CHAPTER 2
BACKGROUND REVIEW

2.1. Tornadoes

Tornadoes are among the most destructive forces of nature. On average, more than 1,200 tornadoes have been reported nationwide each year since 1995. Since 1950, tornadoes have caused an average of 89 deaths and 1,521 injuries annually, as well as devastating personal and property losses (FEMA 2000).

A tornado is defined as a violently rotating column of air extending from a thunderstorm to the ground. The most violent tornadoes are capable of tremendous destruction with wind speeds of 250 mph near ground level. Damage paths over 50 miles long and over 1 mile wide have been reported.

Tornadoes are commonly categorized according to the Fujita Scale (FEMA 1998), which was created by the late Dr. Tetsuya Theodore Fujita, University of Chicago. Figure 2.1 shows the detail of the Fujita Scale. It categorizes tornado severity by damage observed instead of recorded wind speeds. Ranges of wind speeds have been associated with the damage descriptions of the Fujita Scale, but their accuracy has been called into question by both the wind engineering and meteorological communities, especially the ranges for the higher end (F4 and F5) of the scale. The wind speeds are estimates that are intended to represent the observed damage. They are not calibrated wind speeds, nor do they account for variability in the design and construction of buildings.
F0: Light Damage (< 73 mph)
Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign-boards damaged (Columbus GA, on 13 March 1997)

F1: Moderate Damage (73-112 mph)
Peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos blown off roads (The Spencer SD tornado, 30 May 1998).

F2: Considerable Damage (113-157 mph)
Roofs torn off frame houses; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground (Paris, MS, 3 January 2000)

F3: Severe Damage (158-206 mph)
Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown (Moore, OK, 3 May 1999).

F4: Devastating Damage (207-260 mph)
Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated (Moore, OK, 3 May 1999).

F5: Incredible Damage (261-318 mph)
Strong frame houses levelled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 meters (109 yds); trees debarked; incredible phenomena will occur (the Bridge Creek/Moore, Oklahoma, tornado of 3 May 1999).

Figure 2.1: Fujita Tornado Damage Scale (National Weather Service 2003)
2.2. Hurricanes

Hurricanes are also one of the most destructive forces of nature. Views of hurricanes from satellites thousands of miles above the earth show the power of these very large, but tightly coiled weather systems. A hurricane is a type of tropical cyclone, the general term for all circulating weather systems (counter clockwise in the Northern Hemisphere) originating over tropical waters. Tropical cyclones are classified as follows (FEMA 2000):

- **Tropical Depression** – An organized system of clouds and thunderstorms with a defined circulation and maximum sustained winds of 38 mph or less.

- **Tropical Storm** – An organized system of strong thunderstorms with a defined circulation and maximum sustained winds of 39 to 73 mph.

- **Hurricane** – An intense tropical weather system with a well-defined circulation and sustained winds of 74 mph or higher. In the western Pacific, hurricanes are called “typhoons,” and similar storms in the Indian Ocean are called “cyclones.”

Hurricanes that affect the U.S. mainland are products of the tropical oceans (Atlantic Ocean, Caribbean Sea, or Gulf of Mexico) and the atmosphere. Powered by heat from the sea, they are steered by the easterly trade winds and the temperate westerlies as well as by their own ferocious energy. Around their core, winds grow with great velocity, generating violent seas. As the storm moves ashore, it can push ocean waters inland while spawning tornadoes and producing torrential rains and floods.

Hurricanes are categorized according to the Saffir-Simpson Hurricane Scale, which was designed in the early 1970s by Herbert Saffir, a consulting engineer in Coral Gables, Florida, and Robert Simpson, who was then director of the National Hurricane Center (FEMA 2000). The
Saffir-Simpson Hurricane Scale is shown in Fig. 2.2. The scale is used by the National Weather Service to estimate the potential property damage and flooding expected along the coast from a hurricane landfall. The scale is a 1–5 rating based on the hurricane’s current intensity. Wind speed and barometric pressure are the determining factors in the scale. Storm surge is not a determining factor, because storm surge values are highly dependent on the slope of the continental shelf in the landfall region.

