr>
<tr>
<td>Steel Moment Frames</td>
<td>Primary</td>
<td>Extensive distortion of beams and column panels. Many fractures at moment connections, but shear connections remain intact.</td>
<td>Hinges form. Local buckling of some beam elements. Severe joint distortion; isolated moment connection fractures, but shear connections remain intact. A few elements may experience partial fracture.</td>
<td>Minor local yielding at a few places. No fractures. Minor buckling or observable permanent distortion of members.</td>
</tr>
<tr>
<td></td>
<td>Secondary</td>
<td>Same as primary.</td>
<td>Extensive distortion of beams and column panels. Many fractures at moment connections, but shear connections remain intact.</td>
<td>Same as primary.</td>
</tr>
<tr>
<td>Drift</td>
<td></td>
<td>5% transient or permanent</td>
<td>2.5% transient; 1% permanent</td>
<td>0.7% transient; negligible permanent</td>
</tr>
<tr>
<td>Braced Steel Frames</td>
<td>Primary</td>
<td>Extensive yielding and buckling of braces. Many braces and their connections may fail.</td>
<td>Many braces yield or buckle but do not totally fail. Many connections may fail.</td>
<td>Minor yielding or buckling of braces.</td>
</tr>
<tr>
<td></td>
<td>Secondary</td>
<td>Same as primary.</td>
<td>Same as primary.</td>
<td>Same as primary.</td>
</tr>
<tr>
<td>Drift</td>
<td></td>
<td>2% transient or permanent</td>
<td>1.5% transient; 0.5% permanent</td>
<td>0.5% transient; negligible permanent</td>
</tr>
</tbody>
</table>
The ICC Performance code (ICC, 2001) places all buildings into one of four Performance Groups. The Performance Group of a building corresponds with the Category (I, II, III, or IV) of the building as defined in Table 1-1 in ASCE 7-02, entitled “Classification of Buildings and Other Structures for Flood, Wind, Snow, and Earthquake Loads” (ASCE, 2002). Category I buildings are classified as structures that “represent a low hazard to human life in the event of failure,” such as minor storage facilities and agricultural facilities. Category III buildings are defined as structures that “represent a substantial hazard to human life in the event of failure,” such as school facilities. Category IV buildings are defined as essential facilities, such as hospitals, fire, rescue, and police stations. Category II includes all buildings that do not fit into any of the other Categories. For example, if a building falls into Category I in Table 1-1 of ASCE 7-02, then the building is in Performance Group I.

For various magnitudes of the design event under consideration, there is an allowable level of impact (mild, moderate, high, severe) to buildings in each of the Performance Groups (I, II, III, IV). The magnitude of the design event is broken into four levels; small (frequent), medium (less frequent), large (rare), and very large (very rare). The Mean Recurrence Interval (MRI) associated with each design event is different depending upon the type of hazard.

The choice of recurrence interval corresponding to each magnitude of design event is to be decided upon by the designer. The relationship between the allowed level of damage to a building in each of the four Performance Groups for each magnitude of design event is shown in Table 2.7, followed by definitions of the impact levels. The Mean Recurrence
Interval (MRI) associated with each design event is different depending on the type of hazard, as shown in Table 2.8.

Table 2.7 – Maximum Level of Damage to be Tolerated Based on Performance Groups and Design Event Magnitudes, reproduced from the International Performance Code for Buildings and Facilities (ICC, 2001)

The impact levels are defined as:

**Mild Impact**

- **Structural Damage.** There is no structural damage and the building or facility is safe to occupy.

- **Nonstructural Systems.** Nonstructural systems needed for normal building or facility use and emergency operation are fully operational.

- **Occupant Hazards.** Injuries to building or facility occupants are minimal in number and minor in nature. There is a very low likelihood of single- or multiple life loss. (1,2)

- **Overall Extent of Damage.** Damage to building or facility contents is minimal in extent and minor in cost. (1)

- **Hazardous Materials.** Minimal hazardous materials are released to the environment.
Moderate Impact

- **Structural Damage.** There is moderate structural damage, which is repairable; some delay in re-occupancy can be expected.

- **Nonstructural Systems.** Nonstructural systems needed for normal building or facility use and emergency operation are fully operational, although some cleanup and repair may be needed. Emergency systems remain fully functional.

- **Occupant Hazards.** Injuries to building or facility occupants may be locally significant, but general moderate in numbers and in nature. There is a low likelihood of single life loss, very low likelihood of multiple life loss. (1,2)

- **Overall Extent of Damage.** Damage to building or facility contents may be locally significant, but is generally moderate in extent and cost. (1,2)

- **Hazardous Materials.** Some hazardous materials are released to the environment, but the risk to the community is minimal. No emergency relocation is necessary.

High Impact

- **Structural Damage.** There is significant damage to structural elements, but no large falling debris; repair is possible. Significant delays in re-occupancy can be expected.

- **Nonstructural Systems.** Nonstructural systems needed for normal building or facility use are significantly damaged and inoperable; egress routes may be impaired by light debris; emergency systems may be significantly damaged, but remain operational.

- **Occupant Hazards.** Injuries to building or facility 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 single life loss, with a low probability of multiple life loss. (1,2)

- **Overall Extent of Damage.** Damage to building or facility contents may be locally total and generally significant. (1,2)

- **Hazardous Materials.** Hazardous materials are released to the environment with localized relocation needed for buildings and facilities in the immediate vicinity.

Severe Impact

- **Structural Damage.** There is substantial structural damage, but all significant components continue to carry gravity load demands. Repair may not be technically possible. The building or facility is not safe for re-occupancy, as re-occupancy could cause collapse.
o **Nonstructural Systems.** Nonstructural systems needed for normal building or facility use may be completely nonfunctional. Egress routes may be impaired; emergency systems may be substantially damaged and nonfunctional.

o **Occupant Hazards.** Injuries to building or facility occupants may be high in numbers 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. (1,2)

o **Overall Extent of Damage.** Damage to building or facility contents may be total. (1,2)

o **Hazardous Materials.** Significant hazardous materials are released to the environment, with relocation needed beyond the local vicinity.

1. Applies only to hazard-related loads.

2. The nature of the applied load (i.e., fire hazard) may result in higher levels of expected injuries and damage in localized areas, whereas the balance of the areas may sustain fewer injuries and less damage.

Table 2.8 – MRI Associated with Each Design Event (ICC, 2001)

<table>
<thead>
<tr>
<th>Magnitude of Design Event</th>
<th>Type of Hazard</th>
<th>Wind</th>
<th>Flood</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind</td>
<td>Flood</td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td>50 years</td>
<td>100 years</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>75 years</td>
<td>500 years</td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>100 years</td>
<td>See note below</td>
<td></td>
</tr>
<tr>
<td>Very Large</td>
<td>125 years</td>
<td>See note below</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rain</th>
<th>Drainage System</th>
<th>MRI (years)</th>
<th>Storm Duration (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Primary</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>Small</td>
<td>Secondary</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>Medium</td>
<td>Primary</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Medium</td>
<td>Secondary</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Large</td>
<td>Primary</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Large</td>
<td>Secondary</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>Very Large</td>
<td>Primary</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Very Large</td>
<td>Secondary</td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>

Note: Floods of greater mean return periods shall be determined on a site-specific basis.
2.2.3 Consequence-Based Engineering - A New Form of Performance-Based Design

The earthquake engineering community has recently introduced a new design approach (Abrams and Beavers, 2002) for building structures located in earthquake hazard areas. This new design approach is called Consequence-Based Engineering and it is in some ways similar to the Performance-Based design approach, but applied at a systems level. The purpose of Consequence-Based Engineering is to “provide engineers with a new framework for minimizing losses due to property damage, human life, and business interruption, that implicitly considers system-related losses when prescribing mitigation actions.” In other words, this design approach looks at minimizing monetary loss to the building owner and all “stakeholders” from an earthquake or other natural hazard, considering not only the performance of the structure itself, but also the ability to continue with “business as usual” as soon as possible after the event with as little interruption as possible. In order to achieve this goal, four processes are outlined in order to define the possible consequences of a natural hazard and ways to reduce the impact of these consequences. These four processes are described below:

- **Rapid Assessment**

  The first step of the rapid assessment is to define the system of interest. Second, a rapid estimate of the consequences of the natural hazard is performed. Third, the acceptable consequences of the natural hazard are defined. The results of this are used to decide if the consequences of the natural hazard are such that a more detailed study needs to be performed and if major system changes are likely.

- **Decision Making**
In the decision making process, it is determined if the consequences determined in the rapid assessment are acceptable and if not, what steps need to be taken to rectify the situation.

- **Damage Synthesis**

  The damage synthesis process is a detailed study performed using the latest research and knowledge of the natural hazard event and building performance, and the resulting impact on the system of interest. The damage synthesis process is designed to be very flexible so that the latest knowledge of the above-mentioned parameters can be input into the model.

- **Consequence Minimization**

  During the consequence minimization process, all of the various system options are studied to determine the system that will be most beneficial to the building owner and the stakeholders.

2.2.4 **Summary**

As described on the previous pages, performance-based design is a relatively new design concept that has received much attention from the earthquake engineering community in recent years. Performance-based designs generally result in a more economical building design by allowing for the use of the latest technology, materials, and construction practices (Harris, 2002). Also, the performance-based design approach generally results in a more efficient design by allowing for different levels of damage depending on the relative importance of the building. Several precodes, codes, and standards have been written within the past few years that are committed solely to the performance-based design approach. The general concepts outlined in these documents are adapted to create a set of guidelines for the
performance-based design of facilities designated as essential during a hurricane event, as shown in Chapter 3.

2.3 Wind, Wind Load, and Load Combinations

Following is a review of the development of wind loads and load combinations used in the ASCE 7 standard (Minimum Design Loads for Buildings and Other Structures) throughout the years, with emphasis on aspects that pertain to hurricane winds. The intent of this review is to give an overview of the advances in the knowledge of the effect of wind on structures (with special emphasis on the effect of hurricane winds) and how this has affected the design of structures against the effects of wind. Also included is an overview of selected papers that were not referenced in the ASCE 7 standard but provide additional information on hurricane winds.

2.3.1 ANSI A58.1-1982

The precursor to the ASCE 7 standard was produced by the American National Standards Institute (ANSI) and was entitled ANSI A58.1, Minimum Design Loads for Buildings and Other Structures. The wind load chapter and the load combinations in the 1982 version (ANSI, 1982) were not changed in the 1988 version (ASCE, 1988), produced by ASCE. The information provided in the review of ASCE 7-88 in the following section can also be applied to ANSI A58.1-1982.

2.3.2 ASCE 7-88

The ASCE 7-88 (ASCE, 1988) provisions concerning the wind loads on structures are discussed in the following section. Information regarding load factors and load combinations, as is the case throughout this thesis, refers to those used for strength design. No reference is made to allowable stress design, which is now obsolete.
• **Basic Wind Speed Definition**

The basic wind speed is defined as the fastest-mile wind speed at 33 ft (10 meters) above the ground in terrain Exposure C (open terrain with scattered obstructions) and associated with an annual probability of occurrence of 0.02. Expressed another way, each year there is a 1/50 (2%) probability of the design wind speed being exceeded.

• **Inland Wind Speeds**

The data used by ASCE 7-88 to determine the design wind speed for the region of the United States not affected by hurricane winds, also called the extratropical region, was described in a publication by Simiu, et al. (1980) entitled “Extreme Wind Speeds at 129 Airport Stations.” The data from 129 airport stations with long, reliable wind records was used to formulate an empirical model to determine the statistics on the extreme wind speeds of the inland United States. It is important to note that none of the stations were subjected to hurricane winds. Therefore, this data is only to be used in extratropical regions of the United States. The data presented is meant to be used as a tool to evaluate the design wind speed for a given inland area. The results of this paper lead the researchers to conclude that the extreme wind speeds experienced by inland regions of the United States are best defined by a Fisher-Tippett Type I extreme value distribution. The paper points out that some stations seemed to have a Type II probability distribution, but this is likely due to sampling errors.

• **Wind Speeds at the Hurricane Coast**

Researchers recognized that a difference existed between extratropical and hurricane winds. At the time, however, the correct extreme probability distribution of hurricane winds was not yet known. The design wind speeds used in this edition of the Standard for the hurricane-prone regions of the United States were determined using research performed by Batts, et al. (1980). The Batts paper takes a great deal of information known about hurricane
winds and applies it to produce a number of probabilistic models defining the various characteristics of a hurricane, including maximum gradient wind speed, wind speeds at 10 m above the ocean surface, storm decay, reduction of wind speeds due to friction over land, and dependence of wind speeds upon averaging times. They then broke the hurricane coastline into a number of “mileposts,” spaced at 100 nautical miles (approximately 115 statute miles), and ran a large number of Monte Carlo simulations (based on the assumed probabilistic models) to determine extreme wind speeds for the hurricane-prone coast of the United States.

Based on the results of the Monte Carlo simulation it was found that the best probabilistic model for fitting 1-min hurricane winds was the Weibull distribution with tail length parameter ($\gamma$) of 4, as opposed to an Extreme Value Type I distribution. Design fastest-mile wind speeds for the entire hurricane coast of the United States (defined as the region from the coastline to 200 km inland) were then proposed. An important note is that the storm decay was found to be very weak at milepost 650 (in the vicinity of New Orleans.) It was assumed that this was due in part to the configuration of the coastline. They suggest that the probabilistic models be refined to account for this.

- **Importance Factor**

  The Importance Factor is used to adjust the design wind speed depending upon the Mean Recurrence Interval (MRI) chosen for the building being designed. The MRI used for design is selected based on the relative danger to life safety resulting from a collapse of the building. ASCE 7-88 gives two values for the Importance Factor, an importance factor to use at locations 100 miles and farther inland from a hurricane oceanline and a factor to use at the hurricane oceanline, with linear interpolation allowed for sites located in between. The importance factor used at the hurricane coastline is higher than the one used inland. This is to
account for the fact that a difference exists in the probability distributions of extratropical and hurricane winds.

- **Load Factor**

  The wind load factor used in ASCE 7-88 was obtained from Ellingwood, et al. (1980). The main purpose of the researchers was “to recommend a methodology and set of load factors and corresponding load definitions for use in the A58 Standard which would be appropriate for all types of building materials”. The basic idea was to get a uniform level of safety against failure for all loadings and building materials. A summary of the procedure used to determine the load factors and load combinations presented by Ellingwood follows:

  1) An analysis of the level of safety achieved by the use of the existing standards and specifications was performed.

  2) The reliability index ($\beta$) achieved by using the available design guides was investigated and a $\beta$ value to be used was chosen. It was found that a $\beta$ value of 2.5 was appropriate for use in load combinations involving wind load. The reliability index is defined as a measure of the probability of failure of a structure.

  3) The appropriate load factors and load combinations using the desired reliability index ($\beta$) were determined.

    Fastest-mile wind speeds were used for the analysis. The wind speed was assumed to have a Type I extreme value distribution. The wind load used in the load combinations is the result of the 50 year MRI wind speed, which was based on data from seven sites: Baltimore, MD; Detroit, MI; St. Louis, MO; Austin, TX; Tucson, AZ; Rochester, NY; and Sacramento, CA. All of the sites were inland and were chosen because they “span the range of data reported and provide broad geographical representation.” None of the sites were exposed to hurricane winds. The load factor included a reduction factor of 0.85 to account for wind directionality effects, which accounts for “the reduced probability that the maximum wind speed will occur in a direction most unfavorable to the response of (the) building.”
results of the research were directly integrated into ASCE 7 and are shown in the next section.

**Load Combinations**

Load combinations for strength design methods are listed below. Equation (4) maximizes wind effects when they act in the same direction as gravity and equation (6) maximizes wind effects when they counteract gravity. The load factor on the live load (L) in load combinations (3), (4), and (5) shall equal 1.0 for areas designated as places of public assembly, garages, and any other areas where the live load exceeds 100 lb/ft². Also, the Standard requires that the structural influence of F, H, P, and T loads be accounted for by the following factored loads: 1.3F, 1.6H, 1.2P, and 1.2T.

1. 1.4D
2. 1.2D + 1.6L + 0.5(L_r or S or R)
3. 1.2D + 1.6(L_r or S or R) + (0.5L or 0.8W)
4. 1.2D + 1.3W + 0.5L + 0.5(L_r or S or R)
5. 1.2D + 1.5E + (0.5L or 0.2S)
6. 0.9D – (1.3W or 1.5E)

where:

D = dead load  
E = earthquake load  
F = loads due to fluids with well-defined pressures and maximum heights  
L = live load  
L_r = roof live load  
S = snow load  
R = rain load, except ponding  
H = loads due to the weight and lateral pressure of soil and water in soil  
P = loads, forces, and effects due to ponding  
T = loads due to movement (shrinkage, settlement, etc.)  
W = wind load

### 2.3.3 ASCE 7-93

All aspects of the wind load portion of ASCE 7-93 (ASCE, 1993) remained the same as the 1988 version.
2.3.4 ASCE 7-95

- **Basic Wind Speed Definition**

  In ASCE 7-95 (ASCE, 1996) the definition of the basic wind speed was changed from fastest-mile to the 3-second gust speed at 33 ft (10 m) above the ground in Exposure C and associated with a 50 year MRI. The use of the 3-second gust wind speed required the changing of a number of the wind parameters used in the Standard.

- **Basic Wind Speed Map**

  The difference in the probability distributions of extratropical and hurricane winds is handled differently in ASCE 7-95. The separate Importance Factor in ASCE 7-88 for buildings located in the hurricane region was removed and the effects were accounted for in the Basic Wind Speed Map instead. Also accounted for in the basic wind speed map was the difference in the gust factor for extratropical and hurricane regions.

- **Inland Wind Speeds**

  The inland portion of basic wind speed map was produced from research performed by Peterka (1992). This research was intended to reduce the sampling error of 50 year wind speeds used in design due to the short data records of many of the sites. The assumption was made that the variation in the fifty year design wind speeds for small inland areas of the country with similar wind climates is due primarily to sampling error caused by short wind records and, in order to prove this assumption, an area in the Midwestern United States that exhibited an unexplained variation in the 50 year design wind speed was chosen for study. The area was composed of 29 weather stations with the same wind climate and exposure (all were located at airports). A wind map for the area enclosed by the 29 weather stations was then produced from the 924 years of data from the superstation along with 10,000 years of data produced by a random function generator with the same Type I distribution as the data
from the superstation. The author concluded that the wind speed map produced by creating contours between each individual station was not correct due to sampling error. The author also concluded that combining similar wind stations into a “superstation” greatly reduced the sampling error and therefore gave a better representation of the actual 50 year design wind speed. It was suggested that applying this type of procedure over the entire interior region of the United States had the potential to greatly reduce the variability in the design wind speed due to sampling error. This “superstation” philosophy for getting inland design wind speeds was applied to the entire inland United States to produce the map for the design wind speed of that region.

- **Wind Speeds at the Hurricane Coast**

  The hurricane-prone region of the basic wind speed map was produced by synthesizing the data and models of Batts (1980), described in Section 2.2.2, Georgiou, et al. (1983), and Vickery and Twisdale (1995a). The intention of the Georgiou work was to improve the prediction of the design wind speeds for the hurricane-prone regions of the United States through the use of a new hurricane model.

  Design wind speeds for regions of the United States dominated by hurricanes are predicted by the use of simulation techniques. This is done because the small number of hurricane events and the relatively small landmass exposed to the effects of a hurricane event would result in extremely high sampling errors if wind records were used to determine design wind speeds. A “Monte Carlo” simulation is used, which entails using computer techniques to pass a large number of different hurricane events over the hurricane coastline to determine the wind speed corresponding to various return periods. This technique requires simulation of both the frequency characteristics and the wind field characteristics of hurricanes. Table 2.9 summarizes the assumptions that were made in the Georgiou, et al. (1983) model.
Table 2.9 – Assumptions Made by Georgiou, et al. (1983) for Monte Carlo Simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Probability Distribution Function Used in the Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Occurrence Rate</td>
<td>Poisson</td>
</tr>
<tr>
<td>Minimum Approach Distance</td>
<td>Polynomial</td>
</tr>
<tr>
<td>Approach Angle</td>
<td>Von Mises</td>
</tr>
<tr>
<td>Central Pressure Difference</td>
<td>Weibull</td>
</tr>
<tr>
<td>Radius of Maximum Winds</td>
<td>Log-normal (conditionally dependent upon the CPD)</td>
</tr>
<tr>
<td>Translation Velocity</td>
<td>Log-normal</td>
</tr>
</tbody>
</table>

It was found that the Weibull distribution was best for modeling the Central Pressure Difference (CPD). The previous models of the CPD, which did not use the Weibull distribution, tended to overestimate the mean hourly extreme wind speed by approximately 10%. Also, the researchers pointed out that the rate of the rate of decrease of the gradient wind of a hurricane once it makes landfall is affected primarily by the CPD and not by the change in surface roughness, which mainly affects the surface wind.

The results of research by Vickery and Twisdale (1995a) were also used in ASCE 7-95 to determine the design wind speeds for the hurricane coast of the United States. These researchers produced a new hurricane model, the intent of which was to make new predictions of hurricane wind speeds in coastal regions and in inland regions of the United States. The researchers chose a number of hurricane-prone locations and a series of Monte Carlo simulations were performed using the latest hurricane wind field and filling models. All of the necessary hurricane parameters used in the hurricane model were chosen based on the most recent data and these parameters were then input into an updated Monte Carlo hurricane simulation model. The wind field model was based on work done by Shapiro (1983) entitled “The Asymmetric Boundary Layer Flow Under a Translating Hurricane.” The filling model used was presented in a separate paper by Vickery and Twisdale (1995b),
which also described the wind field. The 50-year and 100-year MRI wind speeds were found and compared to values obtained by previous researchers. The authors compared their results with those of Batts, et al. (1980), which were used in the previous versions of ASCE 7, and found that the Batts results tended to overestimate the hurricane wind speeds inland. Another important difference between the Vickery and Twisdale (1995a) results and the results obtained by Batts is the higher wind speeds along the coastline from New Orleans to the Florida panhandle that Vickery and Twisdale obtained. It was also found that as the MRI of the hurricane winds increased the difference between the Shapiro and Batts hurricane wind field models became larger, with the Shapiro model yielding higher wind speeds. Vickery and Twisdale also found that for an MRI of 50 to 100 years, the hurricane winds have almost no effect at distances greater than 100 km (62 miles) inland. They also suggest that if the MRI exceeds 100 years, however, the effects of the hurricane winds at distances greater than 100 km inland needs to be investigated, a factor that has been addressed since the publication of their paper.

- Importance Factor

As mentioned earlier, ASCE 7-95 only has one importance factor. The higher importance factor used in ASCE 7-88 for the hurricane region was incorporated into the basic wind speed map.

- Load Factor

The wind load factor in ASCE 7-95 was obtained from NBS SP 577 (Ellingwood, 1980), which was unchanged from the previous edition.

- Load Combinations

The six load combinations for strength design in ASCE 7-95 were modified slightly from the previous edition. Flood loads \(F_a\) were included for the first time. The definitions
for all other terms in the load combination equations were provided in Section 2.3.2. The Standard states the following, “The structural effects of $F_a$ shall be investigated in design using the same load factors as used for $L$ (live load) in the basic combinations of 2 and 4. The structural effects of $F_a$ shall also be included when investigating the overturning and sliding in the basic combination 6 using a load factor of 0.5 when wind also occurs and 1.6 when acting alone.” Other changes are highlighted in red. Note the change in sign in combination 6, which allowed for the use of a single and consistent sign convention for all loads (with loads in the gravity direction commonly taken as positive and uplift loads as negative).

1. $1.4D$
2. $1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R)$
3. $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (0.5L \text{ or } 0.8W)$
4. $1.2D + 1.3W + 0.5L + 0.5(L_r \text{ or } S \text{ or } R)$
5. $1.2D + 1.0E + 0.5L + 0.2S$
6. $0.9D + (1.3W \text{ or } 1.0E)$

2.3.5 ASCE 7-98

- Basic Wind Speed Definition
  The definition of the basic wind speed in ASCE 7-98 (ASCE, 2000) was not changed from the previous edition of ASCE 7. See Section 2.3.4 for an explanation of the basic wind speed.