On average, 10 tropical storms, 6 of which become hurricanes, develop each year in the Atlantic Ocean. Approximately five hurricanes strike the United States mainland every 3 years; two of those storms are major hurricanes (Category 3 or greater on the Saffir-Simpson Hurricane Scale). The loss of life and property from hurricane-generated winds and floodwaters can be staggering. Tornadoes of weak to moderate intensity occasionally accompany tropical storms and hurricanes that move over land. These tornadoes are usually to the right and ahead of the path of the storm center as it comes onshore.

2.3. Forces – Tornadoes and Hurricanes

Tornadoes and hurricanes are extremely complex wind events that cause damage ranging from minimal or minor to extensive devastation. Tornadoes and hurricanes damage to buildings can occur as a result of three types of forces:

1. Wind-induced forces
2. Forces induced by changes in atmospheric pressure
3. Forces induced by debris impact
C1: Minimal Damage (74-95 mph)
Damage is done primarily to shrubbery and trees, unanchored manufactured homes are damaged, some signs are damaged, and no real damage is done to structures on permanent foundations.

C2: Moderate Damage (96-110 mph)
Some trees are toppled, some roof coverings are damaged, and major damage is done to manufactured homes.

C3: Extensive Damage (111-130 mph)
Large trees are toppled, some structural damage is done to roofs, manufactured homes are destroyed, and structural damage is done to small homes and utility buildings.

C4 Enhanced-B Damage (131-155 mph)
Extensive damage is done to roofs, windows, and doors; roof systems on small buildings completely fail; some curtain walls fail.

C5 Catastrophic Damage (156 mph and up)
Roof damage is considerable and widespread, window and door damage is severe, there are extensive glass failures, and some buildings fail completely.

Figure 2.2: Saffir-Simpson Hurricane Scale (FEMA 2000, National Weather Service 2003)
Tornadic and hurricane winds tend to lift and accelerate debris (missiles) consisting of roof gravel, sheet metal, tree branches, broken building components, and other items. The debris can impact building surfaces and perforate them. Large debris, such as automobiles, tends to tumble along the ground. The impact of this debris can cause significant damage to wall and roof components. However, each debris impact affects the structure for an extremely short duration, probably less than 1 sec. For this reason, the highest wind load and the highest impact load are not likely to occur at precisely the same time.

2.4. Effect of Extreme Wind Forces

Wind-induced damage to residential and commercial buildings indicates that extreme winds moving around buildings generate loads on building surfaces that can lead to the total failure of a building (FEMA 2000). In addition, internal pressurization due to a sudden breach of the building envelope (the failure of the building exterior) is also a major contributor to poor building performance under severe wind loading conditions. The effects of wind on buildings can be summarized as follows (FEMA 2000):

- **Inward-acting, or positive** pressures act on windward walls and windward surfaces of steep-sloped roofs.
- **Outward-acting, or negative** pressures act on leeward walls, sidewalls, leeward surfaces of steep-sloped roofs, and all roof surfaces for low-sloped roofs or steep-sloped roofs when winds are parallel to the ridge.
- **Airflow** separates from building surfaces at sharp edges and at points where the building geometry changes.
• Localized suction or negative pressures at eaves, ridges, edges, and the corners of roofs and walls are caused by turbulence and flow separation. These pressures affect loads on Components and Cladding (C & C).

• Windows, doors, and other openings are subjected to wind pressures and the impact of windborne debris (missiles).

High winds are capable of imposing large lateral (horizontal) and uplift (vertical) forces on buildings. The strength of the building’s structural frame, connections, and envelope determine the ability of the building to withstand the effects of these forces.

2.5. Building Failure Modes – Elements, Connections, and Materials

Building failures can be independently categorized by one or a combination of the four failure modes illustrated in Fig. 2.3 (FEMA 2000):

• A sliding failure occurs when wind forces move a building laterally off its foundation.

• An overturning failure occurs when a combination of the lateral and vertical wind forces cause the entire building to rotate about one of its sides.

• A racking failure occurs when the building’s structural system fails laterally, but the building typically remains connected to the foundation system.

• A component failure, the most common failure seen during high-wind events (and typically a contributing failure to the first three failure modes listed), may be caused by
Overturning
Translation or Sliding (Lateral Movement)

Overturning

Racking (Lateral Collapse)

Material Failure

Figure 2.3: Forces on a Building due to Wind Moving Around the Structure (FEMA 2000)

Figure 2.4: Internal Pressures Caused Windward Wall Openings
wind pressures or windborne debris (missile) impacts. Component failures may be either full-system failures or individual element failures.

2.6. Effects of Windborne Debris

Windborne debris has been established as a principal cause for the breaching of the building envelope during windstorms, and fluctuating cyclic pressures have been shown to produce fatigue failures in components and cladding. Wind loads and the impact of windborne debris are both capable of damaging a building envelope. Post-disaster investigations of wind-damaged buildings have shown that many building failures begin because a component or a segment of cladding is blown off the building, allowing wind and rain to rapidly enter the building. An opening on the windward face of the building can also lead to a failure by allowing positive pressures to occur that, in conjunction with negative external pressures, can “blow the building apart.” Figure 2.4 depicts the forces that act on a structure when an opening exists in the windward wall.

Wind-borne projectiles are a major factor in building damage and destruction during a hurricane. Penetration of the building envelope by wind-borne debris was directly responsible for many catastrophic failures of roof systems during Andrew because such penetration allowed the uncontrolled build-up of internal air pressure (Minor and Behr 1994, Mitrani et al. 1995). An opening on the windward wall of a building of only 5% is enough to allow full internal pressurization and effectively doubles the pressures acting to lift the roof and push the side walls outward (Minor and Behr, 1994).
A notable example of damage from wind-borne debris prior to Andrew resulted from Tropical Cyclone Tracy in 1974. Debris damage was so severe that 90% of the homes in Darwin, Australia, a city of 40,000, were made uninhabitable (Minor and Behr, 1994). Mitrani et al. (1995) reported that window breakage and door failure on the windward side of buildings caused most of the roof failures, which were the most important damage due to Tracy.

Hurricane Allen crossed the Texas coast about 124 miles south of Corpus Christi on August 10, 1980 (Minor et al. 1981). This hurricane caused substantial glass failure to the 18-story Guaranty Bank Building (Fig. 2.5). It was discovered upon investigation that almost all the glass failures occurred on the windward elevations and that the failures were caused by both missile impact and wind pressure. Similar damages were observed during Hurricane Frederic in the Mobile bay area in 1979 and Hurricane Alicia in downtown Houston in 1983 (Minor 1994).

The importance of windborne debris protection to building performance in hurricanes became quite evident to experts involved in the building industry following the devastating effects of Hurricane Andrew in 1992. Andrew was a Category 5 hurricane (NHC 2002) with a minimum central pressure at landfall (Miami-Dade County) of 922 mb and peak winds of 165 mph. Afterwards, about 20 buildings in Miami, Miami Beach, Kendall, Cutler Ridge and Homestead were examined by Minor and Behr (1993). With few exceptions, glazing systems performed poorly, largely due to the impact of windborne debris, and damage to building contents was extensive (Figs. 2.6 and 2.7). After examining damage caused by Andrew, the Florida Department of Community Affairs concluded: “The loss of doors (primarily garage and sliding glass doors) and windows was the second most important and costly aspect of the storm. Wind-borne debris (particularly from roofing materials) contributed to a significant portion of
Figure 2.5: Glass Failure of the Guaranty Bank Building during Hurricane Allen, Corpus Christi, Texas

Figure 2.6: Effect of Windborne Debris on Glazing Systems, Hurricane Andrew
Figure 2.7: Palm Tree Pierced by Plywood Missile, Hurricane Andrew