- Basic Wind Speed Map (Including the Inland and Hurricane Regions)
  The wind speed map used in ASCE 7-98 was updated from the 1995 version based on the results of the latest research by Peterka and Shahid (1998) and Vickery, et al. (2000a and 2000b). Peterka and Shahid (1998) presented a new design wind speed map for the entire United States, including both the coastal and extratropical regions, to be used in the 1998 edition of ASCE 7. The new map included the effects of the use of a 3-second averaging
time (as was done in ASCE 7-95) and new wind speed records that had become available since the 1995 edition. The Vickery, et al. maps presented contours to be used along the hurricane prone areas of the coast.

In the extratropical region, Peterka and Shahid used the superstation-type analysis used in the 1995 edition, which combined stations with similar winds to form “superstations.” This had the effect of decreasing the sampling error and gave a more accurate design wind speed. This procedure was performed on extratropical 3-second gust data from 487 stations assuming a Type I extreme value distribution.

In the hurricane region, the design wind speeds presented by Peterka and Shahid (1998) were updated to account for the hurricane importance factor and were based on Monte Carlo simulations that used the statistical parameters of hurricanes assumed in Batts, et al. (1980), Georgiou, et al. (1983), and Vickery and Twisdale (1995a and 1995b). Peterka and Shahid (1998) used the assumptions inherent in each of these papers to establish a set of contours that most closely matched the results of previous work. For the inland speed of hurricane winds, a compromise was made between the work done by Batts, et al. (1980), which was slow to reduce hurricane winds inland, and the work done by Vickery and Twisdale (1995a and 1995b), which reduced inland hurricane winds more rapidly. The hurricane region of the basic wind speed map in ASCE 7-98 was also updated based on research by Vickery, et al. (2000a and 2000b). The authors used the latest data on hurricane winds to produce the best models for the predication of hurricane winds. Maps were given in Vickery, et al. (2000b) containing wind speeds corresponding to MRIs of 50, 100, and 500 years for the hurricane-prone regions of the United States.

Peterka and Shahid (1998) used different curves to adjust the wind speed to the 3-second averaging time wind speed. For the extratropical regions of the United States, they
used the Durst curve. For the hurricane region, however, research by Krayer and Marshall showed that hurricane winds are gustier than extratropical winds. This was accounted for by Peterka and Shahid when converting the averaging times for the hurricane regions. The Krayer-Marshall curve was also used by Vickery, et al. (2000b) for adjusting hurricane winds for different averaging times. ASCE 7-98, however, suggests that the Durst curve be used for both extratropical and hurricane regions. This appears to be a contradiction between some of the data ASCE 7-98 used in making their maps and the recommendations that are made in the standard.

- **Wind Directionality Factor**

  All previous versions of the ASCE 7 standard included a reduction factor of 0.85 in the wind load factor to account for the reduced probability of the worst wind coming from the worst direction. This reduction factor is a “Wind Directionality Factor.” The wind directionality factor was separated out of the wind load factor in ASCE 7-98 and was presented in a separate table, allowing values of the wind directionality factor to be based on the shape of the structure being designed.

- **Importance Factor**

  The use of different importance factors for hurricane-prone regions was brought back in ASCE 7-98. The only situation in which they are different, however, is for structures designed using an MRI of 25 years. Although the importance factors for the hurricane and non-hurricane regions are different, their use in their respective regions will result in approximately the same level of risk. The difference stems from the fact that, while the same type of probability distribution of wind speeds corresponding to long MRI events can be assumed to be the same for both the hurricane and extratropical regions, the same can not be said for wind speeds corresponding to a 25 year MRI.
• **Load Factors**

The load factors, with the sole exception being the earthquake load factor, were all derived from NBS SP 577 (Ellingwood, 1980), which was discussed previously. There is a good discussion of NBS SP 577 in Galambos, et al. (1982) and in Ellingwood, et al. (1982). Although derived from NBS SP 577, the wind load factor used in ASCE 7-98 is not the same as the one suggested by that publication. It was increased from 1.3 to 1.6, for the following reasons:

- The wind directionality factor of 0.85 discussed in Ellingwood (1981) and in NBS SP 577 (Ellingwood, 1980) has been removed from the cumulative distribution function (c.d.f.) of the wind load factor and has been added to the wind load portion of ASCE 7-98 to allow for the latest knowledge of how different structures react differently to wind. This change increased the wind load factor from 1.3 to approximately 1.53.

- The value of 1.3 computed in NBS SP 577 (Ellingwood, 1980) for the wind load factor and used in all previous editions of ASCE 7 did not account for hurricane winds; all of the data used to arrive at the load factor was from extratropical regions (Ellingwood, 1981). There is a good discussion on the wind load factor in the hurricane region in Ellingwood and Tekie (1999). Ellingwood and Tekie pointed out the deficiencies of using the 1.3 load factor used in all previous versions of ASCE 7 and points out the following issues of contention about the 1.3 load factor:
  
  1. The use of a reliability index of 2.5 for load combinations involving wind load as compared to 3.0 for load combinations involving only gravity loads is called into question. It is questioned if this gives a lower level of reliability when wind load governs the design.

  2. The directionality factor being included in the load factor is questioned. It is suggested that the directionality factor be removed from the load factor and made to be a stand-alone value so that it can be accounted for on a case by case basis, as was done in ASCE 7-98.

  3. The wind pressures used in the design of the Main Wind Force Resisting System (MWFRS) and the Components and Cladding (C&C) are questioned.

  4. The probability model used in NBS SP 577(Ellingwood, 1980) to determine the load factor is called into question. The load factor used was a Fisher-Tippett Type I extreme value distribution, while later research suggests that a Type III distribution (Weibull) might be a better representation of hurricane winds.
Ellingwood and Tekie (1999) also concluded the following:

- The wind load variability is higher for hurricane-prone regions.
- For the load case where wind load controls the design (with no account for directionality) the wind load factor should be between 1.5 and 1.6 to achieve the same reliability as the load case where live load controls the design.
- For buildings within 10 km of the coastline, it appears that the wind load factor should be between 1.6 and 1.7. This is due to the increased coefficient of variation of hurricane winds as compared to extratropical winds.

An interesting note on page 246 of ASCE 7-98 says: “Of the uncertainties affecting the wind load factor, the variability in wind speed has the strongest influence (Ellingwood and Tekie, 1999), such that changes in the coefficient in variation in all other factors by 25% gives less than a 5% change in load factor.”

- **Load Combinations**

  The main changes in the load combinations were the increase of the wind load factor from 1.3 to 1.6 as shown in the following equations, and changes in the flood load combinations. The changes from the 1995 edition are shown in red.

1. \(1.4(D + F)\)
2. \(1.2(D + F + T) + 1.6(L + H) + 0.5(L_r \text{ or } S \text{ or } R)\)
3. \(1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (0.5L \text{ or } 0.8W)\)
4. \(1.2D + 1.6W + 0.5L + 0.5(L_r \text{ or } S \text{ or } R)\)
5. \(1.2D + 1.0E + 0.5L + 0.2S\)
6. \(0.9D + (1.6W \text{ or } 1.0E)\)

For definitions, see Sections 2.3.2 and 2.3.4. For structures located in a Special Flood Hazard Area, which is defined as an area in the floodplain subject to a 1% or greater chance of flooding in any given year, the standard specifies that the following load combinations shall be considered:

1. In V Zones or Coastal A Zones, \(1.6W\) in combinations (4) and (6) shall be replaced by \(1.6W + 2.0Fa\). V Zones are defined as the area “extending from offshore to the
inland limit of a primary frontal dune along an open coast, and any other area which
is subject to high velocity wave action from storms or seismic sources.” Coastal A
Zones are areas “landward of a V Zone or landward of an open coast without mapped
V Zones.” The primary source of flooding must be from storm surges or the like, not
riverine flooding.

2. In Non-coastal A Zones, 1.6W in combinations (4) and (6) shall be replaced by 0.8W
   + 1.0Fa. Non-coastal A Zones are areas where the primary source of flooding is from
   riverine sources or ponding, not from storm surge.

2.3.6 ASCE 7-02

The calculation of design wind pressures on structures changed very little in ASCE 7-
02 (ASCE, 2002) from ASCE 7-98. The primary changes are to the Exposure Categories and
in the definition of debris impact resistant glazing. Specifically, Exposure Category A was
completely eliminated and the definition of Exposure Categories B and C were modified.
Also, in order for an opening component to be deemed “debris impact resistant” ASCE 7-02
requires that the component meet the requirements of ASTM E 1886 and ASTM 1996
(ASTM, 2001; ASTM, 1997). A new load combination was also added. The new load
combination is 0.9D + 1.0E + 1.6H, which only affects buildings subject to earthquakes.

2.3.7 Additional Recent Research on Hurricane Wind Speed, Distributions, and Load
Factors

Simiu (1995) provided an overview of the current knowledge about high-speed wind
events. Simiu pointed out that, due to the complex nature of wind, the current state of
practice when determining wind load factors to be used in design is to use traditional values
that have worked in the past, a practice commonly referred to as “calibration against current
practice.” Due to advances in the understanding and modeling of wind events, Simiu stated
that it is now questionable if the traditional values are conservative enough, especially for
hurricane events. A few key points were addressed by Simiu concerning the calculation of wind loads due to extreme wind events, including the effects of turbulence and wind directionality. Also, a number of different methods used to determine wind loads resulting from extreme wind speeds were discussed. Simiu made a very interesting comment, that if nominal loads (50 year MRI) are of concern, the type of probability distribution used makes little difference (less than 5%), but if the extreme loads or load factors are of concern, the use of the incorrect distribution can have a large effect on the results obtained. Simiu suggests that extreme wind speeds may be best fit by a reverse Weibull distribution due to the fact that the reverse Weibull has a finite upper tail, just as wind speeds do.

Simiu, et al. (1998) again stated that the reverse Weibull distribution is best for extreme wind speeds in both the hurricane and non-hurricane regions, but the type of distribution used for nominal wind loads makes little difference. Also, the researchers stated that the use of the wind directionality factor of 0.85 for structures with long MRI may be unconservative. The researchers also stated that using the wind speed map given in ASCE 7-93 for the hurricane regions of the United States can lead to inconsistent MRIs when compared to the MRI obtained using the map for extratropical regions.

Simiu, et al. (1998) also addressed the wind load factor. The wind load factor used in ASCE 7 was determined from results obtained from extratropical regions. The researchers determined that the use of the same load factor for the hurricane regions of the United States is questionable. Even with the use of the “hurricane importance factor”, which was included in the basic wind speed map of ASCE 7, the MRI of the ultimate wind load (wind load causing collapse) in the hurricane-prone regions of the United States are much shorter than the ultimate wind load for the extratropical regions.
Simiu and Heckert (1998) used the “peaks over threshold” approach for estimating extreme winds specifically hurricane winds, taking wind directionality effects into account. They found that for wind events with very large MRI the effects of directionality need to be considered, or the design may not be conservative enough. They also found that for a structure designed using ASCE 7-95; the MRI of the design wind speed for hurricane regions was much lower than the MRI of the design wind speed in extratropical regions, which they suggest may play a role in the large losses incurred during hurricane events.

One of the things Rigato, et al. (2001) addressed was the inadequacy of using the 0.85 wind directionality factor proposed by ASCE 7-98 for many buildings located in hurricane prone regions. For wind events with long MRIs (on the order of 500 years or more) the use of the 0.85 wind directionality factor recommended by ASCE 7-98 underestimates the wind load on the structure. A value of 0.95 is recommended until more research can be done.

Whalen and Simiu (1998) suggested that the wind load factor used in ASCE 7-95 results in structures in the hurricane-prone region being placed at a higher risk than those in the extratropical region and that for this reason, the wind load factor for buildings in the hurricane regions of the United States should be increased. They also suggested that the reverse Weibull extreme value distribution is best when modeling extreme winds, instead of the Type I distribution. Wind directionality effects were not taken into account in this paper.

 Heckert, et al. (1998) addressed the apparent increase in the level of risk of a building along the hurricane coast when subjected to the design wind speed using ASCE 7-95 as compared to a building located in the extratropical regions of the country. They used a reverse Weibull (finite upper tail) distribution in order to model extreme winds, as was used in ASCE 7-95. In order to determine the wind speed corresponding to a given MRI, the researchers broke the United States into a number of “Mileposts” spaced at 100 nautical mile
intervals, and the tail length parameter, c, and the mean hourly wind speed, Xr, was
determined for MRIs of 25, 50, 100, 1000, and 2000 years. From their research, the authors
stated that the risk level for buildings located in hurricane-prone regions and extratropical
regions of the country are inconsistent when designed using the wind speed map in ASCE 7-95. More specifically, buildings located in the hurricane-prone region are placed at a higher
level of risk. It was determined that the MRI of the ultimate wind speed for buildings along
the hurricane coast designed using ASCE 7-95 would be on the order 500 years, while the
MRI of the ultimate wind speed for a building in the extra-tropical regions would be two
orders of magnitude greater. It was suggested that the load factor in ASCE 7-95 be increased
to account for this difference. No recommendation was given; however, as to what the
amount the load factor should be increased.

Kriebel, et al. (1997) performed a reliability study using the latest information on
hurricane characteristics. It was found that in order to achieve a reliability index of
approximately 2.5, as is done in NBS SP 577, the load factor on hurricane winds is required
to equal 1.8.

Minciarelli, et al. (2001) pointed out the fact that the safety indices for wind loads are
currently not the same as those for dead and live loads in load combinations. One of the
things the researchers attempted to do was determine the required wind load factor in order
for wind loads to have the same safety indices as dead and live loads. Also, the increased
uncertainty for hurricane winds as opposed to extratropical winds is not taken into account in
ASCE 7-98. This paper determined the required wind load factor accounting for knowledge
uncertainties. They found that, without consideration for wind directionality factors, the
correct wind load factor for hurricane winds should be approximately 2.15.
2.3.8 Summary

The knowledge gained through research the past twenty or thirty years has greatly advanced the field of wind engineering. Much has been learned about the characteristics of high-wind events, particularly hurricanes. This knowledge has been reflected in each edition of ASCE 7, leading to much more efficient and safer structures, in general. As shown by data presented previously, however, the design methodology suggested by this thesis for designing structures designated as essential during hurricane events requires a deviation from some of the parameters presented by ASCE 7.

2.4 Inland Decay of Hurricane Wind Speeds

For areas along the Gulf Coast and the hurricane-prone regions of the Atlantic Coast of the United States, the design wind speeds are based on winds produced by hurricane events. An inspection of ASCE 7-02 will show that the design wind speed for coastal regions is a maximum at the coastline and decreases with distance inland from the coast, until the hurricane winds are no longer strong enough to affect the design wind speed. The wind speeds associated with a hurricane decrease once the hurricane strikes the coast. This is due to:

- Once the hurricane makes landfall, the source of its energy (the warm, moist waters of the Gulf of Mexico and the Atlantic Ocean) is cut off.
- The increased friction over the land as compared to the open water causes the wind speed to be reduced.

The rate of decay of hurricane winds once the storm makes landfall has been a topic of much interest and research over the years. A discussion of the state of the practice of predicting the rate of decay of a hurricane once it makes landfall follows.

One of the first papers to address the filling of hurricanes over land was Malkin (1959). He provided reduction factors for reducing the maximum winds of a hurricane after
landfall, based on time since landfall. The data from thirteen storms was analyzed in order to determine the reduction factors. The maximum wind speeds were assumed to decrease in direct proportion to the square root of the average pressure depth of the thirteen storms studied. Two sets of reduction factors were given. One set reduced the winds based on a change in the pressure depth ($p_n - p_o$) and the other reduced the winds based on change in pressure gradient ($(p_n - p_o)/D_n$), where $p_o$ = central pressure (mb), $p_n$ = pressure at periphery (mb), and $D_n$ = average distance from the pressure center to the point where $p_n$ is observed (degrees latitude). Two sets of reduction factors were presented because it was noticed that the wind speeds of some storms seemed to decrease in direct proportion to the change in the pressure depth, while others seemed to decrease in direct proportion to the change in the pressure gradient. The two sets of reduction factors are shown in Table 2.10

Table 2.10 – Factors for Reducing Hurricane Wind Speeds Over Land, (Malkin, 1959)

<table>
<thead>
<tr>
<th>Time After Landfall (hours)</th>
<th>Adj. Ratio for Wind Speeds (based on change in pressure depth)</th>
<th>Adj. Ratio for Wind Speeds (based on change in pressure gradient)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfall</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>0.98</td>
<td>0.92</td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>0.94</td>
<td>0.85</td>
</tr>
<tr>
<td>4</td>
<td>0.92</td>
<td>0.82</td>
</tr>
<tr>
<td>5</td>
<td>0.90</td>
<td>0.80</td>
</tr>
<tr>
<td>6</td>
<td>0.88</td>
<td>0.78</td>
</tr>
<tr>
<td>7</td>
<td>0.86</td>
<td>0.76</td>
</tr>
<tr>
<td>8</td>
<td>0.85</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Malkin also made the following observations:

- Generally, the lower the central pressure, at landfall or after landfall, the higher the corresponding rate of filling, and vice versa.

- A higher ratio of water to land in the underlying surface helps maintain the strength of a hurricane.
The reduction of the peak gust wind speeds of a hurricane after landfall for three hurricane events since Malkin’s study was given in Goldman, et al. (1974). The results of Goldman’s research, along with a comparison to Malkin’s work are shown in Figures 2.8, 2.9, and 2.10.

Figure 2.8 – Reduction of Wind Speeds of Hurricane Carla, reproduced from Goldman, et al. (1974)
Figure 2.9 – Reduction of Wind Speeds of Hurricane Camille, reproduced from Goldman, et al. (1974)
In summary, Goldman’s research determined the reduction factor for the peak gust wind speed of a hurricane event after landfall to be approximately 0.90, 0.80, and 0.70 for
locations 50, 100, and 150 km inland, respectively. As shown in Figures 2.8, 2.9, and 2.10, the values for the reduction factors agree somewhat with Malkin’s reduction factors. It is pointed out, however, that there are large local differences, which are not accounted for by Malkin’s factor, and which should be accounted for in the future. Goldman also pointed out that the wind speed in Hurricane Celia, which struck Corpus Christi Bay, actually increased once the hurricane made landfall. This is assumed to have occurred due to the added time over water because the hurricane entered the coastline at the bay, along with the impact the warm, shallow water had on feeding the hurricane.

Schwerdt, et al. (1979) also addressed the filling of a hurricane once it makes landfall. The researchers broke the United States into three separate regions and developed a different formula for decreasing the sustained wind speeds due to filling as a hurricane moves inland. For the Gulf Coast region (Region A), the following equation was given for calculating the reduction factor of the hurricane wind speeds. Note that the formula depends on the time since landfall only, and does not account for the size of the hurricane or the forward speed of the hurricane.

\[
\frac{W_I}{W_C} = e^{(-.035t+.00013t^2)}
\]

where \( W_I \) = overland wind speed at some specified time after landfall (friction effects not considered); \( W_C \) = the overwater wind speed at landfall; and \( t \) = time, in hours. A graph of the results of this formula is shown in Figure 2.11. It is important to note that this equation does not address the effect of surface friction on the filling of hurricane winds. Also, the reduction factor presented was for sustained winds, not peak gust wind speeds, as was the case in Malkin (1959).
Another publication that addressed the filling rate of hurricane winds is Batts, et al. (1980). When determining the rate of decay of a hurricane once it makes landfall, the researchers assumed the decay of the hurricane was a function of the decrease in the difference between the pressure at the center and the outer edge of the hurricane. (i.e., the difference between the pressure at the outer edge of the storm and at the center of the storm decreases once the storm makes landfall). The relationship was assumed to be:

\[ \Delta p(t) = \Delta p_{\text{max}} - 0.02[1 + \sin \phi]t \]

where \( t \) = travel time in hours (\( t \) at landfall = 0); \( \Delta p(t) \) and \( \Delta p_{\text{max}} \) in inches of Hg; and \( \phi \) = angle between the track of the hurricane and the coast (from 0 to 180 degrees).

Also noted in Batts, et al. (1980) was the fact that the wind speeds associated with a hurricane are reduced at landfall due to the increased friction of the surface of the land as...
compared to the open ocean exposure. Batts referenced the following sources that discuss this topic:

- *(Revised Standard Project Hurricane Criteria for the Atlantic and Gulf Coasts of the United States, Memorandum HUR 7-120, U.S. Department of Commerce, NOAA, June, 1972)* estimated a value of 0.78 for reducing overwater hurricane strength wind speeds to overland wind speeds.


\[
\frac{V^i(10)}{V^w(10)} = \frac{1}{0.2p \ast \ln \frac{10}{z_o}}
\]

where the values of the reduction factor \(p\) and the roughness coefficient \(z_o\) were assumed to be 0.83 and 0.005 m respectively, yielding a reduction factor of 0.79. Batts, et al. (1980) eventually selected a conservative value of 0.85 as the reduction factor between the 10-minute mean wind speed of overland and overwater (at a height of 10 m). This value was conservatively taken to be greater than the value obtained using the preceding equation, due to the fact that the similarity relationships used to formulate that equation were for geostrophic winds, which do not represent the winds in a hurricane.

Batts, et al. (1980) also presented fastest-mile hurricane wind speeds at the coastline and at 200 km (124 miles) inland corresponding to various Mean Recurrence Intervals (MRIs). This is shown in Figures 2.12 (a) and (b). Linear interpolation is allowed for locations between these points. The coastal locations corresponding to the mileposts are shown in Figure 2.13. It was found that the results obtained using their decay model differed from those obtained by Malkin (1959) by only approximately 2%. Also, it was found that hurricanes decayed very slowly as they moved inland at milepost 650 (the New Orleans area). It was suggested that this may be due to the large bodies of water near the coastline and that future research needs to be performed on these types of locations.
Figure 2.12 (a) – Estimated Fastest-Mile Hurricane Wind Speeds Blowing From Any Direction at 10 m Above Ground in Open Terrain Near the Coastline and (b) – at 200 km Inland, reproduced from Batts, et al. (1980)
Georgiou, et al. (1983) used significantly different models than Batts, et al. (1980) for the central pressure difference and rate of decay. The rate of filling in Georgiou’s research was assumed to be a function of a filling parameter \( f_d \) that varies depending upon the coastal region in which the structure is located. The filling parameter accounts for the decrease in the central pressure difference and also accounts for the change in the wind profile of the hurricane as it makes landfall and moves inland. The following formula is
suggested for determining the filling rate of mean hourly hurricane winds in the coastal region from New Orleans, LA to Apalachicola, FL (the Gulf Coast region):

\[ \frac{\Delta p}{\Delta p_o} = \frac{1}{1 + \left( \frac{d}{f_D} \right)^2} \]

where \( \Delta p \) = central pressure difference, \( \Delta p_o \) = central pressure difference at landfall, \( d \) = distance traveled inland after landfall (km), and \( f_D \) (filling parameter) = 150 for the Western Gulf Coast (Tampico, Mexico to Houston, TX) and 350 for the Mid Gulf Coast (from New Orleans, LA to Apalachicola, FL) (no units). It should be noted that this model used distance inland as the measurement of decay, instead of time since landfall, as is the case with many other cited sources.

The wind speeds corresponding to various mean recurrence intervals calculated using the model presented in Georgiou, et al. (1983) were given for the entire Gulf Coast and part of the Atlantic Coast. These results are shown in Figure 2.14 along with comparisons with the results obtained by Batts, et al. (1980). Georgiou’s results match rather closely with Batts results in the Atlantic Coast region as well as the Gulf Coast region from New Orleans to the Florida peninsula. Batts results are approximately 10-15% less than Georgiou’s over the Florida peninsula.