Table 2.1: Windborne Debris and Debris Classification for Tornadoes and Hurricanes (FEMA 2000)

<table>
<thead>
<tr>
<th>Missile Size</th>
<th>Typical Debris</th>
<th>Associated Damage Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small (Light Weight)</td>
<td>Aggregate roof surfacing, pieces of trees, pieces of wood framing members, bricks</td>
<td>Broken doors, windows, and other glazing; some light roof covering damage</td>
</tr>
<tr>
<td>Medium (Medium Weight)</td>
<td>Appliances, HVAC units, long wood framing members, steel decking, trash containers, furniture</td>
<td>Considerable damage to walls, roof coverings, and roof structures</td>
</tr>
<tr>
<td>Large (Heavy Weight)</td>
<td>Structural columns, beams, joists, roof trusses, large tanks, automobiles, trees</td>
<td>Damage to wall and roof framing members and structural systems</td>
</tr>
</tbody>
</table>
this damage. The loss of windows and doors, along with the loss of roof coverings, caused the large amount of damage to building interiors and contents. (Mehta et al. 1994).

Experience with hurricanes in the U.S. and with tropical cyclones around the world have established the importance of windborne debris to the performance of buildings in windstorms. Compromising of the building envelope by windborne debris during a hurricane leads to major economic loss through damage to building content and to the possible failure of structural systems. Hence, it is important that the building design process address these important hurricane effects, which impact building performance.

2.6.1. The Nature of Windborne Debris: Most extensive windstorms, which affect built-up areas, are accompanied by turbulent winds that generate windborne debris. To preserve the integrity of the building envelope, cladding systems must be able to sustain impacts from the debris and cover openings, following impact, for the duration of the storm.

Reed (1970) observed that windborne debris was a significant factor in the relatively large window glass breakage rates on high-rise buildings during the Lubbock Storm of May 11, 1970. Minor et al (1972) observed that the windows are traditionally designed for wind pressures, but the breakage from impacts by windborne debris is the most common failure mechanism.

In extensive wind damage surveys conducted throughout the 1970s, a common pattern was observed in all enhanced-B wind events (Minor and Mehta 1979). Small debris, principally roof gravel, can be carried into all elevations of building facades at velocities sufficiently large to break glass. Large debris, including framing timbers and roofing materials, can impact the building envelope near ground level with sufficient force to penetrate wall coverings and break windows.
The quantity, size, and force of windborne debris (missiles) generated by tornadoes and large hurricanes are unequalled by those of other windstorm debris. Missiles are a danger to buildings because the debris can damage the structural elements themselves or breach the building envelope. If the missile breaches the building envelope, wind may enter the building, resulting in an over-pressurization of the building that often leads to structural failures. In addition, windborne debris may kill or injure people who cannot find shelter or refuge during a tornado or hurricane. Most experts group missiles and debris into three classifications (FEMA 2000). Table 2.1 lists the classifications, presents examples of debris, and describes expected damage.

2.6.2. Potential of Debris: Debris impacting buildings during a severe windstorm can originate from both the surrounding area and from the building. The pool of potential projectiles that can be picked up by hurricane-force winds and turned into wind-borne debris includes roofing materials such as shingles, tiles, and gravel; inadequately attached cladding components such as sheathing and siding; and rocks and tree limbs (HUD, 1993). Smith (1995) reported that wind-borne debris from Andrew included tree limbs, fences, dislodged rooftop antennas and HVAC equipment, and components from failed buildings. FEMA (1992) observed that the failure of metal-clad buildings and mobile homes generated considerable wind-borne debris during Hurricane Andrew. Other sources of debris include roof sheathing materials, wall coverings, roof-mounted mechanical equipment, parapets, garbage cans, lawn furniture, missiles originating from trees and vegetation in the area, and small accessory buildings. Missiles originating from loose pavement and road gravel have also been observed in intense windstorms. In one area impacted by Hurricane Andrew, mailboxes were filled with rocks and asphalt from surrounding roadways (FEMA 2000).
As buildings break apart in severe windstorms, the failures progress from the exterior building elements inward to the structural members (e.g., trusses, masonry units, beams, and columns). The literature on tornadoes and hurricanes contains numerous examples of large structural members that have been transported by winds for significant distances (FEMA 2000). Generally, large debris such as structural members are transported significant distances by the wind-field when a portion of exterior sheathing remains connected and provides an aerodynamic sail area on which the wind can act.