Georgiou et al. (1983) also noted that “An important observation concerning the behavior of tropical cyclones making landfall is that, at least for the first 10 to 15 hours, gradient wind speeds are substantially affected only by the change to the central pressure and not by surface changes which serve mainly to decrease surface wind speeds.”
Research by Ho, et al. (1987) also addressed the rate of fill of hurricanes, but did not give a suggestion as to how the filling of hurricane winds affects the wind speed. This paper divided the coastline of the United States into three regions; Region A (the Gulf Coast), Region B (the Florida peninsula), and Region C (the Atlantic Coast) and gives a rate of fill, which is based on the pressure deficit at landfall, for time since landfall. It is important to note that the regions are similar to those used by Schwerdt, et al. (1979), but are not identical. Only the findings for Region A (the Gulf Coast) will be discussed here, as this is the only region covered by this thesis. The filling rate for Region A as the hurricane moves inland is shown in Table 2.11 for various initial (land falling) central pressure deficits.
Table 2.11 – Pressure Deficit vs. Time After Landfall, from Ho, et al. (1987)

<table>
<thead>
<tr>
<th>Time After Landfall (hrs)</th>
<th>Pressure Deficit (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40 60 80 85 90 95 100 105 110</td>
</tr>
<tr>
<td>2</td>
<td>34 51 68 72 76 78 80 81 82</td>
</tr>
<tr>
<td>4</td>
<td>30 44 59 63 66 67 68 69 70</td>
</tr>
<tr>
<td>6</td>
<td>26 40 53 56 58 59 60 61 62</td>
</tr>
<tr>
<td>8</td>
<td>22 34 45 48 50 51 52 53 54</td>
</tr>
<tr>
<td>10</td>
<td>20 30 40 42 44 45 46 47 47</td>
</tr>
<tr>
<td>12</td>
<td>18 27 36 38 39 40 41 41 42</td>
</tr>
<tr>
<td>14</td>
<td>16 24 32 34 35 36 36 36 36</td>
</tr>
<tr>
<td>16</td>
<td>14 21 28 30 31 32 32 32 32</td>
</tr>
<tr>
<td>18</td>
<td>12 19 25 26 27 28 28 28 28</td>
</tr>
</tbody>
</table>

A new hurricane wind model and wind filling model was defined in Vickery and Twisdale (1995b). The wind field model is based on work done by Shapiro (1983). Three different wind filling models were used based on the region of the coast; Gulf Coast, Florida peninsula, and Atlantic Coast subject to hurricanes. The filling model used takes into account the fact that more intense hurricanes fill more rapidly than weak hurricanes. The basic form of the model is:

\[
\Delta p(t) = \Delta p_o \times \exp(-at)
\]

where \( \Delta p_o \) is the central pressure difference at landfall; \( t \) is the time since landfall in hours and the filling constant \( (a) \) is equal to:

\[
a = a_o + a_1 \Delta p_o + \varepsilon
\]

where \( a_o \) and \( a_1 \) are filling rate constants that vary depending on the region of the country and \( \varepsilon \) is a normally distributed error term with a mean of zero. The variation of the filling constant \( (a) \) versus the central pressure difference at landfall is shown in Figure 2.15. An
interesting thing to note is that, for the Gulf Coast region, the filling model best matched the observed data if a two hour delay was incorporated into the model.

Vickery and Twisdale’s results were compared to storm data and the results of other wind field and filling models. Their results were found to be slightly conservative for the Gulf Coast, while the Batts, et al. (1980) model was very conservative and that the conservatism increased with distance inland. They noted that the design wind speed (50 year MRI) appears to be influenced by hurricane events as far as 200 km (124 miles) inland using
the Batts model, while their model limits the influence of hurricanes on the design wind speed to approximately 100 km (62 miles) inland.

Kaplan and DeMaria (1995) developed a model to calculate the maximum sustained 1-minute surface wind speed (MSSW) of a hurricane, based on distance inland, as it moves inland,

\[ V(t) = V_b + (RV_o - V_b)e^{-at} - C \]

where, for the Gulf Coast region, \( V(t) \) = maximum sustained 1-minute surface wind speed (MSSW, in knots\(^1\)), \( V_b \) = background wind speed = 26.7 Kt, \( R \) = a reduction factor to account for the rapid decrease in wind speed as soon as the hurricane makes landfall = 0.9, \( V_o \) = maximum 1-minute sustained wind speed just before landfall, \( a \) = a decay constant = 0.095 h\(^{-1}\), and \( C \) is a correction factor for distance inland, given by:

\[ C = m[\ln(D/D_0)] + b \]

where, for the Gulf Coast region, \( m = c_1(t_o - t) \), \( b = d_1(t_o - t) \), \( c_1 = 0.0109 \) kt*\( h^{-2} \), \( d_1 = 0.0503 \) kt*\( h^{-2} \), \( t_o = 50 \) hours, and \( t \) = time since landfall (hours), \( D \) = distance inland (km), and \( D_o = 1 \) km.

Using this formula they examined different category hurricanes, moving at different speeds, and determined an envelope of the maximum wind speeds along the coast due to the given storm. The results were then plotted on a map of the coastal United States, an example of which is shown in Figure 2.16. The wind speeds shown are the maximum 1-min surface winds (in knots).

---

\(^1\) Abbreviated as Kt. 1 Kt = 1 nautical mile/hour = 1.15 mph = .514 m/s
2.5 Windborne Debris

Debris impact is a very important design consideration for any structure that is designed to resist a hurricane event. Many types of objects, including gravel, 2” x 4” wooden members, and sheets of plywood can be picked up and carried by hurricane-force winds. The consequences of impact of these types of objects to the building envelope can be quite extreme. If a building envelope component is not designed to resist the penetration of windborne debris, the debris and/or the building component(s) that are carried with it, can severely injure anyone inside the building. It is also possible for debris penetration to lead to a complete collapse of a structure. If the building envelope on the windward face of a structure is breached, positive internal pressurization will result, which increases the uplift on the roof and the negative pressure on the leeward wall of the building. Also, a breach in the
building envelope allows wind and water to enter the structure, causing damage to the building interior and contents. There are documented cases where the monetary damage to contents due to wind and rain entering the building have exceeded the value of the structure, while the building itself experienced little damage. This is often the case for an office building that has a large number of its windows broken by flying roof gravel.

2.5.1 Windborne Debris and Flight Characteristics

The debris generated by high-wind events can be classified into three primary categories: (1) Lightweight – roof gravel, etc; (2) Medium weight – timber plank, etc; and (3) Heavyweight – utility poles, automobiles, etc (McDonald and Bailey, 1985). The most important missile parameters relative to impact of a building component are the types of missiles anticipated, the speed of the missile, and the length the missile travels. There has been a great deal of research performed to determine the flight characteristics of windborne debris. Much of this research has focused on windborne debris generated by tornados, but there has recently been more research performed on windborne debris generated by hurricanes. Research was performed by Lee and Wills (2002) on three different types of objects (compact objects representative of roof gravel, rod-like objects representative of 2” x 4” timber planks, and sheet materials representative of plywood sheeting) in order to determine their theoretical flight characteristics in hurricane events. Their findings are shown in the following Tables. Also, Lee and Wills (2002) determined the minimum wind speed at which an 8’ long 2” x 4” wooden member would be lifted off of the ground to be approximately 70 mph. It was not clear what the averaging time of the wind speed discussed in both of these papers was. A paper by Wills, et al. (2002) also has information on the flight characteristics of wind borne debris. Table 2.12 gives the formulas given by Wills, et al. (2002) for the threshold of flight for various shaped objects. Table 2.13 gives the wind speed
at which a compact object (such as roof gravel) would be picked up in a wind speed (Will, et al., 2002).

Table 2.12 – Threshold of Flight for Various Shaped Objects, from Wills, et al. (2002)

<table>
<thead>
<tr>
<th>Type of Object</th>
<th>Threshold of Flight ($U^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact (roof gravel)</td>
<td>$U^2 = 2(\rho_m / \rho_a)(I / C_F)l^*g$</td>
</tr>
<tr>
<td>Rod-Like (2” x 4” wooden members)</td>
<td>$U^2 = \pi / 2(\rho_m / \rho_a)(I / C_F)d^*g$</td>
</tr>
<tr>
<td>Sheet Materials (Plywood Sheeting)</td>
<td>$U^2 = 2(\rho_m / \rho_a)(I / C_F)t^*g$</td>
</tr>
</tbody>
</table>

where: $\rho_m$ = material density; $\rho_a$ = air density; $I$ = fixity parameter based on attachment of the object (an object resting on the ground has $I = 1.0$); $C_F$ = force coefficient of the object; $l$ = typical dimension of the object; $d$ = equivalent diameter; $t$ = thickness; $g$ = acceleration of gravity

Table 2.13 – Diameter of Compact Objects (roof gravel) Transported for a Given Wind Speed, reproduced from Wills, et al. (2002)

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Material</th>
<th>Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Wood</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>Stone</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>Wood</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>Stone</td>
<td>9</td>
</tr>
<tr>
<td>40</td>
<td>Wood</td>
<td>200</td>
</tr>
<tr>
<td>40</td>
<td>Stone</td>
<td>37</td>
</tr>
</tbody>
</table>
Holmes (2001) made the following suggestions concerning distance traveled by windborne debris:

Time (in seconds) taken to accelerate from 0 to \( v_m \):

\[
D = U \left[ T - \left( \frac{1}{kU} \right) \ln(1 + kUT) \right]
\]

where:

\[
T = \frac{v_m}{kU(U - v_m)}
\]

where \( D \) is in meters; \( T \) is in seconds; \( v_m \) = missile speed (m/s); \( U \) = wind speed (m/s);

\[ k = \left( \frac{\rho_a C_D}{2 \rho_m l} \right) \]

(with units of 1/m); \( \rho_a \) = density of air (kg/m\(^3\)); \( C_D \) = coefficient of drag (no units); \( \rho_m \) = density of object (kg/m\(^3\)); \( l \) = length of object (meters)

Table 2.14 shows the time taken and the distance traveled for a steel ball and a timber missile to reach a given speed for a wind speed of 32 m/s. In discussion with Holmes, it was determined that the averaging time of the wind speed is not a peak gust wind speed, but rather a sustained wind speed on the order of one to ten minutes.

Table 2.14 – Flight Times and Distance Traveled for Two Objects, reproduced from Holmes (2001)

<table>
<thead>
<tr>
<th>Object/Final Speed</th>
<th>Time Taken (seconds)</th>
<th>Distance Traveled (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Ball* to 20 m/s</td>
<td>5.4</td>
<td>71</td>
</tr>
<tr>
<td>Steel Ball* to 30 m/s</td>
<td>49</td>
<td>1270</td>
</tr>
<tr>
<td>Timber Piece* to 20 m/s</td>
<td>69</td>
<td>910</td>
</tr>
<tr>
<td>Timber Piece* to 30 m/s</td>
<td>625</td>
<td>16300</td>
</tr>
</tbody>
</table>

*Steel Ball – 8 mm diameter and 2 gram mass
*Timber Piece – 50 mm x 100 mm cross section, 1.6 m long; and weighing 4 kg
One of the first recommendations made for the missile speed to use for testing building envelope components against the effects of medium weight debris impact was by Minor, et al. (1978). Minor suggested a 12’ long 2” x 4” wooden member traveling at ½ of the design wind speed of the building be used for testing the impact resistance of building envelope components. Wills, et al. (2001) and Lee and Wills (2002) made this same suggestion.

2.5.2 Debris Impact Resistance

Much research has been performed on the impact resistance of materials most commonly used in residential and commercial construction to determine the protection afforded occupants of a building subjected to flying debris generated in a high-wind event. These tests all entail firing various projectiles representative of the types of missiles common in the debris field of a high wind event.

A large amount of research has been performed over the years of the most common types of wall construction. Many researchers have tested the impact resistance of concrete masonry walls (commonly referred to as CMU walls). McDonald and Bailey (1985); McDonald (1990); McDonald (1992) used a compressed air cannon at Texas Tech University to fire 2” x 4” missiles at different types of walls to test their debris impact resistance. Both reinforced and unreinforced CMU walls as well as the typical residential wall type (wood stud wall with brick veneer cladding) were tested to determine their debris impact resistance. The stud wall results won’t be discussed herein because they are not commonly found in commercial or industrial buildings, which is the focus of this thesis.

Hollow 8” unreinforced masonry walls were found to be perforated by 2” x 4” wooden missiles traveling at only 65 mph. Also, the back of the 8” CMU broke into many large pieces (some of them weighting as much as 2 lb), which could be a deadly threat to
people on the other side of the wall. This lead the researchers to the conclusion that unreinforced masonry walls were not proficient at stopping the typical missile found in a high wind event. When all of the cells of the 8” CMU were grouted and reinforced with #4 rebar the wall became essentially impervious to the effects of the missile. At test speeds of up to 130 mph the missile was destroyed when it struck the wall, but the wall was not damaged. Also, 12” CMU walls were tested, with results very similar to the 8” wall, leading the researchers to make the following conclusions:

- All cells must be grouted and reinforced to stop the missile at high speeds. If the missile hits an unreinforced cell, the wall will be penetrated.

- The use of grout only will stop the missile, but the wall will experience a great deal of cracking.

- The use of horizontal reinforcement has no impact resistance benefit.

- The shape of the nose of the missile had little effect.

- A missile impacting the wall at 45° tends to glance off the wall without causing damage.

Concrete panels were also tested by McDonald (1992) to determine their impact resistance. It was found that an unreinforced 4” thick concrete wall panel is able to resist penetration from a 15 lb 2”x4” wooden member traveling at speeds exceeding 130 mph, but it will experience a great deal of cracking. Placing #4 rebar at 12” on center spacing each direction prevented the cracking. The use of thicker wall panels and higher impact speeds caused the missile to be destroyed.

Glazing is vulnerable to debris impact not only from large debris such as 2” x 4” wooden missiles, but also to small missiles, such as roof gravel. Research has shown that the three most common types of glass (annealed, heat strengthened, and fully tempered) are all vulnerable to impact from small missiles (Minor, et al., 1978, Minor, 1994). The most common type of small missile found in high-wind events is roof gravel with a weight of 68
between 0.5 g and 5.0 grams (Minor, 1994). There are many products available, including laminated glass and various types of shutters systems, which increase the debris impact resistance of glass openings.

2.5.3 Debris Impact Criteria of Various Codes and Standards

Debris impact resistance is an important consideration when designing for hurricanes. There are a number of different codes and standards that have established criteria for building envelope components to be deemed “debris impact resistant.”

- **ASTM E 1886–97 and ASTM E 1996-01**

  ASTM E 1886–97 (ASTM, 1997) and its companion specification, ASTM E 1996-01 (ASTM, 2001) outline a procedure to determine the debris impact resistance and subsequent cyclic pressure loading resistance of building envelope components. Depending upon the installed height of the component above the ground and the Wind Zone classification of the building, the components are subjected to small and/or large missile impacts followed by cyclic pressure loading. The missiles used in the procedure are described below:

  o **Small Missile** – “A solid steel ball having a mass of 2 g (0.004 lb) ± 5 %, with an 8-mm (5/16-in.) nominal diameter, and an impact speed between 0.40 and 0.75 of the basic wind speed (3-s gust in accordance with ANSI/ASCE 7).”

  o **Large Missile** – “A No. 2 or better Southern Yellow Pine or Douglas Fir 2 x 4 in. lumber having an American Lumber Standard Committee accredited agency mark having a mass of between 2050 g ± 100 g (4.5 ± 0.25 lb) and 6800 g ± 100 g (15.0 ± 0.25 lb) and having a length between 1.2 m ± 100mm (4 ft ± 4 in.) and 4.0 m ± 100 mm (13.2 ft ± 4 in.) and an impact speed between 0.10 and 0.55 of the basic wind speed (3-s gust in accordance with ANSI/ASCE 7).”

  Three separate test specimens are subjected to the missile impact test(s) and each are impacted at different locations. If one of the test specimens fails, the component is rejected. To be deemed acceptable, after the required testing, there must be no tears longer than 5” or any openings that a 3” diameter sphere can pass.
For all heights, components on a building located in Wind Zone 1 and Wind Zone 2 must withstand impact from a 9.0 lb, 8 ft. long wooden member with 2” x 4” nominal dimensions traveling at 50 ft/s.

Components less than 30’ high on a building located in Wind Zone 3 must withstand impact from a 9.0 lb, 8 ft. long wooden member with 2” x 4” nominal dimensions traveling at 80 ft/s.

Components greater than 30’ high on a building located in Wind Zone 3 must withstand impact from a 9.0 lb, 8 ft. long wooden member with 2” x 4” nominal dimensions traveling at 50 ft/s.

Wind Zone 1 is defined as a location having a basic wind speed between 110 mph and 120 mph; Wind Zone 2 is defined as a location having a basic wind speed between 120 mph and 130 mph and located at distances greater than one mile from the coast; and Wind Zone 3 is defined as a location having a basic wind speed greater than 130 mph or a basic wind speed greater than 120 mph and within one mile of the coast. If the components pass the requirements of the small and/or large missile impact test, the performance of the building envelope components must also be tested for cyclic static air pressure loading resistance after completion of the missile impact test(s). The cyclic pressure loading sequence requires that the impacted component be subjected to a series of pressure fluctuations and continue to remain unbreached. The magnitude of the pressure the component is subjected to is determined by the engineer based upon the pressure resistance needed for design. For an “Essential Facility”, which includes hospitals with emergency treatment facilities, fire and police stations, emergency shelters, and emergency response facilities, all building envelope components must withstand impact from both large and small missiles.

- ASCE 2002

ASCE 7-02 (ASCE, 2002) requires that all components of the building envelope for a structure located in “wind borne debris regions” that is not classified as being open during a high wind event must be “Impact Resistant” or have an “Impact Resistant Covering”. It
requires that for a building envelope component to be defined as “Impact Resistant”, it must pass the requirements of ASTM E 1886 - 97 and its companion Specification ASTM E 1996 - 01. The wind borne debris regions are defined as areas within hurricane prone regions located: 1) in areas where the basic wind speed is 120 mph or greater or 2) within one mile of the coastal mean high water line where the basic wind speed is 110 mph or greater and in Hawaii.

- **Texas Department of Insurance Standard TDI 1-98**

  TDI 1-98 (TDI, 1998) was produced in order to “minimize public and private losses due to wind and windborne debris damage to impact protective systems and exterior opening systems.” The test program consists of three identical specimens tested for large and/or small missile impact resistance and cyclic pressure loading. For a component to be deemed acceptable, at least two of the three specimens must pass the criteria of this standard. Components other than impact protective systems with openings larger than 3/16” need not be tested for the small missile impact resistance if they pass the large missile impact resistance test.

  In order for a building envelope component to be deemed to pass the large missile impact test, it must withstand impact from a 7 ft. long Southern Pine or Douglas Fir-Larch with nominal dimensions of 2” x 4” and weighing between 9 and 9.5 lbs traveling at approximately 50 ft/s (34 mph). In order for a building envelope component to be deemed to pass the small missile impact test, it must withstand impact from 10 spherical steel balls each weighing 2 grams traveling at approximately 130 ft/s (89 mph). Components are also required to pass a cyclic wind pressure loading sequence after passing the debris impact test.

  The missile impact tests and cyclic pressure tests are different if the building envelope component is defined as an impact protective system or an exterior opening system.
Impact protective systems are defined as components that are placed over the exterior opening system, either temporarily or permanently. Examples include shutters, plywood, etc. Exterior opening systems are defined as systems that may be breached in a high wind event, such as doors, windows, etc.

- **Florida Building Code 2001**
  
  The Florida Building Code (SBCCI, 2001) requires that all building envelope components located up to and including 30’ above the ground are required to pass the large missile impact test, in which the specimen is impacted with a 9 lb. wooden member having nominal dimensions of 2” x 4” traveling at 50 ft/s. Building envelope components located at heights greater than 30’ above the ground are required to pass the small missile impact test, in which the specimen is impacted with 10 solid steel balls, each weighing 2 grams, traveling at 130 ft/s. Glazing components that pass the missile impact test(s) are also required to pass a cyclic wind pressure loading test to be deemed acceptable.

- **FEMA 361 – Design and Construction Guidance for Community Shelters**
  
  FEMA 361 (FEMA, 2000a) is intended to be used for the design of community shelters in high wind events. It is intended primarily for the design of tornado shelters. The wind speed used for the design of buildings in FEMA 361 is considered to be an ultimate wind speed, therefore the debris impact requirements must also be for an ultimate event. All building envelope components must be able to withstand being breached by a 12’ long, 15 lb. wooden member with nominal dimensions of 2” x 4”, traveling 100 mph for missiles traveling horizontally and 67 mph for missiles traveling vertically.

- **Standard for the Design, Construction, and Performance of Storm Shelters**
  
  The publication entitled “Standard for the Design, Construction, and Performance of Storm Shelters” (NSSA, 2001) was produced by the National Storm Shelter Association
(NSSA) and is intended to be a further developed into “A Storm Shelter Industry Standard.”
The standard uses ultimate wind speeds and references FEMA 361 (FEMA, 2000a) for debris impact requirements.

- **National Performance Criteria for Tornado Shelters**

  The publication entitled “National Performance Criteria for Tornado Shelters” (FEMA, 1999b) was produced by FEMA to give designers a set of guidelines to follow when designing tornado shelters. The standard uses ultimate wind speeds and references FEMA 361 debris impact requirements.

- **Guidelines for Design and Evaluation of Department of Energy Facilities Subjected to Natural Hazard Phenomenon**

  The Department of Energy (DOE) of the United States has issued publication containing a set of criteria on debris impact requirements that must be met for any energy facility. The publication is called “Guidelines for Design and Evaluation of Department of Energy Facilities Subjected to Natural Hazard Phenomenon” (UCRL 15910.) Two different sets of criteria are given depending upon the relative importance of the building. Also, the requirements are different for buildings subject to tornadic winds. The recommendations given by UCRL 15910 are shown in Table 2.15. A High Hazard Facility is defined as a facility in which a failure would result in life threatening consequences to the public surrounding the site. A failure of a Moderate Hazard Facility would result in life threatening consequences to workers surrounding the facility. For comparison purposes, a failure of a Low Hazard Facility would result in life threatening consequences to workers in the local area of the facility.
Table 2.15 – Debris Impact Test Criteria for Department of Energy Critical Facilities, from McDonald (1992)

<table>
<thead>
<tr>
<th></th>
<th>Moderate Hazard Facility</th>
<th>High Hazard Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Straight Winds</strong></td>
<td>15 lb 2x4 timber plank</td>
<td>15 lb 2x4 timber plank</td>
</tr>
<tr>
<td></td>
<td>@ 50 mph (horiz)</td>
<td>@ 50 mph (horiz)</td>
</tr>
<tr>
<td></td>
<td>max height 30 ft</td>
<td>max height 50 ft</td>
</tr>
<tr>
<td><strong>Tornadoes</strong></td>
<td>15 lb 2x4 timber plank</td>
<td>15 lb 2x4 plank</td>
</tr>
<tr>
<td></td>
<td>@ 100 mph (horiz), 70 mph (vert)</td>
<td>@ 150 mph (horiz), 100 mph (vert)</td>
</tr>
<tr>
<td></td>
<td>max height 50 ft</td>
<td>max height 200 ft</td>
</tr>
<tr>
<td></td>
<td>75 lb 3” dia. steel pipe</td>
<td>75 lb 3” dia. steel pipe</td>
</tr>
<tr>
<td></td>
<td>@ 50 mph (horiz), 35 mph (vert)</td>
<td>@ 75 mph (horiz), 50 mph (vert)</td>
</tr>
<tr>
<td></td>
<td>max height 75 ft</td>
<td>max height 100 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000 lb automobile @ 25 mph rolls and tumbles</td>
</tr>
</tbody>
</table>

2.6 Rainfall and Rain Load

2.6.1 Rainfall Rate

The current rate of rainfall used by many building codes for the design of a building is the 1-hour, 100-year Mean Recurrence Interval (MRI) rainfall rate. This is the rate of rain that falls in one hour that has a 1/100 chance of being exceeded each year. This rainfall rate was determined using rainfall associated with extratropical rain events. Research into rainfall rates of past tropical events and extratropical events appears to indicate that design rainfall rates associated with hurricane events has not been proven to be statistically different from that of extratropical events (Schoner and Molansky, 1956; Hershfield, 1961; NOAA, 1977; Grymes, 2002; and Faiers, et al., 1997).

2.6.2 Rain Load

The most common method of calculating rain load on the roof of a building is the method given in ASCE 7-02. The ASCE 7-02 method of determining the Rain Load is outlined in the following equation:
R = 5.2(d_s + d_h)

where:

- R = rain load on the undeflected roof, in lb/ft^2. The phrase “undeflected roof” means that the deflections from loads (including dead load) are not considered when determining the amount of rain on the roof. i.e., this load does not take into account the effects of ponding. The structure must be designed such that ponding does not occur.

- d_s = depth of water on the undeflected roof up to the inlet of the secondary drainage system when the primary drainage system is blocked (i.e., the static head), in inches. The static head is simply the distance to the secondary drainage system. For example, if the secondary drains are 2” from the roof surface, d_s = 2”.

- d_h = additional depth of water on the undeflected roof above the inlet of the secondary drainage system at its design flow (i.e., the hydraulic head), in inches. The hydraulic head is a function of a number of factors; the rainfall intensity used for design, the area of roof each drain is assumed to empty, and the type and area of the drainage system used. For example, for a given size drain, the hydraulic head will increase as the rainfall intensity and/or the area the drain empties increases.

2.7 State of the Practice of Hurricane Shelter Design and Assessment

2.7.1 Design of Hurricane Shelters

There are relatively few codes or standards that address the planning and design of facilities to be used as shelters during high wind events. Two such publications were produced by the Federal Emergency Management Agency (FEMA) and are entitled “Taking Shelter From the Storm: Building a Safe Room Inside Your House,” also known as FEMA 320 (FEMA, 1999c) and “Design and Construction Guidance for Community Shelters,” also known as FEMA 361 (FEMA, 2000a). As the names suggest, FEMA 320 provides a set of guidelines for the design of small shelters to be constructed within a single-family residence, while FEMA 361 provides a set of guidelines for the design of a community shelter to be used to protect a large number of people. Although both of these publications address hurricane and tornado events, the main focus is the design of tornado shelters. Some of the
important guidelines and recommendations given by these publications are given in the following paragraphs.

- **Wind Speed**

  The design wind speed used in both publications is selected to provide the occupants of the shelter “near-absolute protection from death and injury.” This means that no matter the magnitude of the wind event, the occupants of the shelter are deemed to be safe. This gives individuals a place to go for any wind event, but results in a very expensive design. The wind speed used for design by both publications, though applicable to hurricane wind events, is controlled primarily by the wind speeds generated by tornadoes. This level of protection is mandated for a tornado shelter because the wind speed associated with a tornado can change very rapidly, and if someone is going to seek shelter in the structure, it is imperative that the structure remains standing if the tornado intensifies. See Figure 2.17 for the design wind speed used by these publications. For a hurricane shelter, however, the wind speed to be anticipated at the shelter location for a given hurricane event can be predicted ahead of time. This enables the designer to design a structure for any given hurricane intensity. When a hurricane is approaching, a decision can be made as to the suitability of a structure to be used as a hurricane shelter based on the hurricane intensity used during the design process.

- **Debris Impact**

  Along with being able to withstand the high winds associated with an extreme wind event, all components of a structure also have to be able to resist penetration by flying debris. For a residential shelter, this is the case that will most likely control the design of the shelter due to the small wall area. For a community shelter, however, the large wall areas cause higher wind pressures, which usually controls design. For large and small shelters, the loads
produced by both the design wind speed and the debris impact loading must be investigated and designed and the structure designed accordingly. FEMA gives the following criteria for debris impact resistance:

- The test member must be able to withstand the impact from a 15-lb wood 2”x4” (nominal) member, typically 12’ long, traveling at 100 mph for horizontally traveling missiles and 67 mph for vertically traveling missiles and striking the test specimen at a 90° angle.
- All components of the shelter (walls, roof, doors, windows, etc.) must be able to withstand the above criteria. Several recommendations are given as to the best way to ensure that each component is sufficient.
• **Additional Considerations**

   Along with the design wind speed and debris impact, there are a number of other considerations that must be taken into account. Some of these include:

   o Is the shelter in an area that is susceptible to flooding? If so, the shelter must be designed accordingly. If possible, the shelter should be moved outside of the flood area.

   o Is the shelter in a seismically active area? If so, the building must be designed accordingly.

• **Human Factors**

   It is important that due consideration is given to the fact that individuals will be sheltering inside the facility during a high wind event. FEMA 320 (FEMA, 1999c), suggests that a minimum of 10 ft$^2$ per person be provided in a residential shelter. FEMA 361 (FEMA, 2000a) suggests that 20 ft$^2$ per person be provided for a length of stay of only a few days, but if the length of stay is anticipated to be longer, that 40 ft$^2$ per person be provided in a community shelter. Also, the local building code should be checked to ensure that all of its requirements are met.

   In 1999, as part of the state of Florida Statewide Emergency Shelter Plan, the state of Florida produced a set of design criteria that were required to be met when designing an educational facility entitled “Public Shelter Design Criteria” (Florida Dept. of Education, 1999). The purpose of the guidelines was to decrease the shelter deficit of the state by designing all educational facilities that were being built such that they could be used as shelters in the event of a hurricane event. Some of the recommendations of the publication are given in the following bullet list:
The entire structure is to be designed using ASCE 7-93 (ASCE, 1993) as a minimum.

It was suggested that the portion of the structure to be used as a shelter be designed using a wind speed of 40 mph greater than that given by ASCE 7-93, with an Importance Factor (I) of 1.0.

All building envelope components were required to resist penetration from flying debris.

In 2002, Lee County, Florida produced their own set of hurricane shelter guidelines, entitled “Lee County Emergency Shelter Guidelines and Criteria” (Lee County, FL, 2002). Relevant structural design considerations of this publication are:

- ASCE 7 procedures are to be used with a design wind speed of 150 mph peak gust.
- Importance Factor (I) of 1.0 is to be used for design.

In 2001, the state of Florida also produced a new building code (SBCCI, 2001) with assistance from the SBCCI that was intended to improve the performance of structures that are subjected to hurricane strikes. Different guidelines were given depending on location from the coast and many other considerations. This was also done by the state of Texas. In 1998, Texas adopted the “Building Code for Windstorm Resistant Construction” (TDI, 1998). Two sets of guidelines were given depending on if the structure was located inward or seaward of an imaginary line dividing the hurricane coastal area an inland areas.

2.7.2 Assessment of Hurricane Shelters

In October of 1997 the state of Louisiana, with help from the University of Florida School of Building Construction, released a document entitled “Hurricane Evacuation Shelter Selection Guidelines,” (LOEP, 1997) the purpose of which was to aid in the selection of existing facilities to be used as hurricane shelters. Fifteen different building planning and design issues are considered. A least risk decision making process is then used
to determine the suitability of using the building as a hurricane evacuation shelter. The fifteen building facets to be considered are:

- Storm Surge Inundation
- Rainfall Flooding / Dam Considerations
- Hazardous Materials and Nuclear Power Plant Consideration
- Lay-Down Hazard Exposure
- Wind and Debris Exposure
- Wind Design Verification
- Construction Type / Loadpath Verification
- Building Condition
- Exterior Wall Construction
- Fenestrations and Window Protection
- Roof Construction / Roof Slope
- Roof Open Span
- Roof Drainage / Ponding
- Interior Safe Space
- Life Safety / Emergency Power

Each of the previously mentioned building facets are investigated and categorized in one of three different categories: Preferred, Acceptable, or Marginal. Based upon the overall results from the least risk decision making process, it is then determined if the building is able to be used “As Is”, if the building can be used with some modifications, or if the building is not suitable for use.

Another publication that addresses the selection of viable hurricane shelters is “Standards for Hurricane Evacuation Shelter Selection,” (ARC, 2002) which is produced by the American Red Cross. This publication gives guidelines on the following topics:

- Surge Inundation
- Rainfall Flooding
- High Winds
- Hazardous Materials
- Interior Building Safety Criteria During Hurricane Conditions

A least risk decision making process is then used to determine the suitability of the building for use as a hurricane shelter based on how well the building meets the previously mentioned topics.
CHAPTER 3: FORMULATION OF DESIGN GUIDELINES

3.1 Introduction

Historically, buildings, including facilities designated as essential in a hurricane event, have been designed using a probabilistic approach. Buildings designed using this approach have a certain probability against failure when subjected to the anticipated loads. The acceptable probability of failure is based on a great deal of research along with input from the general public on the acceptable probability of structural collapse. For buildings located in hurricane prone regions, the wind speed used for design is the wind speed corresponding to a 500 year Mean Recurrence Interval (MRI) divided by a factor of 1.225. For a facility designated as essential, the wind speed is increased by an Importance Factor of 1.15 to increase the MRI. After all of the anticipated loads have been determined, the loads are combined in the appropriate load combinations to get the overall loads on each component of the structure. Once the loads to be used for design have been determined, all components of the building are designed. Currently, almost all building codes are based on a prescriptive design approach, which results in a “no damage” design when the facility is subjected to the design event (Harris, 2002 and Hamburger, 2002).

Another option available for designing facilities designated as essential in a hurricane event is to use a publication produced by the Federal Emergency Management Agency (FEMA) entitled Design and Construction Guidance for Community Shelters, otherwise known as FEMA 361. The wind speed presented in this publication is an “extreme” wind speed with a very small chance of ever being exceeded, i.e., a very long MRI, on the order of 2,000 to 10,000 years, depending on location. This gives shelter inhabitants “near absolute” protection from any wind event, but results in a very expensive building. There are also other publications that address the design of hurricane shelters (FEMA, 2000c; FEMA,
1999c; FEMA and Texas Tech, 1999; NSSA, 2001). All of these publications, however, produce an “ultimate event” design as well.

There have recently been guidelines produced outlining procedures to be used when designing hurricane shelters in the state of Florida. In 1999, the state began requiring that any new educational facilities have an area designated to be used as a hurricane shelter. It was highly recommended by the 1999 “State Requirements for Educational Facilities” (Florida Department of Education, 1999) that the wind speed used for design of these facilities be the wind speed from the ASCE 7 map plus 40 mph. Recently, Lee County in Florida produced a hurricane shelter design guideline (Lee County, 2002) specifying a design wind speed of 150 mph peak gust for hurricane shelters.

This thesis proposes a totally different approach for the design of facilities designated as essential during a hurricane event. When designing a new essential facility, the building owner can select the hurricane strength to be used as the design event for a given facility based on the shelter demand, the available budget, and any other relevant considerations. The associated loads for the design hurricane event can then be determined and the building designed accordingly. Then, when a hurricane is approaching, the building owner will have a much clearer understanding of the strength of the building relative to the strength of the approaching hurricane, and manage the emergency preparedness operations accordingly.

For a given hurricane approaching the coast, the approximate wind speed is known. The MRI of the wind speed associated with the approaching hurricane is of little concern to emergency managers. The hurricane is coming and the probability associated with the winds of that hurricane event does not matter. The only thing that matters is that the building performs up to the desired design objective when exposed to the hurricane about to strike.
Since there are several types of essential facilities, which are required to perform different functions before, during, and after a hurricane event, all facilities designated as essential need not perform to the same level for a given hurricane event. For example, a building used to store equipment for emergencies during the hurricane does not need to perform to the same level as a hospital that is required to be fully operational during and after the hurricane event. In order to produce the most economical design for each of the building use classifications, a different design approach from the “no damage” approach used by most building codes is required. A performance-based design approach is proposed for facilities designated as essential during a hurricane event. Each type of essential facility is assigned a required performance level, and the building is then designed to meet these performance requirements.

This type of approach allows for the most efficient building design. The use of the building before, during, and after the hurricane, as well as the building owner’s desired design hurricane event, can be taken into account in the planning and design of the structure. Also, the performance-based design approach allows for the use of the latest products in the design of the building. These two aspects of the performance-based design approach make it ideal for the design of essential facilities because it allows for the best, most cutting-edge, and most efficient structural design. This thesis will provide structural engineers and architects a document to use as a reference when building a structure designated as an essential facility during a hurricane event using the previously-mentioned design philosophy.

3.2 Performance Criteria for Essential Facilities

3.2.1 Types of Essential Facilities

Five different categories of essential facilities have been identified for use during hurricane events, as shown in Table 3.1. The facility categories were decided upon based on
the use of the facility during and after the hurricane event and the corresponding relative performance level required by the facility. The five facility categories and the associated buildings in each category were determined by first reviewing existing Performance-based Design standards (SEAOC, 1995; FEMA, 2000b; ICC, 2001), which were discussed in Section 2.2 of this thesis. Next, the recommendations made by these standards were modified to reflect the special use requirements of facilities utilized during hurricane events. The determinations made were then reviewed by experts in the field of emergency management operations (Sean Fontenot – Assistant Division Chief of the Louisiana Office of Emergency Preparedness (LOEP) and Dr. Walter Maestri, III – Director of the Jefferson Parish OEP). It is important to recognize that, in most instances, the use of the building during and after the hurricane event is a secondary function of the facility.

Table 3.1 – Essential Facility Classifications

<table>
<thead>
<tr>
<th>Essential Facility Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function Critical Facilities</td>
<td>Facilities that must remain operational before, during, and after the hurricane event. Examples include emergency operations centers and certain hospitals.</td>
</tr>
<tr>
<td>Base of Operations for Response</td>
<td>Buildings that house emergency response functions needed in the immediate wake of the hurricane, but do not necessarily need to remain fully operational at the height of the storm. A fire station would generally fit in this category.</td>
</tr>
<tr>
<td>Hurricane Shelter</td>
<td>Intended to provide a safe place to go during the hurricane and a place to stay for some length of time after the storm has passed.</td>
</tr>
<tr>
<td>Refuge of Last Resort</td>
<td>Intended for people who did/could not evacuate or travel to a shelter, but do not wish to remain in their homes. It may or may not be safer than their homes. There is no minimum implied level of safety as there is in a shelter.</td>
</tr>
<tr>
<td>Emergency Equipment/Supplies</td>
<td>A facility used to house equipment and supplies needed for emergency response and recovery beginning immediately after the storm event. Different from the other four building categories above, it is not intended to be occupied during the hurricane, but individuals will be going inside after the hurricane in order to retrieve the stored materials.</td>
</tr>
</tbody>
</table>
3.2.2 Development of Performance Criteria

For each Essential Facility Classification, the allowed level of damage to the various components of the building for the design event of the building must be determined. The building systems investigated and the damage levels considered are shown in Table 3.2. Also shown in Table 3.2 are the graduations in the various levels of danger to life safety of people inside one of the facilities. The building systems suggested by existing Performance-based Design standards (SEAOC, 1995; FEMA, 2000b; ICC, 2001) were reviewed and modified to account for the special needs of facilities utilized during hurricane events. The Primary Structural System is defined as girders, load bearing walls, wind bracing, and columns. Not included in the Primary Structural System are secondary structural elements, such as roof joists, girts, etc. These are considered part of the roof and wall systems. The Building Envelope consists of the roof cladding, glazed openings, doors, wall cladding, roof joists, girts, etc. It should be noted that the performance of the building envelope has a direct impact on the damage to the interior of the building. The building envelope was broken into two different systems; Windows/Doors and Roof and Wall Systems. The damage levels and the definitions associated with each damage level were determined by reviewing existing Performance-based Design standards and modifying them as appropriate for hurricane facilities.

3.2.3 Performance Criteria Survey

A survey was given to members of the emergency management community to determine appropriate levels of building damage and danger to occupants for a building in each of the five essential facility classifications. The survey was developed by first giving a trial version to peers of the author. Feedback was received and a final version was created. A description of the final layout of the survey follows (the complete survey is given in
### Table 3.2 – Definition of Damage Levels for Various Building Systems/Components

<table>
<thead>
<tr>
<th>System</th>
<th>Damage Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall Danger to Life Safety</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Severe</strong> – Injuries to building occupants may be high in numbers 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.</td>
<td></td>
</tr>
<tr>
<td><strong>High</strong> – Injuries to building 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 single life loss, with a low probability of multiple life loss.</td>
<td></td>
</tr>
<tr>
<td><strong>Moderate</strong> – Injuries to building occupants may be locally significant, but generally moderate in numbers and in nature. There is a low likelihood of single life loss, very low likelihood of multiple life loss.</td>
<td></td>
</tr>
<tr>
<td><strong>Mild</strong> – Injuries to building occupants are minimal in numbers and minor in nature. There is a very low likelihood of single- or multiple life loss.</td>
<td></td>
</tr>
<tr>
<td><strong>Primary Structural System Damage</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Severe</strong> – Building is near collapse. Little residual strength or stiffness left in the structure. Rehabilitation to achieve pre-storm load-carrying capability likely to be impossible or impractical for economic or other reasons. The building is likely a complete loss.</td>
<td></td>
</tr>
<tr>
<td><strong>Moderate</strong> – Some residual strength and stiffness left in the structure. Rehabilitation to achieve pre-storm load-carrying capability likely to be very costly.</td>
<td></td>
</tr>
<tr>
<td><strong>Light</strong> – Structure retains most of its pre-storm strength and stiffness. Little rehabilitation needed to achieve pre-storm load-carrying capacity.</td>
<td></td>
</tr>
<tr>
<td><strong>None to Very Light</strong> – Little to no damage to the structural components. Structure possesses pre-storm load-carrying capacity with very little or no rehabilitation.</td>
<td></td>
</tr>
<tr>
<td><strong>Building Envelope Damage: Windows/Doors</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Severe</strong> - Most of the windows and doors are completely destroyed. Many door openings blocked or impassable. Replacement of many opening components required. Building interior experiences significant damage in areas adjacent to failed exterior.</td>
<td></td>
</tr>
<tr>
<td><strong>Moderate</strong> - Significant damage to some opening components. Many doors and windows are breached. Some opening components are able to be repaired, while many must be replaced. Most door openings free of obstructions. Some damage to the building interior due to wind and water entering through the failed opening.</td>
<td></td>
</tr>
<tr>
<td><strong>Light</strong> - Opening components experience little damage. Openings able to be returned to their pre-hurricane functionality with minor repair or replacement. Very little damage to the building interior.</td>
<td></td>
</tr>
<tr>
<td><strong>None to Very Light</strong> - Little or no damage to any of the opening components. The damage which does occur has no effect on use of building and repair of the opening components does not interfere with the use of the building. Damage to the opening components is mainly cosmetic in nature. No damage to the building interior.</td>
<td></td>
</tr>
</tbody>
</table>

(table cont.)
<table>
<thead>
<tr>
<th>Building Envelope Damage: Roof and Wall Systems</th>
<th>Severe</th>
<th>Moderate</th>
<th>Light</th>
<th>None to Very Light</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Most cladding/roofing components either removed or completely destroyed. Repair likely to be impractical for economic or other reasons. Replacement probably needed. Large holes likely in the roof and/or walls. Major wind and water penetration of structure, causing a great deal of damage to the interior and contents.</td>
<td>Small cladding/roofing elements removed or destroyed. Many of the larger elements retain most of their functionality, but may be damaged beyond repair. Large holes possible and small holes likely in the roof and/or walls. Some damage to the building interior due to wind and water entering the structure.</td>
<td>Roofing/cladding components remain functional, but some components must be replaced in order for building envelope to function the same as it did before the storm. Small holes possible in the roof and/or walls, allowing water to leak into the building. Very little damage to the building interior.</td>
<td>Almost no damage to the roofing/cladding components. Functionality of the roofing/cladding components remains the same after the event as it was before the event with little or no repair or replacement. No damage to the building interior.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical and Plumbing Systems Damage: Electrical/Lighting Systems</th>
<th>Severe</th>
<th>Moderate</th>
<th>Very Light</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Many to most of the components are out of order and some damaged beyond repair and require replacement.</td>
<td>A small percentage of the components are in working order. Primary lighting likely to be non-operational. Emergency lighting is in working order during and after the event. Replacement or repair of some components required.</td>
<td>Components are operational during the event, but are ready to be reactivated immediately after the storm. Emergency lighting in working order during and after the event.</td>
<td>All components remain fully operational during and after the event.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical and Plumbing Systems Damage: HVAC Equipment</th>
<th>Severe</th>
<th>Moderate</th>
<th>Very Light</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Many to most of the components are out of order and some damaged beyond repair and require replacement. Some components may be lost due to wind.</td>
<td>A small percentage of the HVAC system is in working order. Replacement or repair of some components required.</td>
<td>Components are operational during the event, but are ready to be reactivated immediately after the storm.</td>
<td>All components remain fully operational during and after the event.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical and Plumbing Systems Damage: Plumbing Systems</th>
<th>Severe</th>
<th>Moderate</th>
<th>Very Light</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Many to most of the components are out of order and some damaged beyond repair and require replacement.</td>
<td>A small percentage of the plumbing system is in working order. Replacement or repair of some components required.</td>
<td>Components are operational during the event, but are ready to be reactivated immediately after the storm.</td>
<td>All components remain fully operational during and after the event.</td>
</tr>
</tbody>
</table>
Appendix A). The first page of the survey described the five different facility categories. The second page was intended to obtain information about the people filling out the survey. It included a section for the survey participant to give his/her profession, experience with sheltering, and Parish/City. Each of the next seven pages was devoted to the seven topics to be decided upon (six building systems and overall life safety). Definitions were given for building components considered to be a part of the primary structural system and the building envelope. The various damage levels for each system were given along with a table for the survey participant to select what he/she believes to be the appropriate damage level for each of the five facility classifications. Also provided on each sheet was a place for any additional notes that the survey participant felt a desire to provide.

The survey was given to two different sets of individuals. The survey was first given to a group of people who attended a Shelter Assessment Training Workshop in St. Tammany Parish that was given by Dr. Marc Levitan of the LSU Hurricane Center on June 27, 2002. Twelve individuals took part in the survey. Most of the respondents were from the emergency management community, but many had little or no experience with sheltering. There were also four people from the engineering and architecture community, as well as a building official. The survey was given out again on July 2, 2002 to twenty-four individuals that attended the Southeastern Louisiana Hurricane Task Force meeting at Lafreniere Park in Metairie. Again, almost all of the survey participants were employed in emergency management, but the respondents of this survey had much more experience in shelter management and selection. Also taking part in the survey were a police officer, two people in the medical profession, and two Red Cross workers. In both instances, a brief overview of the reasoning behind the survey was given. Also, assistance was given to any individuals
with questions about the survey. Respondents were given approximately thirty minutes to complete the survey.

It is important to realize that this is an initial survey. There was no research performed on survey format in order to achieve the best answers. Also, the sample size was small. It can also be expected that there will be a degree of bias from the survey participants due to the high storm surge associated with hurricane events in coastal Louisiana (where the participants were from).

3.2.4 Survey Results

The results of the survey are shown in Table 3.3. The numbers in the boxes represent the numbers of respondents that chose that damage level for each facility classification. The symbols #1 and #2 represent the results from the first and second time the survey was given out, respectively and the third number is the total number of survey participants that chose each damage level. The damage level with the most responses (the Mode) for each facility category is shaded. The damage level descriptions can be obtained from Table 3.2. It should be pointed out that some people left some of the boxes blank, therefore there will not be the same total number of responses every time. A box left blank was not deemed to be the same as someone filling in the “Not Sure” box.