Rooftop mechanical equipment that is kept in place only by gravity connections is a source of heavy deformable debris when displaced during high-wind events. Furthermore, additional vulnerabilities to missile and wind are created when rooftop equipment is displaced from the roof, leaving large openings in the roof surface. Cars and trucks are also moved by strong winds.

2.6.3. Induced Loads from the Missile and Other Debris: Determination of static design loads from a propelled missile is complex. This computation depends on a number of factors, such as (FEMA 2000):

- Material that makes up the missile or falling debris
- Material of the wall, door, window, or roof section being impacted
- Stiffness of the individual elements being impacted
- Stiffness of the structural system supporting them
- Angle of impact between the missile and the structure

Because of the complex nature of missile and debris impacts, there are no design criteria that can be used to calculate the static force of a missile impact on any part of a building. To
determine adequate missile impact resistance for a building, the designer has to use the performance criteria of the wall, door, window or roof section in the Missile Impact Test.

2.7. Large Missile Loads and Successful Test Criteria

Minor *et al* (1978) investigated tornadoes and concluded that the most prevalent type of windborne debris in residential areas was timber from wood frame houses. Individual timbers were observed to have penetrated walls and roofs. Additional timbers were attached together as parts of failed roofing systems, timber trusses and timber walls. These observations led to the selection of a 2x4 in. timber weighing 15 lb as a representative object for use in defining impact criteria for tornado shelters (DCPA 1975).

In 1974, Tropical Cyclone Tracy devastated the City of Darwin in Australia’s Northern Territory. A 9 lb 2x4 in. timber (9 ft long) first appeared as a design missile in a building code in the Darwin Area Building Manual (1976).

A 2x4 in. timber, 12 ft in length, and half of the design wind speed was recommended as the large missile object for use in the design of lower elevation cladding on urban buildings by Minor *et al* (1978). This recommendation was based upon extensive field documentation conducted by the Institute for Disaster Research at Texas Tech University (Minor and Mehta 1979).

It was observed in Hurricane Andrew that roof tile was the most prevalent type of windborne debris. The Dade county Building Code Committee initially selected the roof tile as the design missile for the missile impact test standard in the South Florida Building Code (Minor 1994). However, it was observed that it would be difficult to define a representative roofing tile
for use in a test standard because there are many types of roofing tile to choose from. Further, it would be difficult to propel a piece of roofing tile, repeatedly, in the same orientation and at the same speed as part of a standard test. The Committee ultimately recommended a 9 lb 2x4 in. timber traveling at 50 ft/s as representative large object for use in design and product qualification testing.

2.8. Windborne Debris Impact Test Standards

In 1978, the Australian advanced TR 440, “Guidelines for the testing and evaluation of products for cyclone-prone areas” (EBS 1978) prescribed a debris impact criterion consisting of 9 lb 2x4 in. member impacting end-on at a speed of 50 ft/s. This standard also prescribed “fatigue loading” for cladding and its connections. In 1989, the 2x4 in. timber and a “fatigue loading sequence” for roof cladding were adopted in the Australian National Standard for Wind Loads (SAA Loading Code 1989).

A requirement that windows in hurricane prone regions be designed for windborne debris was proposed as a change to the SBC in the United States in 1983 (SBCCI 1983). This proposal was patterned after the 1978 Australian precedent and required windows or external protective devices to resist a 9 lb 2x4 in. lumber traveling at 50 ft/s. This proposed code change was not adopted.