3.2.5 Recommended Performance Criteria

The recommended performance of each of the building components/systems for a facility in each of the five essential facility classifications is shown in Table 3.5. Also shown is the allowed danger to the building occupants. The recommendations agree closely with the data obtained from the survey results. For descriptions of the damage levels, see Table 3.2.
<table>
<thead>
<tr>
<th>Building Component/ System and Levels of Damage Investigated</th>
<th>Function Critical</th>
<th>Base of Operations for Response</th>
<th>Hurricane Shelter</th>
<th>Refuge of Last Resort</th>
<th>Emergency Equipment/ Supplies Storage Facility*</th>
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<tr>
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<td>1 1 2</td>
<td>2 0 2</td>
<td>4 3 7</td>
<td>5 11 16</td>
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<tr>
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<td>4 15 20</td>
<td>4 10 14</td>
<td>5 13 18</td>
<td>5 6 11</td>
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<tr>
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<td>5 13 18</td>
<td>5 8 13</td>
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<tr>
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<td>2 14 6</td>
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<td>5 9 14</td>
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<tr>
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<td>1 0 1</td>
<td>1 1 2</td>
<td>1 0 1</td>
<td>1 1 2</td>
</tr>
</tbody>
</table>

(table cont.)
The results obtained each time the survey was handed out were fairly similar. The overall results matched closely with anticipated results and also matched closely, in most instances, to the damage levels believed to be acceptable by the author. As mentioned earlier, the second audience was more experienced in hurricane shelter management and selection, which lead to slightly less scatter in the responses. One set of results from the first survey issuance had to be discarded because it appeared that the respondent was confused. The greatest amount of scatter was found in the responses to the “Danger to Life Safety” category. A few people seemed to be confused, as indicated by the results, although the overall results follow closely with the results of other categories. A definite trend can be seen in the results. The allowed level of damage decreases as the intended function of the facility becomes more critical. As anticipated, the results obtained for the Function Critical facilities suggested almost no damage would be accepted to any of the building components/systems. Also, the threat to loss of life for an individual inside of a Function Critical facility was very low. The performance of building envelope components (windows/doors and roof and wall systems) was quite important to survey respondents, due perhaps to the perceived danger to building occupants and the consequences of envelope failure. The required performance of the mechanical systems (electrical/lighting, HVAC
equipment, and plumbing systems) dropped off quickly, however, as the facility classification became less critical.

In order to have another method to view the results of the survey, a numerical average was computed for each building component/system for each essential facility classification. Each damage level was assigned a numerical value, with the damage level corresponding to the most damage being assigned a number (3) and the damage level corresponding to the least damage being assigned a number (0), as shown in Table 3.4. The number in the box represents the average value of the response for each building component/system for each essential facility classification.

The recommended performance levels to be used for the design of facilities in each of the essential facility classifications were determined primarily by using the results of the surveys that were distributed to members of the emergency management community. Engineering judgment was used in some instances. Also, the performance levels suggested by existing Performance-based design standards (SEAOC, 1995; FEMA, 2000b; ICC, 2001) for facilities similar to the types discussed in this thesis were taken into account when choosing the recommended performance level.

In most instances, the recommended performance level corresponded to the results of the survey. This was especially the case for the Function Critical and Base of Operations categories. There were particular instances, however, where the recommendations deviated from the results of the survey. In these instances, engineering judgment was used to determine the recommended performance level. These cases will be addressed in the following paragraphs.
| Building Component/ 
System and Levels of 
Damage Investigated | Function Critical | Base of Operations for Response | Hurricane Shelter | Refuge of Last Resort | Emergency Equipment/ Supplies Storage Facility |
<table>
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<th></th>
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<th></th>
</tr>
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<tbody>
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<td>None to Very Light (0)</td>
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<td><strong>Windows/Doors</strong></td>
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<tr>
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*The danger to life safety in this case is from individuals entering the building after the storm in order to retrieve the needed equipment.*
Table 3.5 – Recommended Performance Criteria

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<th>Building Component/ System and Levels of Damage Investigated</th>
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<th>Base of Operations for Response</th>
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<th>Refuge of Last Resort</th>
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<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Plumbing Systems</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very Light</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Danger to Life Safety</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The danger to life safety in this case is from individuals entering the building after the storm in order to retrieve the needed equipment.
Although the mode for the allowed damage to the Roof and Wall Systems category matched the damage level recommended (“None to Very Light”) for the Base of Operations for Response category, the average was closer to “Light.” The “None to Very Light” damage level was recommended because it was determined that the amount of damage associated with the “Light” damage level (water entering the building through small holes) may keep the building from being able to meet its intended function. Also, the recommendation made by this thesis and the survey result were different for Roof and Wall Systems for the Refuge of Last Resort category and the Emergency Equipment/ Supplies Storage Facility. Although the survey results deemed the appropriate damage level to be “Light,” it is the recommended by this thesis that the “Moderate” damage level by used. An investigation of the averages for these two categories will reveal that they are almost one-half-point higher than the Hurricane Shelter category. It is the feeling of this author that there needs to be some type of difference between the performance of the Refuge and the Hurricane Shelter categories, therefore the “Moderate” damage level was chosen for design.

The “Danger to Life Safety” category produced conflicting results for many essential facility categories. This was the case for the Hurricane Shelter. Although the mode and recommendation were different, the average of the responses was closer to the recommendation made by this thesis. Due to this fact along with the fact that the Moderate level was deemed to be more appropriate for a Hurricane Shelter, the Moderate level was chosen for design. Also, the recommended danger level was higher than the survey results for the Refuge of Last Resort category. The recommended danger was chosen to be High, while the survey results determined it to be Moderate. The average of the Refuge category, however, was over one-half-point higher than the Hurricane Shelter category. For this reason, the High danger level was chosen. It is believed that the Emergency Management
community would prefer a performance that can not feasibly be provided given economical and other considerations.

The recommendations made for the HVAC category for the Refuge of Last Resort and the Emergency Equipment/ Supplies Storage categories were higher than that suggested by the survey results. The higher damage level (Severe) was chosen because it was determined that there is no need for the HVAC to be operational for either of these facility classifications. This is also the case for the Plumbing Systems for the Refuge of Last Resort. The Severe damage level was chosen even though the survey results suggested Moderate. It is the feeling of the author that the Emergency Managers desire more than can be provided economically and feasibly for the Refuge of Last Resort category.

It is important to realize that the recommendations given in this thesis are intended to be a **minimum** Performance Criteria and special cases may require that the recommendations be modified to fit the specific needs of a given facility. Also, the primary function of the facility being designed may require that more stringent performance criteria be implemented.

No recommendations are given as to how to meet the required performance levels suggested for the various building components. The design methodologies presented in current building codes can be used for the design of components with a damage level of “None” or “None to Very Light” using the recommended analysis procedures outlined by this thesis. For the other damage levels, more research needs to be performed to determine how the performance levels would be achieved. There has been much research along these lines performed by the Earthquake Engineering community.
3.3 Determination of Hurricane Wind Loads

3.3.1 Design Wind Speeds

3.3.1.1 Rationale for Choosing Hurricane Categories as Design Event

This thesis presents a new methodology for determining the design wind speed of facilities designated as essential during a hurricane event. The design wind speed in ASCE 7-02 (ASCE, 2002) for critical facilities located along the hurricane coast corresponds to a Mean Recurrence Interval (MRI) of approximately 100 years (the Importance Factor of 1.15 for critical facilities converts the MRI of the wind speed given in the design wind speed map from approximately 50 to 100 years). What is proposed is to choose the design wind speed based not on a desired MRI, but on a selected hurricane category (based on the Saffir-Simpson Hurricane Scale) that it is determined the facility would be designed to resist. Section 2.1.1 of this thesis has a discussion of the Saffir-Simpson Hurricane Scale.

There are a number of reasons for using hurricane of specific intensity as the design events. This design methodology allows for facilities to be designed based on the needs of the building owner. For example, if it is determined that there exists a need for the facility to be designed to resist the impact of a Category 4 hurricane, then it can be designed accordingly. If it is determined that the building only needs to be designed to resist a Category 3 hurricane, however, this can also be accomplished. This design methodology also makes the decisions about which facilities are to be utilized during a hurricane event much easier. Since the maximum wind speed of a specific hurricane can be estimated from the Saffir-Simpson Hurricane Scale assigned to the storm, a decision can be made as the hurricane is approaching as to whether or not to use the facility.

Another consideration that should go into the choice of the hurricane category used for design is the probability of occurrence (MRI) associated with a hurricane of a given
intensity for the facility location. The number of years between hurricane strikes for various locations along the hurricane coastline of the United States is shown in Figure 3.1. Boxes (a) and (b) in Figure 3.1 are comparable to the MRI associated with a Category 1-3 and a Category 4-5 hurricane, respectively.

Figure 3.1 – Average Number of Years Between Occurrences of a Hurricane with Maximum Winds of: Box (a) - greater than 74 mph and Box (b) - greater than 125 mph (Simpson and Riehl, 1981)
3.3.1.2 Wind Speeds at the Coastline

The wind speeds given in the Saffir-Simpson hurricane scale are maximum sustained wind speeds (1-minute averaging time). To design a facility using the Saffir-Simpson hurricane scale as the basis for the design wind speed, the wind speed given in the table must be converted into a peak gust wind speed. The conversion of sustained wind speed to gust speed is shown in Table 3.6. Also shown is the wind speed reduction due to the hurricane passing over land. The “Over Land” wind speed is the wind speed to use for design purposes. If a building owner determines that the building is to be designed for a Saffir-Simpson Category 3 hurricane, the wind speed at the coastline to use for design would be 156 mph, as taken from Table 3.6.

Table 3.6 – Maximum Wind Speeds for Saffir-Simpson Hurricane Categories, (Vickery, et al., 2000b)

<table>
<thead>
<tr>
<th>Saffir-Simpson Category</th>
<th>Maximum Sustained Wind Speed Over Water (mph)</th>
<th>Maximum Gust Speed Over Water (mph)</th>
<th>Maximum Gust Speed Over Land, ( z_o = 0.1 ) ft (0.03 m) (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74-94</td>
<td>91-116</td>
<td>82-108</td>
</tr>
<tr>
<td>2</td>
<td>94-110</td>
<td>116-140</td>
<td>108-130</td>
</tr>
<tr>
<td>3</td>
<td>110-130</td>
<td>140-165</td>
<td>130-156</td>
</tr>
<tr>
<td>4</td>
<td>130-155</td>
<td>165-195</td>
<td>156-191</td>
</tr>
<tr>
<td>5</td>
<td>&gt;155</td>
<td>&gt;195</td>
<td>&gt;191</td>
</tr>
</tbody>
</table>

3.3.1.3 Reduction of Hurricane Wind Speeds Inland

The winds associated with a hurricane event decrease as the hurricane makes landfall and moves inland. There are a couple of reasons for this. First, the hurricane loses its source of energy; the warm, moist waters of the body of water the hurricane is traveling over. Second, the increased surface friction of the land as compared to the water causes the surface level wind speed to be decreased. The first determination that must be made when estimating
the amount the winds of a hurricane will decrease once the hurricane makes landfall is the location of the coastline. Due to the fact that the hurricane may cause extensive flooding and/or tidal surge, the coastline should not be assumed to be the coastline observed from an aerial photograph or map. Because much of the usual coastline could be covered with water from storm surge, the hurricane will continue receiving energy from the water. Also, the surface friction of the land once it is covered with water is not as high as if it was dry, which means the hurricane winds do not decrease as fast. The coastline should be the location of the maximum extent of storm surge flooding during the design hurricane event. One way this can be determined is from a SLOSH model (NWS, 2001). The SLOSH Model (Sea, Lake, and Overland Surges from Hurricanes) is a mathematical model that was developed by the National Weather Service to calculate potential surge heights from hurricanes. From the SLOSH model, the location where the land is determined to no longer be underwater is the new “coastline.” This results in the coastline being farther inland for a severe storm than for a minimal hurricane. The shortest distance from the new coastline to the building location is now the distance “inland” that the building is located.

Once the “coastline” has been determined, the correct rate of decay model for the hurricane winds must be determined. There have been a number of papers that address this issue, as discussed in the literature review. A comparison of these is shown in Figure 3.2. It is important to realize that these papers dealt with different wind speed averaging times. Some papers adjusted the peak wind speed, while others adjusted the sustained winds. It is assumed in this thesis that the gust factor (the ratio of peak gust wind speed to the mean wind speed) does not vary with distance inland.
Figure 3.2 – Wind Speed Adjustment Factor vs. Time Since Landfall

It is important to realize that the adjustment factors presented in Figure 3.2 are to be used only for the Gulf Coast region of the United States. The adjustment factors that were suggested for use by Malkin (1959) were presented previously in this thesis in Table 2.10. The Schwerdt (1979) suggested adjustment factors were also presented previously in Figure 2.11. As presented earlier, Ho, et al. (1987) did not present wind speed adjustment factors, but suggested values to use for the change in hurricane pressure deficits due to overland filling once the hurricane makes landfall, which was shown in Table 2.11 of this thesis. In order to determine a wind speed adjustment factor using the data presented by Ho, it was assumed that the wind speed decreased with the square root of the of the pressure deficit at a specified time over the pressure deficit at landfall, as was assumed by Schwerdt (1979). The resulting wind speed adjustment factors using this assumption are shown in Table 3.7. The
wind speed adjustment factor presented in Figure 3.2 as suggested by Kaplan and DeMaria (1995) is the same as the one discussed in Section 2.4 of this thesis. The Kaplan and DeMaria model contains a 0.9 reduction factor at landfall to account for the effect of the increased surface roughness of the land as compared to the open water, where the maximum winds are measured. This effect is accounted for by using the “Maximum Gust Speed Over Land” column of Table 3.5 as the input to the model. Therefore, the 0.9 adjustment factor was removed from the Kaplan and DeMaria model plotted in Figure 3.2.

Table 3.7 – Wind Speed Adjustment Factors Using Data Presented by Ho, et al. (1987)

<table>
<thead>
<tr>
<th>Time After Landfall (hours)</th>
<th>Pressure Deficit at Landfall</th>
<th>Wind Speed Adjustment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 85 mb</td>
<td>100 mb</td>
</tr>
<tr>
<td>0</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>0.922</td>
<td>0.894</td>
</tr>
<tr>
<td>4</td>
<td>0.861</td>
<td>0.825</td>
</tr>
<tr>
<td>6</td>
<td>0.812</td>
<td>0.775</td>
</tr>
<tr>
<td>8</td>
<td>0.749</td>
<td>0.721</td>
</tr>
<tr>
<td>10</td>
<td>0.706</td>
<td>0.678</td>
</tr>
<tr>
<td>12</td>
<td>0.670</td>
<td>0.640</td>
</tr>
<tr>
<td>14</td>
<td>0.632</td>
<td>0.600</td>
</tr>
<tr>
<td>16</td>
<td>0.592</td>
<td>0.566</td>
</tr>
<tr>
<td>18</td>
<td>0.556</td>
<td>0.529</td>
</tr>
</tbody>
</table>

As can be seen in Figure 3.2, most publications produce similar results for the adjustment factor of wind speeds of a hurricane once it makes landfall. The Kaplan and DeMaria model, in general, reduces the wind speed the fastest, while Malkin’s model, based on pressure depth change once the hurricane makes landfall, produces the slowest rate of wind speed decay.

The most beneficial way to present the appropriate decay of hurricane winds for facilities designated as essential during hurricane events is not with time since landfall, but with distance inland. In order to do this, a reasonable maximum forward speed for the design
hurricane must be determined. This was done by analyzing the maximum forward speed used by other publications. The forward speed used by the SLOSH model (NWS, 2001) to represent the “FAST” hurricane for the Gulf Coast is 15 mph. The Kaplan and DeMaria model used a forward speed of 16 Kt (18.4 mph) to represent a fast forward speed, which represents the 90\textsuperscript{th} percentile of the distribution of forward hurricane speeds at landfall. It is important to realize that the dataset used by Kaplan and DeMaria included the entire hurricane coast of the United States. An investigation of historical records shows that, on average, forward speeds in the Gulf Coast are slightly less than for other regions (Keim and Grymes, 2002). Therefore, a forward speed of 15 mph is used in this thesis for the determination of the decrease in hurricane wind speeds along the Gulf Coast after landfall. The resulting adjustment factor for the decay models shown in Figure 3.2 based on distance inland and using a forward speed of 15 mph is presented in Figure 3.3.

Also in Figure 3.3, the reductions in wind speed suggested by the publications presented in Figure 3.2 will be compared to the wind speed map given in ASCE 7-02 (ASCE, 2002) in two locations, the Texas-Louisiana border and the Louisiana-Mississippi border. The wind speed map in ASCE 7-02 at the Louisiana-Texas coast has a wind speed at the coastline of approximately 130 mph with the 120, 110, 100, and 90 mph contours located approximately 15, 30 60, and 115 miles inland, respectively. At the Louisiana-Mississippi border, the wind speed at the coast is approximately 140 mph with the 130, 120, 110, 100, and 90 mph contours located approximately 30, 50, 75, 135, and 200 miles inland, respectively.
Figure 3.3 – Wind Speed Adjustment Factor vs. Distance Inland

It is the suggestion of the author of this thesis that the rate of decay used for design follow relatively closely with the decay rate presented in ASCE 7-02, which represents the current state of practice. It is suggested that the wind speed reduction using the data from Ho, et al. (1987) with a forward speed of 15 mph be used for design. This publication follows the contours presented by ASCE 7-02 rather closely and allows for the use of different wind speed adjustment factors depending on the intensity of the hurricane. The curve for hurricanes with a pressure deficit of up to 85 mb should be used for all hurricanes up to a Saffir-Simpson Category 3, the 100 mb curve should be used for Category 4 hurricanes, and the 110 mb curve should be used for Category 5 storms. Although the decay rate presented by Ho does not vary with the size or the forward speed of the hurricane, for a
forward speed of 15 mph, the model appears match closely with ASCE 7-02. Also, it should be pointed out that this decay rate did not account for the effect of increased surface friction once the hurricane makes landfall. The effect of friction on reducing the wind speed was accounted for, however, in the wind speed used at the coast. Also, until further research has been performed, it is suggested that the design wind speed used for any facility designated as essential during a hurricane event be no less than that given in ASCE 7-02.

### 3.3.2 Directionality Factor

The purpose of the directionality factor applied to the design wind speed of a given building is to account for the reduced probability of the worst wind coming from the worst direction. The directionality factor suggested by ASCE 7-02 for both the Main Wind Force Resisting System (MWFRS) and the Components and Cladding (C&C) of regularly shaped buildings is 0.85. There has been research performed over the last few years, however, which suggests that, for buildings subjected to hurricane events, a higher directionality factor should be used.

The origin of the directionality factor used in ASCE 7-02 goes back to research done by Ellingwood (1980). All of the data used in this research was for extratropical regions of the United States. None of the sites were subject to hurricane winds. The results of the research determined that the correct directionality factor to be used for design was 0.85. This factor was included in the wind load factor in all versions of ASCE 7 before ASCE 7-98. In ASCE 7-98 the directionality factor was moved outside of the wind load factor such that the varying behavior of different types of buildings and structures could be taken into account. The value of 0.85 was given for the MWFRS and the C&C of regularly shaped buildings. Since that time, however, research has been performed that determined this value may not be conservative enough for buildings subjected to wind events corresponding to long MRIs,
such as hurricane events. Simiu and Heckert (1998) and Simiu, et al. (1998) determined that for wind events corresponding to long MRIs the use of 0.85 for the directionality factor resulted in a design that was unconservative. It was suggested by Simiu and Heckert (1998) that this might be one of the reasons such severe damage is done by hurricane events. Rigato, et al. (2001) also determined that, for wind speeds corresponding to long MRIs, the use of 0.85 for the directionality factor results in a design that is “only marginally conservative.” Using the results of many computer simulations of typical rectangular steel-framed buildings, the researchers suggested that a directionality factor of 0.95 be used for the design of buildings subjected to wind speeds corresponding to long MRIs. FEMA 361 and NSSA (2001) suggest the use of a wind directionality factor of 1.0 for the design of structures using their publications due to the highly variable winds of a tornado or hurricane event.

Since buildings designed using this publication are generally not designed for 50 year MRI wind speeds, but rather wind speeds corresponding to much longer MRIs, it is suggested that a wind directionality factor of 0.95 be used for the design of buildings designated as essential during a hurricane event following the recommendation of Rigato, et al. (2001). The value of 1.0 suggested by FEMA 361 and NSSA (2001) was not used because those publications are intended mainly for the design of tornado shelters. The winds of a tornado change direction much more rapidly than those of a hurricane, and therefore the probability of the worst winds corresponding with the worst building orientation are greater for a tornado than for a hurricane.

3.3.3 Site Exposure

The correct site exposure to use for the design of a facility designated as essential during a hurricane event is questioned. The site exposure categories were greatly changed in
ASCE 7-02 as compared to previous versions of ASCE 7. The new definitions of the site exposures are defined in the following bullet list.

- **Exposure A**, which was the site exposure used for large city centers with many tall buildings in previous versions of ASCE 7, was done away with in ASCE 7-02. The authors concluded that the extreme variability of the wind around large buildings disallowed the use of this exposure.

- **Exposure B** is to be used in areas where Surface Roughness B is prevalent in the upwind direction for at least 2630 feet or 10 times the height of the building, whichever is greater, unless the mean roof height of the building is thirty feet or less, in which case Surface Roughness B must prevail in the upwind direction for only 1500 feet. Surface Roughness B is defined as urban and suburban areas, wooded areas, and other locations with numerous closely spaced obstructions having the size of single family dwellings or larger.

- **Exposure C** is to be used when Exposures B and D can not be applied. Surface Roughness C is defined as open terrain with scattered obstructions having heights generally less than 30 ft, including flat open country and the shoreline of hurricane prone regions.

- **Exposure D** is to be used where Surface Roughness D prevails in the upwind direction for a distance of at least 5000 feet, or 10 times the height of the building, whichever is greater. Surface Roughness D is defined as flat, unobstructed areas and water surfaces outside of hurricane prone regions. This corresponds to salt flats, smooth mud flats, and open bodies of water that are not located in hurricane regions.

ASCE 7-02 states that if a building is located in a transition zone between two Site Exposure classifications that the Exposure classification causing the greatest wind loads is to be used for the design of the building, unless a rational method presented in recognized literature is used to determine the correct Exposure. One possible method of interpolating between Exposures is given in the commentary of ASCE 7-02.

When designing a building along the hurricane coast, the possible Exposure Classifications are Exposure B and C (unless an interpolation is performed.) If it is determined that the Exposure for a facility designated as essential during a hurricane event is Exposure B, then the designer needs to consider if it will be Exposure B during the design hurricane event. For buildings nominally in Exposure B, if the design wind speed at the
building site is high, what is the likelihood that the surrounding buildings or trees will be
destroyed or removed by the hurricane winds? Would the destruction of these buildings or
trees result in the surrounding Exposure changing from B to C? An example of the type of
damage experienced during Hurricane Andrew is shown in Figure 3.4. The pre-storm
exposure classification of the neighborhood shown would have been B, but at some point
during the storm, the hurricane winds and debris destroyed most of the homes and trees,
changing the effective exposure to C.

Figure 3.4 – Damage Sustained during Hurricane Andrew (NOAA, 2003)

Publications that address the design of hurricane shelters suggest that no matter the
location of the building, the building be designed using Exposure C (FEMA, 2000a; NSSA,
2001). These publications, however, result in an “ultimate” design, which means that the
building is designed to resist the forces of almost any wind event, even tornados. This design
methodology results in extremely high design wind speeds, which it can be assumed will
destroy most buildings and trees, therefore the building should be classified as being located
in an open area.

For the design of a building based on a hurricane of a certain intensity, the choice of
the Exposure classification to use for design becomes a bit more complicated. For a building
nominally located in Exposure B, it would be conservative to use Exposure C for design, but
in many cases this would result in an overly designed and overly expensive building. For
example, a building located near the coastline designed using a strong Category 3 hurricane
as the design event may be subjected to Exposure B winds because it is not likely that a
hurricane of this intensity would destroy all of the surrounding buildings. However, if the
same building were designed using a Category 5 hurricane as the design event, Exposure C
may be more appropriate to use since a hurricane of this intensity is more likely to destroy
many of the surrounding facilities. The decision of which Exposure classification to use
should be made using sound engineering judgment, based on a number of factors including:
the intensity of the design wind speed at the building location; density, size, and type of
construction of the surrounding buildings; and any other considerations the engineer feels
need to be addressed.