Following Hurricane Andrew in 1982, windborne debris was cited as one of the principal cause of damage in several major investigations of building performance (Reed 1970, Minor et al. 1972). In 1993, the Building Code Committee in Dade County, Florida, recommended code changes and attendant test standard that address windborne debris to the Metropolitan Dade County Commission. The Building Code Committee in Broward County, Florida, made similar
recommendations to the board of Rules and Appeals for Broward County, also in 1993. These changes were incorporated into the Dade County and Broward County editions of the South Florida Building Code (SFBC), effective in 1994 (SFBC 1993, 1994).

2.8.1. Federal Emergency Management Agency (FEMA): According to FEMA-361 (2000), the standard missile used to determine impact resistance for all wind conditions is defined as follows:

- 15 lb wood 2x4 in. (nominal) member
- Typically 12 ft. long

The size of the missile is based on a representative debris for a 250 mph windstorm. Figures 2.8 and 2.9 show examples of damage caused by this missile. The missile is assumed to be propelled into wall and roof sections at the following missile speeds and to impact the test specimen at 90° to the surface:

- 100 mph missile speed for horizontally traveling missiles
- 67 mph missile speed for vertically traveling missiles

Three test specimens are required to be tested and all of them must pass the large missile impact test.

2.8.2. Standard Building Code (SBC): The large missile impact test requirements according to SBC SSTD-12 (1999) are as follows:

- Three specimens are required to be tested.
- Each specimen is to be impacted two times: one at the center (within an area of 5 in. radius) of and the other within 6 in. of a corner (within an area of 5 in. radius).
- The missile is a 2x4 in. lumber or weighted pendulum. Table 2.2 presents the size and the speed of the missile.
Figure 2.8: Unreinforced Masonry Wall Pierced by 100 mph 2x4 in. Lumber, WERC, Texas Tech University
Figure 2.9: Refrigerator Pierced by Windborne Missile

Table 2.2: Applicable Missiles in SBC SSTD-12 (1999)

<table>
<thead>
<tr>
<th>Wind speed (mph)</th>
<th>2x4 in. Missile</th>
<th>Pendulum Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-100</td>
<td>3 ft 9 in. long 4 lb 40 ft/s</td>
<td>35.3 lb @ 2 ft 9 in. drop</td>
</tr>
<tr>
<td>100-110</td>
<td>7 ft 6 in. long 8 lb 40 ft/s</td>
<td>35.3 lb @ 5 ft 6 in. drop</td>
</tr>
<tr>
<td>&gt; 110</td>
<td>9 ft long 9 lb 50 ft/s</td>
<td>35.3 lb @ 9 ft 11 in. drop</td>
</tr>
</tbody>
</table>
• A porous specimen passes the test if it can resist missile impacts without penetration. A non-porous specimen is acceptable if it resists the large missile impact with no opening forming through which a 3 in. diameter sphere can pass.

• All three specimens must pass the test.

2.8.3. Florida Building Code (FBC): According to the FBC, the large missile impact test requirements are as follows:

• Entire assembled units are to be subjected to a 2x4 in. lumber weighing 9 lb impacting at a speed of 50 ft/sec (equivalent to 34 mph), representing hurricane conditions in Florida.

• Three specimens are required to be tested.

• Each of three identical specimens is to receive two impacts, one near the center and one near a corner. Figure 2.10 shows the impact area of test specimens.

• The system is acceptable if all three specimens reject the missile impacts without penetration.

2.8.4. Department of Energy (DOE) Standard: Department of Energy (DOE 2002) provides the criteria for selecting performance categories (PC) of structures, systems, and components (SSC) for the purpose of Natural Phenomena Hazard (NPH) design and evaluation.

Performance Category 1: The wind force resisting system of structures should not collapse under design load. Survival without collapse implies that occupants should be able to find an area of relative safety inside the structure during an extreme wind event. Breach of structure envelope is acceptable, since confinement is not essential. Flow of wind through the structure and water damage is acceptable. Severe loss, including total loss, is acceptable, as long as the structure does not collapse and occupants can find safe areas within the building.
Performance Category 2: The structure shall not collapse at design wind speeds. Complete integrity of the structure envelope is not required because no significant quantities of toxic or radioactive materials are present. However, breach of the SSC containment is not acceptable if the presence of wind or water interferes with the SSC function.

Performance Category 3: An SSC shall be placed in preliminary Performance Category 3 (PC-3) if it is not covered in Performance Category 4 (PC-4), and if its failure results in adverse release consequences greater than safety class SSC Evaluation Guidelines limits (DOE 1994), but much less than those associated with PC-4 SSC.

Performance Category 4: An SSC shall be placed in preliminary Performance Category 4 (PC-4) if it is a "safety-class" item as defined in STD-3009 (DOE 1994), and if its failure during an NPH event could result in off-site release consequences greater than or equal to the unmitigated release from a severe accident. Not many such facilities are expected in the DOE complex. Not all safety-class SSC are necessarily PC-4.

The minimum wind design criteria for each PC are summarized in Table 2.3. It is observed from this table that Categories 3 - 4 includes the missile impact criteria as a 2x4 in. 15 lb plank at 50 mph. It is obvious that enhanced DOE missile weight and speed are both larger than the basic FBC and SBC criteria.

2.8.5. American Society for Testing and Materials (ASTM): ASTM standard E-1996 (2004) contains large missile impact test guidelines for windows, walls, doors and storm shutters. Test requirements are as follows:

- Three specimens are to be tested.
- The missile is a 2x4 in. lumber. The size and speed of the missile are determined based on Tables 2.4 in. and 2.5.
Circles designating the impacts have a radius of 5 in. The center of the corner impact circle is located 6 in. from the supporting member.

Figure 2.10: Impact Locations for Large Missile Test According to FBC (2001)

Table 2.3: Summary of Minimum DOE Wind Design Criteria (DOE 2002)

<table>
<thead>
<tr>
<th>Performance Category</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard Annual Probability of Exceedance</td>
<td>$2 \times 10^{-2}$</td>
<td>$1 \times 10^{-2}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Importance Factor</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Missile Criteria</td>
<td>NA</td>
<td>NA</td>
<td>2x4 in. timber plank 15 lb @ 50 mph (horiz.); maximum height 30 ft.</td>
<td>2x4 in. timber plank 15 lb @ 50 mph (horiz.); maximum height 50 ft.</td>
</tr>
</tbody>
</table>
Each specimen is to be impacted once in area as shown in Fig. 2.11.

Acceptance criteria are similar to SBC (1999) criteria.

All three specimens must pass the test.

Tables 2.4 and 2.5 show that the basic ASTM large missile criteria for maximum Florida design wind speeds is similar to that in FBC or SBC. However, the large missile weight for essential facilities is less than that from the DOE enhanced criteria, while the impact speed is slightly larger.

2.8.6. Division of Emergency Management Standard: Table 2.6 provides information regarding EOC survivability Performance Categories for wind hazard. A draft EOC Survivability Performance Category table from DCA lists a hurricane shelter suitability ranking (from 0 – 4 scale), which states that wind and debris resistance can be provided through FBC criteria for Performance Category 0 – 2. The draft mentions that Performance Categories 3 and 4 withstand a missile impact resistance of a 2x4 in. 15 lb stud travelling at 50 mph, similar to the DOE enhanced missile criteria.

2.9. Tests Performed on Wall/Roof Assemblies

Since the early 1970’s, TTU has been involved in research on the effect of debris impact on structures. Numerous large missile impact tests were performed at TTU (TTU 2002). Some of
Circles designating the impacts have a radius of 2.5 in. The centers of the corner impact circles are located 6 in. from supporting members.