For example, consider a building located in the lower portion of each of Figures 3.5
and 3.6. Both figures are examples of Exposure B terrain (ASCE, 2002). In Figure 3.5, the
substantial nature of the surrounding buildings makes it likely that although they may
experience significant damage, the buildings themselves will still be standing even after a
Category 4 or 5 hurricane. In contrast, many of the homes and trees that create the Exposure
B classification in Figure 3.6 may be destroyed in an extreme hurricane, changing the
exposure from B to C.
Figure 3.5 – Example of Exposure B Terrain Unlikely to Change to Exposure C even During a Major Hurricane (photo reproduced from ASCE, 2002)

Figure 3.6 – Example of Exposure B Terrain that may Need to be Considered as Exposure C for Extreme Hurricane Design Events (photo reproduced from ASCE, 2002)
3.3.4 Enclosure Classification

The purpose of the Internal Pressure Coefficient ($GC_{pi}$) in ASCE 7 is to account for loads on a building due to differences between internal pressure and atmospheric pressure. ASCE 7-02 (ASCE, 2002) defines three internal pressure coefficients, which depend on the enclosure classification of the building, as shown in Table 3.8.

Table 3.8 – Internal Pressure Coefficients for Buildings, $GC_{pi}$ (ASCE, 2002)

<table>
<thead>
<tr>
<th>Enclosure Classification</th>
<th>$GC_{pi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Buildings</td>
<td>0.00</td>
</tr>
<tr>
<td>Partially Enclosed Buildings</td>
<td>+0.55</td>
</tr>
<tr>
<td></td>
<td>-0.55</td>
</tr>
<tr>
<td>Enclosed Buildings</td>
<td>+0.18</td>
</tr>
<tr>
<td></td>
<td>-0.18</td>
</tr>
</tbody>
</table>

The plus and minus signs in Table 3.8 signify pressures acting towards and away from the internal surface, respectively. Both cases must be investigated to determine which case produces the greatest load on a given member. The definitions of the three enclosure classifications follow (ASCE, 2002):

- **Open Buildings**: A building having each wall at least 80% open.

- **Partially Enclosed Buildings**: In order for a building to be deemed partially enclosed, both of the following conditions must be met:
  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%.
  2. The total area of openings in a wall that receives positive external pressure exceeds 4 ft$^2$ or 1% 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%.

- **Enclosed Building**: A building that does not comply with the requirements for open or partially enclosed buildings.
For buildings located in the hurricane-prone regions, ASCE 7-02 requires that unless openings in a building have debris impact resistant coverings, the building must be designed as being partially enclosed. ASCE 7-02 defines impact resistant glazing as glazing that “has been shown by testing in accordance with ASTM E 1886 (ASTM, 1997) and ASTM E 1996 (ASTM, 2001) or other approved test methods to withstand the impact of wind borne missiles likely to be generated in wind borne debris regions during design winds.” Any building designed using this thesis will be located in a wind borne debris region, which is defined by ASCE 7-02 as areas within hurricane prone regions located: 1) within one mile of the coast mean high water line where the basic wind speed is equal to or greater than 110 mph and in Hawaii, or 2) in areas where the basic wind speed is equal to or greater than 120 mph. This requirement is specified to account for the likelihood of a building envelope component being breached by flying debris in a hurricane event. Publications that address the design of hurricane shelters, FEMA 361 (FEMA, 2000a) and NSSA (2001), suggest that a building to be used as a community shelter or other essential function be designed as being Partially Enclosed, even if the building envelope openings are debris impact resistant. This provides the building with an added level of safety against failure should the envelope become breached by flying debris.

Given the importance of preventing penetration of the building by wind, debris, and rain, this thesis suggests requiring debris impact resistant openings. The simultaneous use of the Partially Enclosed building classification is also suggested for the proposed method. The use of the Partially Enclosed classification provides an additional factor of safety against failure if the building envelope is breached. As will be discussed later in this thesis, the current debris impact testing requirements are not currently adequate for extreme design wind speeds. It is the opinion of the author that more stringent debris impact requirements
are needed for a facility designated as essential during a hurricane with extreme design wind speeds.

3.3.5 Importance Factor

The Importance Factor in ASCE 7-02 (ASCE, 2002) is used to adjust the design wind speed of a building based upon the relative danger to life safety resulting from a collapse of the building. Essentially, the MRI of the design wind speed (for buildings not in hurricane regions) is increased from 50 years to 100 years for buildings that pose an above average danger to live safety, while the MRI is decreased to 25 years for buildings that pose a below average danger to live safety. Due to the fact that a design wind speed is chosen when using this publication, an Importance Factor of 1.0 should be used for design. This same recommendation was made in FEMA 361 (FEMA, 2000a) and in NSSA (2001).

3.4 Rain Load

From conversations with the state climatologist of Louisiana, Mr. Jay Grymes, along with research into rainfall rates of past tropical events (Keim, 2002), it was determined that the design rainfall rate associated with a hurricane event is not significantly different from that of a severe extratropical event and is not correlated with Saffir-Simpson Hurricane Category. Therefore, it is suggested that the rainfall rate used in the International Building Code (ICC, 2000), which is a one-hour, 100 year MRI event, be used for design purposes of facilities designated as essential during a hurricane event. Also, the recommendations made by the International Building Code in terms of the guidelines to follow when designing the primary and secondary drainage systems are followed. Special attention must be paid to the drainage system utilized for flat or nearly flat roofs to ensure that if the primary drainage system becomes inoperable, either from debris or any other means, that the secondary
drainage system is sufficient to handle the design rain event so that the rain load the roof experiences does not exceed the design rain load.

3.5 Load Factors and Load Combinations

3.5.1 Wind Load Factor Methodology and Guidelines

The use of the wind load factor provided in ASCE 7-02 for the case where wind controls the design is not appropriate for the proposed method. Higher wind load factors are required to achieve the desired reliability against failure for buildings located on the hurricane coast. This is particularly the case for hurricane winds speeds corresponding to long MRI events, i.e., a Category 4 or 5 hurricane. A summary of the suggestions made by various researchers is shown in Table 3.9.

Table 3.9 – Recommended Load Factor for Wind Load suggested by Various Authors

<table>
<thead>
<tr>
<th>Author</th>
<th>Recommended Load Factor</th>
<th>Comments/Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellingwood (1980)</td>
<td>1.3</td>
<td>No adjustment for directionality. Extratropical winds only.</td>
</tr>
<tr>
<td>Ellingwood and Tekie (1999)</td>
<td>1.5-1.6</td>
<td>L.F. to achieve same reliability against failure due to wind loads as gravity loads. L.F. for buildings located within 10 km (6.2 miles) of the coast.</td>
</tr>
<tr>
<td></td>
<td>1.6-1.7</td>
<td></td>
</tr>
<tr>
<td>Kriebel (1997)</td>
<td>1.8</td>
<td>L.F. to achieve same reliability as NBS 577 provided for gravity loads.</td>
</tr>
<tr>
<td></td>
<td>2.15</td>
<td>L.F. for hurricane regions considering knowledge uncertainties.</td>
</tr>
</tbody>
</table>

The use of a higher wind load factor than the 1.6 provided for in ASCE 7-02 is suggested. There have recently been a number of publications that make the same recommendation, which were outlined in the literature review and summarized in Table 3.9. From a thorough investigation of the assumptions used in the papers, the results of the
research, and the conclusions and recommendations made, the recommended load factor to
use for the design of facilities designated as essential in a hurricane event was determined to
be 1.8. The reasoning behind the use of this value follows.

The wind load factor used in all ASCE standards until the release of ASCE 7-98 was
based on research performed by Ellingwood (1980), which determined that the correct wind
load factor was 1.3. This factor included a 0.85 reduction factor to account for wind
directionality effects, or the reduced probability of the worst winds coming from the most
unfavorable direction for the building. Also, this wind load factor did not differentiate
between extratropical and hurricane winds. All wind data used in the research was from
extratropical wind events.

In ASCE 7-98, the wind load factor was increased from 1.3 to 1.6. There are a couple
of reasons for this. For one thing, the wind directionality factor of 0.85 used in Ellingwood
(1980) was taken out to allow for the use of different wind directionality factors depending
on the building geometry. This change alone increased the wind load factor from 1.3 to 1.53.
Also, the wind load factor in ASCE 7-98 was updated to account for the difference in
extratropical and hurricane winds, a consideration that was not accounted for in Ellingwood
(1980). Research performed in Ellingwood and Tekie (1999) was used to determine the
correct wind load factor accounting for these considerations. Ellingwood and Tekie
determined that in order to achieve the same reliability against failure due to wind loading as
to gravity loading, and removing the 0.85 wind directionality factor, the wind load factor
should be increased to between 1.5 and 1.6 for buildings located at a distance of greater than
10 km (6.2 miles) from a hurricane-prone coast. Also, Whalen and Simiu (1998) suggested
that the wind load factor used in ASCE 7-95 resulted in structures in the hurricane-prone
region of the United States being placed at a higher risk than those in the extratropical region.
The researchers suggested that the wind load factor for buildings subjected to hurricane winds should be increased. The same recommendation was also made in Simiu and Heckert (1998). For all of these reasons, the wind load factor was increased from 1.3 to 1.6 in ASCE 7-98. ASCE 7-98 did not take the suggestion given in Ellingwood and Tekie (1999), however, which said for buildings located within 10 km (6.2 miles) of the hurricane coastline, the wind load factor should be increased to between 1.6 and 1.7 to account for the increased coefficient of variation of hurricane winds as compared to extratropical winds.

Other research has been performed that suggests that the wind load factor used in ASCE 7-98 and currently in ASCE 7-02 may be too low for buildings located on the hurricane coastline of the United States. Kriebel, et al. (1997) determined that for the case where wind load controls the design of a building, the wind load factor should equal 1.8 in order for the building to have the same reliability index as if live load controlled the design. Minciarelli, et al. (2001) pointed out the fact that the safety indices used in ASCE 7-98 for wind loads are not the same as those for gravity loads. Also, the researchers state that the increased knowledge uncertainties associated with hurricane winds as opposed to extratropical winds were not taken into account in ASCE 7-98. They found that, without consideration for wind directionality factors, the correct wind load factor for buildings subjected to hurricane winds should be approximately 2.15. By contrast, the load factor they suggested for buildings in which extratropical events control the design was 1.55. The increased load factor for building subjected to hurricane winds was primarily due to the increased knowledge uncertainties associated with hurricane events.

From the previous discussion, it would appear that a better wind load factor to use for the design of facilities designated as essential in a hurricane event is 1.8. From the publications listed in Table 3.5, it would appear that the load factor to apply to the wind load
factor for a building located along the hurricane coast is required to be in the 1.6 to 1.8 range order to have the same reliability against failure due to wind load as to gravity loads. The wind load factor of 1.8 suggested by this publication from Kriebel et al. (1997) appears to better account for the differences in extratropical and hurricane winds as opposed to the wind load factor suggested by ASCE 7-02, without being overly conservative. The 2.15 wind load factor suggested by Minciarelli (2001) was not chosen for use by this publication because this value accounts for the increased knowledge uncertainties associated with a hurricane as opposed to an extratropical event, a factor that needs more research to prove the correctness of the assumptions made in the paper. The fact that the design wind speed in the proposed method is selected based on hurricane category rather than Mean Recurrence Interval; there is less “uncertainty” in the wind speed, which is the most important element of the load factor.

3.5.2 Rain Load Factor Methodology and Guidelines

An investigation was performed on the adequacy of using the rain load factor presented by ASCE 7-02 when rain load controls the design. After performing this investigation, it is the suggestion of this thesis that the rain load factor in ASCE 7-02 remains unchanged. The rainfall associated with a tropical event was assumed to not be significantly different from that of an extratropical event; therefore no change in the load factor is needed.

3.5.3 Load Combinations

The load factors provided in ASCE 7-02 are:

1. $1.4(D + F)$
2. $1.2(D + F + T) + 1.6(L + H) + 0.5(L_r$ or $S$ or $R)$
3. $1.2D + 1.6(L_r$ or $S$ or $R) + (0.5L$ or $0.8W)$
4. $1.2D + 1.6W + 0.5L + 0.5(L_r$ or $S$ or $R)$
5. $1.2D + 1.0E + 0.5L + 0.2S$
6. $0.9D + (1.6W$ or $1.0E)$
7. $0.9D + 1.0E + 1.6H$
See Sections 2.3.2 and 2.3.4 of this thesis for definitions. For structures located in a Special Flood Hazard Area, ASCE 7-02 specifies that the following load combinations shall also be considered:

1. In V-Zones or Coastal A-Zones, 1.6W in combinations (4) and (6) shall be replaced by 1.6W + 2.0Fa.
2. In Noncoastal A-Zones, 1.6W in combinations (4) and (6) shall be replaced by 0.8W + 1.0Fa.

The definitions of the different flood zones was given in Section 2.3.5 of this thesis.

The suggested modifications to be made to these load combinations when designing facilities designated as essential during hurricane events are shown in the following bullet list. The terms that have been changed by this thesis are shown in red.

- Load Combination (1): Load combination (1) maximizes the effect of dead load on a structure. No change is suggested in this load combination.
- Load Combination (2): Load combination (2) maximizes the effect of live load on a structure. The load combination suggested for the design of essential facilities is:

\[ 1.2(D + F + T) + 1.6(L + H) + (0.5L_r \text{ or } 0.5S \text{ or } 1.6R) \]

It is suggested that the rain load factor in this load combination be increased from 0.5 to 1.6 to account for the increased probability of the design rain event occurring simultaneously with the design live load.

- Load Combination (3): Load combination (3) maximizes the effect of roof loads on a structure. It is suggested that a new load combination, called Load Combination (3'), shown next, be investigated along with Load Combination (3).

\[ 1.2D + 1.6R + (1.0L \text{ or } 1.8W) \]

In ASCE 7-02, the live load factor must be increased from 0.5 to 1.0 for places of public assembly. It could be argued that only shelters and refuges should be defined as places of public assembly. It is the belief of the author, however, that the other types of facilities (hospitals, emergency operations centers, fire stations, etc.) are likely to be used as defacto shelters if the need arises. Due to the increased probability of the design wind event and the design rain event occurring at the same time, it is suggested that the wind load factor used for the case where wind load controls design be used in the case where the rain load controls design. As was pointed out in Section 3.5.1, it is suggested that the wind load factor be increased to 1.8.
Load Combination (4): Load combination (4) maximizes the effect of wind load on a structure. It is suggested that a new load combination, called Load Combination (4’), shown next, be investigated along with Load Combination (4).

\[ 1.2D + 1.8W + 1.0L + (0.5L \text{ or } 1.6R) \]

As discussed previously, it is suggested that the wind load factor be increased to 1.8. Also, it is required that the live load factor be increased to 1.0 because the facility is a place of public assembly. It is also suggested that the rain load factor be increased to account for the increased probability of the design rain event and design wind event occurring simultaneously. Also, for buildings located in Special Flood Hazard Areas, the following load combination must be investigated:

1. For buildings located in V-Zones or Coastal A-Zones, the 1.8W shall be replaced by 1.8W+2.0Fa.

2. For buildings located in Noncoastal A-Zones, 1.8W shall by replaced by 0.8W+1.0Fa.

Load Combination (5): Load combination (5) maximizes the effects of an earthquake on a building. No changes are suggested to this load combination.

Load Combination (6): Load combination (6) maximizes the effects of uplift caused by wind. The load combination suggested for design is:

\[ 0.9D + (1.8W \text{ or } 1.0E) \]

The only change suggested is the increase of the wind load factor from 1.6 to 1.8, which was addressed previously. The effects of flood loads also have to be included. This is the same as was described in Load Combination (4).

Load Combination (7): Load combination (7) maximizes the effects of uplift caused by earthquake events. No changes are suggested to this load combination.

3.6 Debris Impact Guidelines

Wind-borne debris impact is a major cause of much of the damage many facilities experience during hurricane events and is a serious danger to building occupants. The breaching of the building envelope has many detrimental consequences and can even lead to a total building collapse. A breach in the building envelope results in internal pressurization of the building, which can double the uplift forces on the roof and the outward acting pressure on leeward and side walls, and in some cases lead to a complete collapse of the
building. Also, a breach in the building envelope can cause severe interior and contents damage, which can be more costly than the structural damage the building sustains. The occupants of the building are also endangered because they are subjected to wind and flying debris.

The debris impact guidelines for a facility designated as essential during a hurricane event need to be determined. There are a number of different recommendations made depending on the many factors, including the use of the building, the location of the building, and many others. ASTM recommends that, for an “essential facility” located within one mile of the coast, all building envelope components be able to withstand impact from a 9 lb 2” x 4” wooden member traveling 80 ft/s (55 mph) if located at a height of less than 30’ and traveling 50 ft/s (34 mph) if located at a height of greater than 30’ (ASTM 2001). The 2001 Florida Building Code (SBCCI, 2001) mandates that all building envelope components located at a height of less than 30’ be able to withstand impact from a 9 lb 2” x 4” wooden member traveling at 50 ft/s (34 mph) and that all building envelope components located at a height of greater than 30’ be able to withstand impact from 10 steel balls each weighing 2 grams traveling at 130 ft/s (89 mph). FEMA 361 (FEMA, 2000a), which is used to design a structure using the ultimate wind event as the design event, requires all building envelope components be able to withstand impact from a 15 lb 2” x 4” wooden member traveling at 100 mph.

When determining the missile speed to use for the testing of building envelope components to be used in facilities designated as essential during a hurricane event, there are a number of considerations that must be made. One of these is the missile type to use for testing. The most common missile tested is a 2” x 4” wooden member with a length of between 9’ and 15’, depending on the publication. The most common recommendation for
building envelope components of “essential facilities” and the like is a 12’ long 2” x 4” wooden member. Another important consideration is the wind speed at which a missile in a high wind event can be picked up and transported. Research performed by Wills, et al. (1992) determined that a 2” x 4” wooden member can be transported at a wind speed of approximately 70 mph. Therefore, at a wind speed any lower than 70 mph, this type of flying debris would not be a concern. This means, however, that all hurricane events have the possibility of transporting 2” x 4” missiles.

There has been much research performed to determine the flight characteristics of debris generated by high wind events, as was outlined in the literature review. The time for a missile to reach a given speed, for a given wind speed, and the distance the missile travels in this time using the equations given in Holmes (2001) and described in Section 2.51. are shown in Table 3.10. The following values were input into the Holmes equations in order to produce Table 3.10:

- Density of air = 1.2 kg/m$^3$
- Density of wooden member = 500 kg/m$^3$
- Coefficient of drag = 1.0

Many researchers (Minor, 1978; Wills, et al., 2002; and Lee and Wills, 2002) have suggested that a missile flight speed of $\frac{1}{2}$ the design wind speed (1-minute averaging time) be used for building envelope component testing purposes. As a check to these recommendations, the equations suggested by Holmes (2001), as shown in Table 3.10, to determine the distance a missile travels to reach a given speed results in a distance traveled of approximately one kilometer for a 12’ long 2” x 4” wooden missile to reach approximately $\frac{1}{2}$ of the one-minute averaging time wind speed.
Table 3.10 – Missile Flight Times and Distance Traveled for a 12' long 2"x4"
*The first row represents the time (in seconds) for the missile to reach the designated velocity for the given wind speed.
*The second row represents the distance (in meters) the missile travels in this time

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<td>82</td>
<td>118</td>
<td>163</td>
<td>219</td>
<td>288</td>
<td>372</td>
<td>475</td>
<td>600</td>
<td>751</td>
<td>935</td>
<td>1160</td>
<td>1437</td>
<td>1779</td>
<td>2207</td>
<td>2747</td>
</tr>
<tr>
<td>1-min</td>
<td>11</td>
<td>13</td>
<td>15</td>
<td>18</td>
<td>21</td>
<td>24</td>
<td>28</td>
<td>32</td>
<td>36</td>
<td>41</td>
<td>47</td>
<td>53</td>
<td>61</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>1-min</td>
<td>76</td>
<td>109</td>
<td>150</td>
<td>202</td>
<td>264</td>
<td>341</td>
<td>433</td>
<td>544</td>
<td>679</td>
<td>842</td>
<td>1039</td>
<td>1278</td>
<td>1571</td>
<td>1933</td>
<td>2384</td>
</tr>
</tbody>
</table>
From all of the relevant considerations to be investigated when determining the correct missile parameters to use for the testing of building envelope components of facilities designated as essential during a hurricane event, the following recommendations are made:

- Any building envelope component must be able to withstand impact from a 12’ long 2” x 4” wooden missile traveling at ½ the 1-minute averaging time wind speed.

- The requirement for the component to be deemed to have passed the impact test depends on the use classification of the building. For example, the requirement for a building classified as a Function Critical facility is far more stringent than that of a building classified as a refuge. For the requirement that the component must meet, see the Performance-based Design Guidelines section of this thesis.

- There are no small missile impact requirements suggested by this paper. As long as the building envelope component is deemed to pass the above requirement, it is assumed that it will be able to resist any type of small missile impact.

A comparison of the recommended debris impact guidelines to current practice was performed. Specifically, the recommendation made by this paper was compared to ASTM E-1996 (ASTM, 2001). The results of this comparison are shown in Table 3.11. It is important to realize that the missile used by ASTM E-1996 is an 8’ long missile, while this thesis suggests a 12’ long missile.

Table 3.11 – Comparison of Existing Test Standard (ASTM) to Test Standard Suggested Herein

<table>
<thead>
<tr>
<th>ASTM Missile Designation</th>
<th>ASTM Missile Test Speed (ft/s)</th>
<th>Corresponding One-Minute Wind Speed (ft/s)</th>
<th>Corresponding One-Minute Wind Speed (mph)</th>
<th>Corresponding 3-Second Design Wind Speed* (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>50</td>
<td>100</td>
<td>68</td>
<td>82</td>
</tr>
<tr>
<td>E</td>
<td>80</td>
<td>160</td>
<td>109</td>
<td>131</td>
</tr>
</tbody>
</table>

* Note: This column shows the equivalent 3-second design wind speed required to generate a missile having the speed used in ASTM testing.
As is shown by Table 3.11, the impact speed a component is required to resist using current debris impact resistance standards would only be appropriate up to design wind speeds of approximately 130 mph using the suggestion of this thesis. A design wind speed of 130 mph would be the wind speed for a building located on the coast that was designed to resist a Category 2 hurricane. It is the recommendation of this thesis that, at least until more testing standards are produced, that any building envelope component of a facility designated as essential during a hurricane event be tested using ASTM Missile Level E.

3.7 Flooding, Mass Care, and Other Design Considerations

Items that must be addressed in the planning stages of a building designated as essential during a hurricane event include, the flood potential of the site, mass care considerations, access issues, and any other special circumstances that are present. These topics are not the focus of this research, but they are considered important and this thesis will provide some guidance. Specifically this paper will summarize some of the guidelines given in a few of the available publications that present specific guidelines on these issues.

- Flooding

Flooding, both from rainfall and from storm surge, is a serious concern when planning and designing a facility to be used during a hurricane event, especially in South Louisiana. The current method of determining if a building is flood prone is to use the Flood Insurance Rate Maps (FIRM maps) that are produced by FEMA. These maps give the areas expected to be flooded and the expected height of the flood waters during a 100 year MRI rainfall event. Since this thesis specifies building requirements to resist a
hurricane of a certain intensity, and not just the loads with a certain probability, this
design methodology is generally not acceptable for the design of facilities designated as
essential during a hurricane. It is suggested that more research needs to be performed on
the rainfall associated with hurricanes of various intensities. At this time, it is the
recommendation of this thesis that essential faculties to be utilized during hurricanes be
sited outside of the 100 year MRI rainfall event as given by the FEMA FIRM maps.
Consideration should be given to increasing this requirement to the 500 year MRI for the
most essential facilities, such as hospitals and emergency management operations
facilities.

Essential emergency facilities to be utilized during hurricanes must also be
investigated for flooding from storm surge. It is suggested that in order to determine if a
building is going to be flooded due to storm surge during the design hurricane event, the
design hurricane event should be input into a storm surge modeling package such as
SLOSH (NWS, 2001), which was described in Section 3.3.1.3, or ADCIRC (Notre
Dame, 2003), which developed by the University of Notre Dame, and the resulting storm
surge model results must be investigated at the building site. It is suggested that if the
results of the storm surge model show that the building will be inundated by storm surge
flood waters during the design hurricane that the building should be either raised or
moved.

If the facility can not be sited such that the threat of storm surge flooding is
avoided, then special considerations must be made. Most importantly, the building must
be designed to resist the forces caused by storm surge flood waters and the debris that is
transported along with it. Guidance on flood loads and designing buildings for flood
resistance is given in ASCE 7-02 (ASCE, 2002), ASCE 24-98 (ASCE, 1998), and Kriebel et al. (1997). Also, if a building is expected to flood, special consideration must be paid to ensure the welfare of the people inside of the building. If the building is to house people during and after the hurricane event, the portions of the building expected to flood should not be considered usable.

It is very important that the people that are to be inside of a flooding building have a means of escape from the facility and that there is a place for them to go once they are outside of the building. One of the most common methods of egress is through a specially designed hatch. The area that the escape hatch opens onto must also be taken into account. There must be an area large enough for the people to gather. This may lead to the use of a flat roof. If it is expected that people will be gathered on the roof, then a suitable roof should be designed in the initial design stages. There must also be a way for rescue personnel to be able to transport the occupants away from the flooding facility after the hurricane event. Also, depending on the performance criteria of the building, the utilities may be required to resist the damaging effects of flood waters. This may entail raising the utilities off of the ground, separating the first and second floor utilities or any other means deemed acceptable.

- **Area Surrounding the Building**

Special consideration must also be given to the area surrounding the building site. Specifically, the potential debris field around the building must be investigated. If there are any areas surrounding the building that require special consideration during the building design process, such as pipe yards or the like, the impact such an item could have on the building in the event of a hurricane must be addressed. The presence of any
items that could fall on the building in a high wind event, also known as a lay-down hazard, must be addressed in the building design. A common type of object that could pose a lay-down hazard is a radio or cellular phone tower. Another important consideration is the presence of any objects that could roll into the building in high wind event, also known as a rollover hazard. Such would include manufactured houses or buildings (such as portable classrooms often found at schools), other small buildings, or vehicles. If there are rollover hazards present, this must be considered during the building design process.

- **Mass Care Considerations**

  Due consideration must be given to the needs of people who will shelter inside a building designated as essential in a hurricane event. The only mass care consideration that will be addressed in this paper is the required space per shelter occupant. FEMA 361 - Design and Construction Guidance for Community Shelters (FEMA, 2000a) suggests that for a hurricane shelter 20 ft$^2$ per person be provided for if the length of stay is anticipated to be only a few days, but if the length of stay is anticipated to be longer than a few days that 40 ft$^2$ per person be provided. Obviously, for other facilities, such as emergency management facilities, etc, the spacing will be that required for normal operations. FEMA also notes that if the shelter occupancy exceeds the normal operating occupancy, the emergency escape requirements of the Building Code may not be met. If this is the case, this should be addressed with building code officials.

  The American Red Cross also produces a publication addressing hurricane sheltering entitled “ARC 4496 – Standards for Hurricane Evacuation Shelter Selection” (ARC, 2002). ARC 4496 suggests that for a hurricane evacuation shelter a minimum of...
be provided per person. On a short-term basis, however, this number is allowed to be reduced to 15 ft$^2$ per person. The 1992 version of ARC 4496 suggested that the minimum spacing on a short term basis be 20 ft$^2$ per person. Another publication by the American Red Cross, “ARC 3041 – Mass Care-Preparedness and Operations” (ARC, 1998) also gives space requirements for sheltering. ARC 3041 suggests that 40-60 ft$^2$ of sleeping space be provided per person for a sheltering event that is expected to last a few days. This publication also recommends 1 toilet per 40 persons (6 toilets per 200 people and 14 per 500 people). The “National Performance Criteria for Tornado Shelters” produced by FEMA and Texas Tech (FEMA, 1999b) suggests that for tornado shelters, the following spacing requirements be met:

- Adults …………………………… 5 ft$^2$ per person standing
- Adults …………………………… 6 ft$^2$ per person seated
- Children (under the age of 10) … 5 ft$^2$ per person
- Wheelchair Bound Persons ….. 10 ft$^2$ per person
- Bed-Ridden Persons ………….. 30 ft$^2$ per person

It should be remembered that tornados are very short-lived events as compared to hurricanes, so the spacing requirements for a tornado shelter are less than those of a hurricane shelter.

Based on the literature reviewed, it appears that 10 ft$^2$ – 15 ft$^2$ per person is appropriate for short term events (such as a tornado) and 40 ft$^2$ – 60 ft$^2$ per person is required for events that are expected to require people to shelter for a few days (such as a hurricane).
• **Other Considerations**

There are other mass care considerations that need to be addressed during the planning process other than the required space needed per anticipated shelter occupant. Some of these include:

- Power Supply
- Water Supply
- Air Handling (ventilation)
- Sewerage
- Feeding of the shelter occupants
- Requirements of individuals with special needs
- Any other relevant considerations for the building.

Guidance on all of these issues can be found in FEMA 361 (FEMA, 2000a), ARC 4496 (ARC, 2002), ARC 3041 (ARC 1998), and other publications produced by FEMA and the American Red Cross. It is wise to consult with local emergency management officials about decisions made concerning any of the previously-mentioned considerations before they are implemented into the design of the building. For any building designated as essential during a hurricane event, there must be a plan addressing the use and functionality of the building before, during, and after the hurricane event. This plan must be well-known by all of the usual occupants of the building as well as individuals that will be inside the building during and after the hurricane event.

3.8 **Summary of Design Guidelines**

3.8.1 **Select the Design Hurricane Event**

The first step in the design of a facility designated as essential using the guidelines presented in this thesis is the selection of the design hurricane event. The selected design hurricane is based on the Saffir-Simpson Hurricane Scale and is chosen by the building owner. Based on sheltering and emergency response needs, budget, and
any other relevant considerations, the building owner, in consultation with the architect and/or engineer, should select a Hurricane Category (1-5) for design. See Section 3.3.1.1 of this thesis for a discussion on the selection of the Design Hurricane Event.

3.8.2 Determine Required Performance Criteria Based on Facility Use

Based upon the use of the facility, the required performance of the various building components/systems when subjected to the design hurricane event must next be investigated. The required performance is different depending upon the function of the building during the hurricane event. The definitions of the facility types, building components/systems, and damage levels can be found in Section 3.2 of this thesis. The required performance of the various building components/systems in each of the essential facility classifications is shown in Table 3.12. See Section 3.2 of this thesis for a discussion on the performance criteria.

Table 3.12 – Required Performance When Subjected to the Design Hurricane Event

<table>
<thead>
<tr>
<th>Building Component/ System and Levels of Damage Investigated</th>
<th>Function Critical</th>
<th>Base of Operations for Response</th>
<th>Hurricane Shelter</th>
<th>Refuge of Last Resort</th>
<th>Emergency Equipment/ Supplies Storage Facility*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Structural System</td>
<td>None to Very Light</td>
<td>Light</td>
<td>Light</td>
<td>Light</td>
<td>Moderate</td>
</tr>
<tr>
<td>Windows/Doors</td>
<td>None to Very Light</td>
<td>Light</td>
<td>Light</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Roof and Wall Systems</td>
<td>None to Very Light</td>
<td>Light</td>
<td>Light</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Electrical/Lighting Systems</td>
<td>None</td>
<td>Very Light</td>
<td>Very Light</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>HVAC Equipment</td>
<td>None</td>
<td>Very Light</td>
<td>Very Light</td>
<td>Severe</td>
<td>Severe</td>
</tr>
<tr>
<td>Plumbing Systems</td>
<td>None</td>
<td>Very Light</td>
<td>Very Light</td>
<td>Severe</td>
<td>Severe</td>
</tr>
<tr>
<td>Danger to Life Safety</td>
<td>Mild</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

*The danger to life safety in this case is from individuals entering the building after the storm in order to retrieve the needed equipment.
3.8.3 Determine Wind Loads

3.8.3.1 Wind Speed at Coast

The wind speed at the coast used for design for a storm in each Hurricane Category used corresponds to the strongest storm that is still classified as a given category. The wind speed at the coastline (peak gust at 10 m height, Exposure C) for each Saffir-Simpson Hurricane Category is shown in Table 3.13. See Section 3.3.1.2 for a discussion on the wind speed at the hurricane coast.

Table 3.13 – Design Wind Speed at the Hurricane Coast

<table>
<thead>
<tr>
<th>Design Hurricane Event (Saffir-Simpson Category)</th>
<th>Design Wind Speed to be Used at Hurricane Coast (peak gust at 10m height, exposure C) (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>108</td>
</tr>
<tr>
<td>2</td>
<td>130</td>
</tr>
<tr>
<td>3</td>
<td>156</td>
</tr>
<tr>
<td>4</td>
<td>191</td>
</tr>
<tr>
<td>5</td>
<td>Chosen by Building Owner in Consultation with Architect and/or Engineer</td>
</tr>
</tbody>
</table>

3.8.3.2 Wind Speed Inland

The design wind speed at the building site must be reduced from the value given for the hurricane coast according to the distance of the facility inland. The reduction factors used to determine the reduction of hurricane wind speeds inland are shown in Figure 3.7. The reduction factor shown is only applicable for buildings located in the Gulf Coast region. Reduction factors for other hurricane-prone regions of the United States, such as the Atlantic Coast and Florida, can be developed as discussed in Section 3.3.1 of this thesis. It is important to realize that in no instance may the design wind speed for a given location be less than the design wind speed given by the Design Wind...
Speed Map in ASCE 7-02 (ASCE, 2002). See Section 3.3.1.3 for a discussion of the reduction in hurricane wind speed inland.

Figure 3.7 – Suggested Reduction Factors for Distance Inland (Gulf Coast Region)

3.8.3.3 Directionality Factor

The Directionality Factor \( (K_d) \) is recommended to be set at 0.95, as opposed to a value of 0.85 used in ASCE 7-02 (ASCE, 2002). This is because research has shown that a value of 0.85 may not be conservative enough for long MRI events, such as hurricanes. See Section 3.3.2 of this thesis for a discussion of the Directionality Factor.
3.8.3.4 Site Exposure

For a building nominally located in Exposure B, it is suggested that the use of this site exposure for the design of essential hurricane facilities be carefully considered. The extreme wind speeds associated with a hurricane event have the potential of destroying surrounding buildings or removing trees, which could change the Exposure classification of the building during the design hurricane event to Exposure C. The decision as to whether or not change the exposure is based on the wind speed at the building site, not the wind speed at the coastline. See Section 3.3.3 for a discussion of the Site Exposure.

3.8.3.5 Enclosure Classification

The enclosure classification recommended for design is Partially Enclosed. This results in an Internal Pressure Coefficient ($GC_{pi}$) of $+/- 0.55$. This value is recommended for design, even if the building has debris impact resistant coverings, because the uncertainty that the coverings will provide full protection, and the consequences associated with a breach in the envelope, are severe. See Section 3.3.4 of this thesis for a discussion on Enclosure Classification.

3.8.3.6 Importance Factor

The Importance Factor ($I$) recommended for design is 1.0. The value of 1.15 provided by ASCE 7-02 (ASCE, 2002) is to increase the MRI associated with the design wind speed, a factor that does not need to be applied with the recommended design philosophy. See Section 3.3.5 for a discussion of the Importance Factor.

3.8.4 Rain Load

No change is suggested in the rain load. No research has been found showing a difference in maximum hurricane and extratropical rainfall rates used for design.
purposes, therefore no change is suggested at this time. See Section 3.4 of this thesis for a discussion on the rain load associated with hurricanes.

3.8.5 Flood Load

Flood elevations used to determine flood loads from storm surge should be based on the maximum flood levels expected during the design hurricane event. These flood elevations could be determined using the SLOSH model (NWS, 2001) or the ADCIRC model (Notre Dame, 2003). Other storm surge flooding models could be used, but enough scenarios would need to be run to provide an “envelope” of worst case flood elevations per storm category. See Section 3.7 of this thesis for a discussion on the flooding associated with hurricanes.

3.8.6 Load Factors and Load Combinations

The following list outlines the recommended changes to the load factors and/or combinations given in ASCE 7-02. No change is recommended to Load Combination (1) given in ASCE 7-02. It is recommended that Load Combinations (2) and (6) in ASCE be replaced with Load Combination (2) and (6a) and (6b), respectively, as shown in the following list. Also, it is suggested that in addition to Load Combinations (3) and (4) given in ASCE 7-02, Load Combinations (3’) and (4a’) and (4b’) be investigated. See Section 3.5 for a discussion of Load Factors and Load Combinations.

(2) \[ 1.2(D + F + T) + 1.6(L + H) + (0.5L_r \text{ or } 0.5S \text{ or } 1.6R) \]

(3’) \[ 1.2D + 1.6(L_r \text{ or } R) + (1.0L \text{ or } 1.8W) \]

(4a’) \[ 1.2D + 1.8W + 2.0F_a + 1.0L + (0.5L_r \text{ or } 1.6R) \]

(4b’) \[ 1.2D + 0.8W + 1.0F_a + 1.0L + (0.5L_r \text{ or } 1.6R) \]

(6a*) \[ 0.9D + ((1.8W + 2.0F_a) \text{ or } 1.0E) \]
(6b) 0.9D + ((0.8W + 1.0F_a) or 1.0E)

* Equations (4a) and (6a) are used if the building is located in a V-Zone or a Coastal A-Zone. Equations (4b) and (6b) are used if the building is located in a Noncoastal A-Zone.

3.8.7 Debris Considerations

It is suggested that any building envelope component be debris impact resistant or have a debris impact resistant covering. These components or coverings must be able to withstand impact from a 12’ long 2” x 4” wooden missile traveling at ½ the 1-minute averaging time wind speed. The requirement for the component to be deemed to have passed the impact test depends on the use classification of the building. For example, the requirement for a building classified as a Function Critical facility is far more stringent than that of a building classified as a refuge. For the requirement that the component must meet, see the Performance-based Design Guidelines section of this paper. If there are no more stringent testing programs available than ASTM E-1996 (ASTM, 2001), then use Missile Level E for approval purposes. See Section 3.6 of this thesis for a discussion on debris impact.

3.8.8 Other Flooding and Mass Care Considerations

All of the recommendations given in Section 3.7 of this thesis concerning flooding, mass care, and siting considerations must also be included in the planning and design process. Wherever possible, the building should be sited such that flooding does not occur when the building is exposed to its design hurricane event. If flooding is not avoidable, however, the necessary issues associated with the building flooding must be considered. This includes, but is not limited to, structural design considerations, mass care considerations, and utility considerations. Also, the building must have adequate
provisions (such as food, water, toiletries, and sleeping spaces) for the individuals that are to be inside of the building during the hurricane event.
CHAPTER 4: COMPARISON TO EXISTING PRACTICE

The recommendations made in this thesis were compared to the current state of practice. Table 4.1 summarizes the major changes effecting estimation of wind loads by the method proposed in this thesis and ASCE 7-02.

Table 4.1 – Comparison of the Recommendations Given Herein and in ASCE 7-02

<table>
<thead>
<tr>
<th></th>
<th>ASCE 7-02</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directionality Factor ($K_d$)</td>
<td>0.85</td>
<td>0.95</td>
</tr>
<tr>
<td>Importance Factor ($I$)</td>
<td>1.15</td>
<td>1.0</td>
</tr>
<tr>
<td>Design Wind Speed ($V$)</td>
<td>Based on MRI between 70 and 90 years</td>
<td>Based on Max Wind Speed Associated with each Saffir-Simpson Category</td>
</tr>
<tr>
<td>Exposure Classification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open</td>
<td>Exposure C</td>
<td>Exposure C (no change)</td>
</tr>
<tr>
<td>Suburban or Wooded</td>
<td>Exposure B</td>
<td>Use Exposure C if expected damage is such that C would be more representative of conditions at some point during the storm.</td>
</tr>
<tr>
<td>Enclosure Classification</td>
<td>“Either/Or” provisions – either provide debris impact protection or design for full internal pressurization</td>
<td>“And” provisions – provide debris impact protection and design for full internal pressurization</td>
</tr>
<tr>
<td>Debris</td>
<td>Missile speed varies with region</td>
<td>Missile speed varies with design wind speed</td>
</tr>
<tr>
<td>Load Factor on Wind</td>
<td>1.6</td>
<td>1.8</td>
</tr>
</tbody>
</table>

A comparison was performed between the resulting velocity pressure achieved using the recommendations presented by this thesis and the values given in ASCE 7-02. The velocity pressure used in ASCE 7-02 is defined as:

\[ q_z = 0.00256K_xK_{zt}K_dV^2I \text{ (lb/ft}^2\text{)} \]
where: $K_z =$ Velocity Pressure Exposure Coefficient
$K_{zt} =$ Topographic Factor
$K_d =$ Directionality Factor
$V =$ Design Wind Speed (mph)
$I =$ Importance Factor

No information was found in the literature suggesting that topographic effects would be different in hurricane and non hurricane wind events, therefore no changes are recommended in $K_{zt}$. Recent research findings from dropwind sonde data have shown that the vertical velocity profile can be quite different in hurricanes from the currently assumed models. However, there is currently not enough data to justify a change in the Velocity Pressure Exposure Coefficient ($K_z$) at this time. In cases where the exposure would change from B to C, because of high levels of damage, this would result in a significant increase in $K_z$ and therefore the wind load, which increases in linear proportion to $K_z$. The impacts of requiring a change in exposure category are shown in Table 4.2. This thesis suggests a different value for the Directionality Factor ($K_d$) and the Importance Factor ($I$) as compared to ASCE 7-02, as shown in Table 4.1. The values for the Directionality Factor are for the Main Wind Force Resisting System and the Components and Cladding of a building.

Another factor affecting the wind load is the change in the wind load factor. Although the wind load factor is part of the load combinations, it in effect becomes a linear multiplier on the wind load. The net effect of the recommended values to be used for $K_d$, $I$, and the wind load factor is rather small. Excluding the velocity term and changes in the internal pressure coefficient (considered later), the ratio of the factored wind loads for the method presented in this thesis and ASCE 7-02 is: $(0.95/0.85)*(1.0/1.15)*(1.8/1.6) = 1.093$, or a 9.3% higher factored wind load, where the bracketed terms represent the ratio of (recommended value/ASCE 7-02 value) for Directionality Factor, Importance Factor, and wind load factor, respectively.
Table 4.2 – Increase in $K_z$ due to a Change in Site Exposure from B to C

<table>
<thead>
<tr>
<th>Height (ft)</th>
<th>$K_z$ Exposure B&lt;sup&gt;*&lt;/sup&gt;</th>
<th>$K_z$ Exposure C</th>
<th>Percent Increase&lt;sup&gt;*&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 1</td>
<td>Case 2</td>
<td>Cases 1 and 2</td>
</tr>
<tr>
<td>0</td>
<td>0.70</td>
<td>0.57</td>
<td>0.85</td>
</tr>
<tr>
<td>15</td>
<td>0.70</td>
<td>0.62</td>
<td>0.85</td>
</tr>
<tr>
<td>20</td>
<td>0.70</td>
<td>0.66</td>
<td>0.90</td>
</tr>
<tr>
<td>25</td>
<td>0.70</td>
<td></td>
<td>0.94</td>
</tr>
<tr>
<td>30</td>
<td>0.70</td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>40</td>
<td>0.76</td>
<td></td>
<td>1.04</td>
</tr>
<tr>
<td>50</td>
<td>0.81</td>
<td></td>
<td>1.09</td>
</tr>
<tr>
<td>60</td>
<td>0.85</td>
<td></td>
<td>1.13</td>
</tr>
<tr>
<td>70</td>
<td>0.89</td>
<td></td>
<td>1.17</td>
</tr>
<tr>
<td>80</td>
<td>0.93</td>
<td></td>
<td>1.21</td>
</tr>
<tr>
<td>90</td>
<td>0.96</td>
<td></td>
<td>1.24</td>
</tr>
<tr>
<td>100</td>
<td>0.99</td>
<td></td>
<td>1.26</td>
</tr>
<tr>
<td>120</td>
<td>1.04</td>
<td></td>
<td>1.31</td>
</tr>
<tr>
<td>140</td>
<td>1.09</td>
<td></td>
<td>1.36</td>
</tr>
<tr>
<td>160</td>
<td>1.13</td>
<td></td>
<td>1.39</td>
</tr>
<tr>
<td>180</td>
<td>1.17</td>
<td></td>
<td>1.43</td>
</tr>
<tr>
<td>200</td>
<td>1.20</td>
<td></td>
<td>1.46</td>
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<tr>
<td>250</td>
<td>1.28</td>
<td></td>
<td>1.53</td>
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<tr>
<td>300</td>
<td>1.35</td>
<td></td>
<td>1.59</td>
</tr>
<tr>
<td>350</td>
<td>1.41</td>
<td></td>
<td>1.64</td>
</tr>
<tr>
<td>400</td>
<td>1.47</td>
<td></td>
<td>1.69</td>
</tr>
<tr>
<td>450</td>
<td>1.52</td>
<td></td>
<td>1.73</td>
</tr>
<tr>
<td>500</td>
<td>1.56</td>
<td></td>
<td>1.77</td>
</tr>
</tbody>
</table>

Note: Case 1 is used for all Components and Cladding and the MWFRS in low-rise buildings. Case 2 is used for the MWFRS for building designed using the method for buildings all any height.

* Cases 1 and 2 are identical for heights greater than or equal to 25 feet.

The factor causing the biggest potential difference in wind loads between ASCE 7-02 and this thesis is in the wind speed used for design. The ASCE 7-02 speed is compared to the proposed design wind speeds for a few select locations in Table 4.3. Under no circumstances is the design wind speed chosen to be less than that specified in ASCE 7-02.
Table 4.3 – Comparison of Proposed Design Wind Speeds and Their Impacts on Wind Loads with ASCE 7-02 Values on the Gulf Coast (peak gust speeds at 33 ft over open terrain)

<table>
<thead>
<tr>
<th>Location of Interest</th>
<th>ASCE Wind Speed (mph)</th>
<th>Design Hurricane</th>
<th>Wind Speed</th>
<th>Percent Change in Wind Load from ASCE 7-02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest Wind Speed per ASCE 7-02 (South FL and South LA)</td>
<td>150</td>
<td>Category I</td>
<td>108</td>
<td>-48%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category II</td>
<td>130</td>
<td>-25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category III</td>
<td>156</td>
<td>+8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category IV</td>
<td>191</td>
<td>+62%</td>
</tr>
<tr>
<td>Lowest Wind Speed per by ASCE 7-02 (Central LA)</td>
<td>125</td>
<td>Category I</td>
<td>108</td>
<td>-25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category II</td>
<td>130</td>
<td>+8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category III</td>
<td>156</td>
<td>+56%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category IV</td>
<td>191</td>
<td>+133%</td>
</tr>
<tr>
<td>°90 mph Contour at LA-TX Line (115 miles inland)</td>
<td>90</td>
<td>Category I</td>
<td>108*0.76 = 82</td>
<td>-17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category II</td>
<td>130*0.76 = 99</td>
<td>+21%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category III</td>
<td>156*0.76 = 119</td>
<td>+75%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Category IV</td>
<td>191*0.73 = 139</td>
<td>+139%</td>
</tr>
</tbody>
</table>

+ Note: The reduction factors determined for the inland location were determined using Figure 3.7.

Since the proposed design event is the “strongest” hurricane in each category, that results in a step change in design speed at various locations along the coast. If ASCE 7-02 wind speeds are used as a minimum speed, that means that for any region with ASCE 7-02 design speeds between 109 and 130 mph, the minimum design hurricane should be a Category 2 with 130 mph winds. Similarly, coastal areas with wind speeds from 131 to 150 mph (maximum ASCE 7-02 speed anywhere), the minimum design event is a Category 3 hurricane with 156 mph winds. The recommended minimum design events corresponding to the ASCE wind speeds in Table 4.3 are shown in bold.

From the comparison shown in Table 4.3, it can be seen that for a building located on the coast where the design wind speed is 125 mph (as given in ASCE 7-02), the minimum wind speed required for design using this thesis is 130 mph (corresponding to a Category II
hurricane). This results in an increase in the factored load of \( \frac{130}{125} \times 1.093 = 1.18 \), or an increase of 18%. The squared term represents the effect of changes in design wind speed and the second term represents the increase due to the combined effect of changes in \( K_d \), \( I \), and the load factor. Similarly, for a building located anywhere along the coast with an ASCE 7-02 design wind speed of 131 mph, the minimum wind speed allowed for design is 156 mph. This results in an increase in the factored wind load of \( \frac{156}{131} \times 1.093 = 1.55 \), or an increase of 55%. The minimum increase would occur at a location on the coast where the design wind speed given in ASCE 7-02 is 130 mph, which actually covers much of the coast. In this case, the only difference in the wind load would be due to the changes in \( K_d \), \( I \), and the load factor, which results in an increase of 9.3%, as presented previously.

Another helpful way to compare the proposed design wind speeds and ASCE 7-02 speeds is shown in Figure 4.1. Here, the wind speeds for each design hurricane are compared to ASCE 7-02 wind speeds versus distance inland. ASCE 7-02 wind speeds shown are for a line normal to the coast, along the Louisiana-Texas border. It is important to realize that the ASCE 7-02 decay rate varies somewhat with location along the Gulf Coast, so the ASCE 7-02 wind speeds shown at various distances inland would not necessarily correspond with other locations along the coast.

The effects of the enclosure recommendations also need to be investigated. ASCE 7-02 uses an “Either/Or” provision for facilities located in wind borne debris regions – either provide debris impact protection or design for full internal pressurization. This thesis recommends an “And” provision – the facility is to have debris impact resistant envelope components and is to be designed for full internal pressurization. For a facility already having debris impact resistant envelope components, this change results in an increase in the ASCE 7-02 Internal Pressure Coefficient from +/- 0.18 to +/- 0.55. For a building without
debris impact resistant envelope components, the use of the Partially Enclosed designation makes no difference in the loads, since ASCE 7-02 requires that a building located in a hurricane prone region without debris impact resistant envelope components be designed as Partially Enclosed in the first place. It would, however, require “upgrading” the envelope components to be impact resistant.

The effect of changing from Enclosed to Partially Enclosed is seen in the calculation of the design pressure. For the Main Wind Force Resisting System (MWFRS), Equation 6.17 in ASCE 7-02 defines the design pressure as:

\[ p = qG_{C_p} - q_l(G_{C_p}) \]

For the Components and Cladding (C & C), Equation 6.22 in ASCE 7-02 defines the design pressure as:
\[ p = q_h[(G C_p) - (G C_{pi})] \]

where \( p \) = design pressure (psf); \( q \) = velocity pressure (psf); \( q_h \) = velocity pressure evaluated at a given height (psf); \( G \) = gust effect factor; \( C_p \) = external pressure coefficient; \( q_i \) = internal velocity pressure; \( (G C_{pi}) \) = internal pressure coefficient.

For purposes of comparison, it will be assumed that \( q_h = q_i = q \), which is commonly the case for low-rise buildings, and \( G \) is taken as 0.85. The relative effects of a change in the internal pressure coefficient \( (G C_{pi}) \) can be analyzed for various surfaces of the building by selecting the largest and smallest external pressure coefficients for typical cases and combining these with each internal pressure coefficient (+/-0.18 and +/-0.55) to give a range in variation. This analysis is shown in Tables 4.4 and 4.5. It is likely that a change in the Enclosure Classification and the resulting change in the Internal Pressure Coefficient would be experienced for most buildings designed using this thesis. This is because if the essential facility was designed using ASCE 7-02 the openings would most likely be protected, which would allow for the use of an Enclosed classification and a smaller internal pressure coefficient as compared to the Partially Enclosed classification requirement of thesis.

Table 4.4 - Variation in Design Pressures on the MWFRS with a Change in the Enclosure Classification

<table>
<thead>
<tr>
<th>Building Surface</th>
<th>( C_p )</th>
<th>Controlling ( G C_{pi} )</th>
<th>Pressure</th>
<th>Percent Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward Wall</td>
<td>+0.8</td>
<td>-0.18</td>
<td>-0.55</td>
<td>+0.86q</td>
</tr>
<tr>
<td>Leeward Wall</td>
<td>-0.2</td>
<td>+0.18</td>
<td>+0.55</td>
<td>-0.35q</td>
</tr>
<tr>
<td>Middle of Flat Roof</td>
<td>-0.3</td>
<td>+0.18</td>
<td>+0.55</td>
<td>-0.44q</td>
</tr>
</tbody>
</table>

* \( C_p \) value from ASCE 7-02 Figure 6.6

Note: Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.
Table 4.5 - Variation in Design Pressures on the C & C with a Change in the Enclosure Classification

<table>
<thead>
<tr>
<th>Building Surface</th>
<th>GC&lt;sub&gt;p&lt;/sub&gt; *</th>
<th>Controlling GC&lt;sub&gt;pi&lt;/sub&gt;</th>
<th>Pressure Enclosed</th>
<th>Partially Enclosed</th>
<th>Percent Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle of Windward Wall</td>
<td>+0.7</td>
<td>-0.18</td>
<td>-0.55</td>
<td>+0.88q</td>
<td>+1.25q</td>
</tr>
<tr>
<td>Middle of Leeward Wall</td>
<td>-0.8</td>
<td>+0.18</td>
<td>+0.55</td>
<td>-0.98q</td>
<td>-1.35q</td>
</tr>
<tr>
<td>Uplift, Middle of Flat Roof</td>
<td>-0.9</td>
<td>+0.18</td>
<td>+0.55</td>
<td>-1.08q</td>
<td>-1.45q</td>
</tr>
<tr>
<td>Uplift, Corner of Flat Roof</td>
<td>-1.1</td>
<td>+0.18</td>
<td>+0.55</td>
<td>-1.28q</td>
<td>-1.65q</td>
</tr>
</tbody>
</table>

*GC<sub>p</sub> values from ASCE 7-02 Figure 6.11 Assuming a Large Effective Wind Area (worst case)

Note: Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.

The effect of the increased design pressure has a tremendous impact on the design of the Components and Cladding elements. The increase does not significantly affect the design of the MWFRS, however, except for the uplift on the entire roof or gable frame structure.

The effect of the modified load combinations also needs to be investigated. The increase in the wind pressure due to the change in the wind load factor has already been addressed. The increased load factor on the rain load for the cases where wind and live load are the maximized loads, while a significant increase, is not anticipated to produce a substantial increase in overall design loads. This is because the rain load, as compared to the wind and live loads, is generally modest in magnitude. The recommendation that all of these facilities be considered as defacto shelters, and therefore be considered as places of public assembly, would result in an increase in the load factor for live load in Load Combination
numbers (3), (4), and (5). This change may result in a significant gravity load increase for some facilities.

The changes in the debris impact requirements were outlined in Chapter 3 and will not be discussed here.
CHAPTER 5: CONCLUSIONS

5.1 Summary and Conclusions

The unacceptable damage experienced by facilities designated as essential during hurricane events has led members of the design community, as well as the general public, to question the current method of design of these types of facilities. The goal of this thesis was to provide a tool for designers of facilities designated as essential during hurricane events to use to improve the safety and serviceability of these facilities. In order to achieve this goal, a more rational design philosophy was developed for the design of these facilities. The following objectives were achieved:

1) A new method for determining the design event was adopted. The basis of this method is to select a hurricane of a specific category (from the Saffir-Simpson Hurricane Scale) that the owner chooses the building be designed to withstand. The building should then be designed to resist all of the hazards associated with a hurricane of that intensity. The current design wind speed given in ASCE 7-02 is the wind speed associated with an acceptable probability of failure. A design wind speed based on Hurricane Category has several advantages: First, it allows the building owner to choose the design level of the facility based on shelter demand and available budget. Second, it makes emergency management operations easier and more reliable. For a given hurricane approaching the coast, emergency management personnel can review the design basis of each facility and compare it to the forecast hurricane intensity at landfall, providing crucial information to help make evacuation and sheltering decisions.

2) A performance-based design methodology for essential facilities was developed. Such an approach was used because it allows for different levels of damage depending on the use of the functionality requirements of the building, resulting in a much more efficient
design. The performance-based design approach also allows for the use of the latest available analysis and design methods, as well as building construction products. This objective consisted of the following tasks:

a) Five different types of essential facilities were identified, through contact with emergency management officials, based on required usage before, during, and after the hurricane event.

b) Appropriate performance levels for each of the five facility types when subjected to their design event were determined, through the use of a survey given to members of the emergency management community.

3) Methods for assessing design loads and load combinations consistent with objectives one and two were developed. Specific changes to current practice (ASCE 7-02) include:

a) The Directionality Factor ($K_d$) was modified. The value of 0.85 used for buildings in ASCE 7-02 was changed to 0.95, reflecting the higher value more appropriate for longer recurrence interval design events.

b) Guidance was given on selecting the site exposure used in analyzing wind loads. Buildings located nominally in Exposure B (urban, suburban, and wooded) must be evaluated - considering if the surrounding roughness elements are likely to remain standing during the design hurricane. If not, Exposure C should be used.

c) The enclosure classification was required to be Partially Enclosed, even if the building envelope includes debris impact resistant coverings, due to the extreme increase in loads caused by a breach in the building envelope. This results in an Internal Pressure Coefficient ($G_{C_{pl}}$) of plus and minus 0.55, even if the building envelope includes debris impact resistant coverings.
d) The Importance Factor (I) of 1.15 required by ASCE 7-02 for the design of essential facilities was changed to 1.0. This was done because the current Importance Factor adjusts the MRI of the design wind speed, a factor that is not needed using the guidelines presented in this thesis.

e) The determination of the design wind speed was changed.

i) At the coast, the maximum wind speed for each hurricane category was used, converted to peak gust over land at 10m height. Values for Category 1-4 hurricanes are 108 mph, 130 mph, 156 mph, and 191 mph, respectively.

ii) For inland locations, peak gust values at the coastline are reduced using decay models. These were developed as a function of distance inland.

f) Several revised load factors and load combinations were recommended in Section 3.5. These were based on the special considerations that must be addressed when dealing with a facility subject to the effects of a hurricane. Specific changes include:

i) Increasing the load factor on wind from 1.6 to 1.8 to achieve the same probability against failure due to winds in a hurricane event as to gravity loads.

ii) Increasing the load factor on rain in several combinations from 0.5 to 1.6 to account for the potential simultaneous action of the design rain load and the design live or wind load.

iii) Use of 1.0 factor on live load in place of 0.5, by interpreting any facility designated as essential during a hurricane event as a de facto shelter, and therefore a place of public assembly.

4) A set of guidelines was presented on the debris impact requirements of essential facilities.

The specific objectives addressed are:
a) It was suggested that debris impact resistant coverings or windows should be used on all openings in the building envelope. Also, the building envelope itself should be debris impact resistant.

b) A suggested missile speed to be used for design purposes was given. The missile test speed should be a function of the wind speed associated with the design hurricane event.

c) A comparison was made between the current impact standards and the recommendation made herein. Guidance was given on the use of current impact standards as it relates to the recommendations given in this thesis.

5) Guidance was given on other considerations to be addressed when designing essential facilities; such as the flooding hazards associated with a hurricane event and mass care issues.

6) A comparison was made between the design pressure resulting from the use of the recommendations given in this thesis to the current state of practice.

a) The change in the directionality factor, importance factor, and wind load factor combined to cause a 9.3% increase in the factored wind load.

b) The change in the design wind speed potentially causes the most variation from the ASCE 7-02 wind load. Depending upon the hurricane category chosen for design and distance inland, the resulting wind speed could possibly be smaller than that of ASCE 7-02 or much greater. It is recommended, however, that under no circumstances may the wind speed used for design be less than that recommended by ASCE 7-02.

c) A change in the site exposure causes a significant of change in the design wind load. A jump from Exposure B to C increases $K_z$, and subsequently the wind load, by as much as 40%, depending on the height of the building.
d) A change in the enclosure classification from Enclosed to Partially Enclosed, which results in a change in the Internal Pressure Coefficient from +/-0.18 to +/-0.55, increases the magnitude of the design pressure on the walls and roof very significantly.

5.2 Recommendations for Future Research

The following recommendations are made concerning future research:

- The methodology presented in this thesis concerning the reduction of hurricane wind speed inland should be expanded to hurricane-prone regions beyond the Gulf Coast.

- A more in-depth survey to determine appropriate performance levels should be performed. Some of the improvements that could be made to the survey are:
  - More participants should be included in the survey.
  - Participants from other areas of the hurricane coast should be included in the survey.
  - Research should be performed on the best way to present a survey.
  - More engineers and architects should be included in the survey.

- Specific recommendations concerning building design practices could be made. Specifically, design guidelines should be given on how to meet the required performance level.

- More research should be performed on the probability associated with a hurricane of a given intensity striking different locations along the hurricane coast. This knowledge could be used for making better decisions about the hurricane category to use for design.

- More research should be performed on the reduction of hurricane winds with distance inland. Specifically, how the reduction is effected by hurricane size, forward speed, wind speed, and orientation to the coast.

- More research should be performed on the forward speed of hurricanes. Specifically, the effect of the intensity and size of the hurricane, the body of water the hurricane is over, and the angle at which the hurricane strikes the coast should be more thoroughly investigated.

- More research should be performed on the directionality factor associated with hurricane events. The effect of the increased turbulence associated with hurricane
events and the increased MRI associated with extreme hurricanes on the directionality factor needs to be investigated.

- More research should be performed on the effect of extreme hurricane winds on suburban and wooded areas to determine if there might be a need to design essential faculties for Exposure C when the facility would nominally be located in Exposure B.

- The rate of rainfall associated with hurricane events needs to be more closely investigated.

- More research needs to be performed on the wind load factor for hurricane winds to determine if a higher wind load factor might be needed.

- A new method of testing and approving debris impact resistant coverings needs to be implemented. Specifically, there needs to be a relative performance level given. For example, there should be a score given differentiating components that barely meet the debris impact requirements as compared to components that perform much better when tested.

- The storm surge and rainfall flooding associated with hurricanes of various intensities needs to be more thoroughly researched in order to obtain more detailed and more accurate storm surge and rainfall flood elevations. Also, mitigation strategies against flooding hazards should be further investigated.

- Current publications have a wide variability in the mass care consideration of space requirements per person for hurricane shelters. More research is needed in this area.

- The effects of the long duration of extreme winds of a hurricane need to be investigated. Specifically, how the long duration of high winds affect the performance of a building, compared with the short duration of high winds in an extratropical event, needs to be investigated.

- The resulting design using this thesis needs to be compared more thoroughly with current practice for various areas of the hurricane coast.

- The results of this thesis should be calibrated against existing practice in order to determine what the minimum recommended wind speed and wind load should be.
REFERENCES


ARC. (2002). “Standards for Hurricane Evacuation Shelter Selection,” ARC 4496, American Red Cross, Washington, DC.


Florida Department of Education. (1999). “Public Shelter Design Criteria,” Appendix B of the State Requirements for Educational Facilities (SREF), Tallahassee, FL.


APPENDIX: PERFORMANCE-BASED DESIGN SURVEY

The following pages are the Performance-Based Design survey that was given in order to determine acceptable damage levels to various building systems/components for facilities with different use classifications.
Survey of Desired Performance Criteria for Buildings Designated as “Special Use” During a Hurricane Event

The LSU Hurricane Center is conducting a survey to determine the acceptable levels of damage to structures designated as Special Use during a hurricane event when subjected to their Design Event, and still be deemed to have performed its intended function successfully. The design event is the hurricane category that the building is designed to “resist.” Five types of special use facilities are described below:

- **Function Critical**
  Facilities that must remain operational before, during, and after the hurricane event. Examples include hospitals and emergency operations centers.

- **Base of Operations For Response**
  Buildings that house emergency response functions needed in the immediate wake of the hurricane, but do not necessarily need to remain fully operational at the height of the storm. A fire station would generally fit in this category.

- **Hurricane Shelter**
  Intended to provide a safe place to go during the hurricane and a place to stay for some length of time after the storm has passed.

- **Refuge of Last Resort**
  Intended for people who did/could not evacuate or travel to a shelter, but do not wish to remain in their homes. It may or may not be safer than their homes. There is no minimum implied level of safety as there is in a shelter.

- **Emergency Equipment/Supplies Storage Facility**
  A facility used to house equipment and supplies needed for emergency response and recovery beginning immediately after the storm event. Different from the other 4 building categories above, it is not intended to be occupied during the hurricane, but individuals will be going inside after the hurricane in order to retrieve the stored materials.

Thank you for your participation in this survey. The results will be used to develop improved engineering and architectural design criteria for hurricane shelters and other special use facilities.

For more information contact the LSU Hurricane Center at 225/578-4813 or info@hurricane.lsu.edu

Please return to Dr. Marc Levitan
LSU Hurricane Center
Suite 3513 CEBA Building
Louisiana State University
Baton Rouge, LA 70803
Or fax to 225/578-7646
Survey Participant Information

Profession:  _  Engineering  
_  Architecture  
_  Emergency Management  
_  Other: ________________________________________

Parish/City: ________________________________________________________

Experience with Sheltering:

- Shelter Management:  _  High  _  Low  _  None
- Shelter Selection:  _  High  _  Low  _  None
- Shelter Design:  _  High  _  Low  _  None

OPTIONAL
If you wish to receive additional information about shelter assessment, selection, and design, please provide the following.

Name: _________________________________________________________
Organization: ________________________________________________________
Address: ________________________________________________________
Address: ________________________________________________________
Phone: ________________________________________________________
E-mail: ________________________________________________________

Thank you for your help with this important project!
**Danger to Life Safety**

- **Severe** – Injuries to building occupants may be high in numbers 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.

- **High** – Injuries to building 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 single life loss, with a low probability of multiple life loss.

- **Moderate** – Injuries to building occupants may be locally significant, but generally moderate in numbers and in nature. There is a low likelihood of single life loss, very low likelihood of multiple life loss.

- **Mild** – Injuries to building occupants are minimal in numbers and minor in nature. There is a very low likelihood of single- or multiple life loss.

<table>
<thead>
<tr>
<th>Allowed Danger</th>
<th>Function Critical</th>
<th>Base of Ops</th>
<th>Shelter</th>
<th>Refuge</th>
<th>E.M. Storage*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Sure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The danger to life safety in this case is from individuals entering the building after the storm in order to retrieve the needed equipment.

Additional Notes: _________________________________________________________________
________________________________________________________________________________
________________________________________________________________________________
Primary Structural System Damage

Primary Structural System elements include girders, load bearing walls, wind bracing, and columns. Not included in the Primary Structural System are secondary structural elements, such as roof joists, girts, etc. These are considered part of the roof and wall systems.

- **Severe** – Building is near collapse. Little residual strength or stiffness left in the structure. Rehabilitation to achieve pre-storm load-carrying capability likely to be impossible or impractical for economic or other reasons. The building is likely a complete loss.

- **Moderate** – Some residual strength and stiffness left in the structure. Rehabilitation to achieve pre-storm load-carrying capability likely to be very costly.

- **Light** – Structure retains most of its pre-storm strength and stiffness. Little rehabilitation needed to achieve pre-storm load-carrying capacity.

- **None to Very Light** – Little to no damage to the structural components. Structure possesses pre-storm load-carrying capacity with very little or no rehabilitation.

<table>
<thead>
<tr>
<th>Allowed Damage</th>
<th>Function Critical</th>
<th>Base of Ops</th>
<th>Shelter</th>
<th>Refuge</th>
<th>E.M. Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe</td>
<td></td>
<td></td>
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<tr>
<td>Moderate</td>
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<tr>
<td>Light</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>None to Very Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Sure</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Additional Notes: _________________________________________________________________
________________________________________________________________________________
________________________________________________________________________________

163
Building Envelope Damage

The building envelope consists of the roof cladding, glazed openings, doors, wall cladding, roof joists, girts, etc. It should be noted that the performance of the building envelope has a direct impact on the damage to the interior of the building.

Windows/Doors Damage

- **Severe** - Most of the windows and doors are completely destroyed. Many door openings blocked or impassable. Replacement of many opening components required. Building interior experiences significant damage in areas adjacent to failed exterior.

- **Moderate** - Significant damage to some opening components. Many doors and windows are breached. Some opening components are able to be repaired, while many must be replaced. Most door openings free of obstructions. Some damage to the building interior due to wind and water entering through the failed opening.

- **Light** - Opening components experience little damage. Openings able to be returned to their pre-hurricane functionality with minor repair or replacement. Very little damage to the building interior.

- **None to Very Light** - Little or no damage to any of the opening components. The damage which does occur has no effect on use of building and repair of the opening components does not interfere with the use of the building. Damage to the opening components is mainly cosmetic in nature. No damage to the building interior.

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Additional Notes: ____________________________________________________________

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Building Envelope Damage (cont.)

Roof and Wall Systems Damage

- **Severe** - Most cladding/roofing components either removed or completely destroyed. Repair likely to be impractical for economic or other reasons. Replacement probably needed. Large holes likely in the roof and/or walls. Major wind and water penetration of structure, causing a great deal of damage to the interior and contents.

- **Moderate** - Small cladding/roofing elements removed or destroyed. Many of the larger elements retain most of their functionality, but may be damaged beyond repair. Large holes possible and small holes likely in the roof and/or walls. Some damage to the building interior due to wind and water entering the structure.

- **Light** - Roofing/cladding components remain functional, but some components must be replaced in order for building envelope to function the same as it did before the storm. Small holes possible in the roof and/or walls, allowing water to leak into the building. Very little damage to the building interior.

- **None to Very Light** - Almost no damage to the roofing/cladding components. Functionality of the roofing/cladding components remains the same after the event as it was before the event with little or no repair or replacement. No damage to the building interior.

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Mechanical and Plumbing Systems Damage

Electrical/Lighting Systems Damage

_ Severe _ - Many to most of the components are out of order and some damaged beyond repair and require replacement.

_ Moderate _ - A small percentage of the components are in working order. Primary lighting likely to be non-operational. Emergency lighting is in working order during and after the event. Replacement or repair of some components required.

_ Very Light _ – No significant damage. Components not necessarily operational during the event, but are ready to be reactivated immediately after the storm. Emergency lighting in working order during and after the event.

_ None _ - All components remain fully operational during and after the event.

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**Mechanical and Plumbing Systems Damage (cont.)**

**Heating, Ventilation, and Air Conditioning (HVAC) Equipment Damage**

- **Severe** - Many to most of the components are out of order and some damaged beyond repair and require replacement. Some components may be lost due to wind.

- **Moderate** - A small percentage of the HVAC system is in working order. Replacement or repair of some components required.

- **Very Light** – No significant damage. Components not necessarily operational during the event, but are ready to be reactivated immediately after the storm.

- **None** - All components remain fully operational during and after the event.

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Mechanical and Plumbing Systems Damage (cont.)

Plumbing Systems Damage

- **Severe** - Many to most of the components are out of order and some damaged beyond repair and require replacement.

- **Moderate** - A small percentage of the plumbing system is in working order. Replacement or repair of some components required.

- **Very Light** – No significant damage. Components not necessarily operational during the event, but are ready to be reactivated immediately after the storm.

- **None** - All components remain fully operational during and after the event.

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VITA

Joffrey Elliott Easley, the son of John and Judy Easley, was born on January 22, 1977, in Baton Rouge, Louisiana. He grew up in Easleyville, Louisiana, and graduated from Oak Forest Academy in Amite, Louisiana. After High School, he attended Louisiana State University, where he was awarded the Louisiana State University Honor’s Scholarship. He earned his bachelor of science degree in Civil and Environmental Engineering from Louisiana State University in May, 2000, and was wed to Moira Leigh Taylor later in the same month. He was awarded the Board of Regents fellowship and began his graduate program in August, 2000. He will receive the degree of Master of Science in Civil Engineering from the Department of Civil and Environmental Engineering in May, 2003.