Figure 2.11: Impact Locations for Large Missile Test According to ASTM E-1996 (2004)

Table 2.4: Applicable Missiles in ASTM E-1996 (2004)

<table>
<thead>
<tr>
<th>Missile Level</th>
<th>2x4 in. Missile</th>
<th>Impact Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>2 lb @ 1 ft 9 in.</td>
<td>50 ft/s</td>
</tr>
<tr>
<td>C</td>
<td>4.5 lb @ 4 ft</td>
<td>40 ft/s</td>
</tr>
<tr>
<td>D</td>
<td>9 lb @ 8 ft</td>
<td>50 ft/s</td>
</tr>
<tr>
<td>E</td>
<td>9 lb @ 8 ft</td>
<td>80 ft/s</td>
</tr>
</tbody>
</table>
Table 2.5: Description Levels in ASTM E-1996 (2004)

<table>
<thead>
<tr>
<th>Level of Protection</th>
<th>Enhanced Protection (Essential Facilities)</th>
<th>Basic Protection</th>
<th>Unprotected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly Height</td>
<td>≤ 30 ft</td>
<td>≤ 30 ft</td>
<td>≤ 30 ft</td>
</tr>
<tr>
<td></td>
<td>&gt; 30 ft</td>
<td>&gt; 30 ft</td>
<td>&gt; 30 ft</td>
</tr>
<tr>
<td>Wind Zone 1</td>
<td>D</td>
<td>C</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Wind Zone 2</td>
<td>D</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Wind Zone 3</td>
<td>E</td>
<td>D</td>
</tr>
</tbody>
</table>

Wind Zone 1: 110 mph ≤ basic wind speed < 120 mph
Wind Zone 2: 120 mph ≤ basic wind speed < 130 mph at greater than one mile from the coastline
Wind Zone 3: basic wind speed ≥ 130 mph or basic wind speed ≥ 120 mph at greater than one mile from the coastline

Table 2.6: EOC Survivability Performance Category for Wind Hazards (Division of Emergency Management 2002)

<table>
<thead>
<tr>
<th>Performance Category</th>
<th>X</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Wind Speed</td>
<td>Code &amp; ARC 4496 (C1+</td>
<td>ASCE 7 or Code &amp; ARC 4496 (C1-C2+)</td>
<td>ASCE 7, essential facility &amp; ARC 4496 (C1-C2+ &amp; F1+)</td>
<td>ASCE 7 plus ~40 mph (C3-C4 &amp; F2)</td>
<td>ASCE 7 plus ~80 mph (C5 &amp; F3)</td>
<td></td>
</tr>
<tr>
<td>Mean Annual Recurrence (Years)</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
<td>50</td>
<td>&gt; 50</td>
<td>1,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Design Wind Speed (mph), 3-second Gust</td>
<td>&lt; 90</td>
<td>100+/-</td>
<td>100 - 150</td>
<td>100 - 150</td>
<td>160 - 200</td>
<td>200 - 230</td>
</tr>
<tr>
<td>Importance Factor</td>
<td>&lt; 1.00</td>
<td>&lt; 1.00</td>
<td>1.00</td>
<td>1.15</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Hurricane Windborne Debris Impact Criteria</td>
<td>N/A</td>
<td>Equivalent to 1/2 in. plywood</td>
<td>2x4 in. timber plank, 9 lb @ 34 mph</td>
<td>2x4 in. timber plank, 9 lb @ 34 mph</td>
<td>2x4 timber in. plank, 15 lb @ 50 mph</td>
<td>2x4 in. timber plank, 15 lb @ 50 mph</td>
</tr>
</tbody>
</table>
the systems tested are: stud wall with plywood and/or metal sheathing, stud wall with concrete infill, reinforced CMU wall, ICF wall, etc. Most of these tests were conducted following FEMA (2000) Large Missile Impact Test protocol. A few tests were conducted with varying missile weights and speeds.

UF has performed a number of tests on wall and roof assemblies (Cook et al 1998, 1999, 2000, Ellifritt and Johnson 1998, Staley 1999, Anderson 1995). A number of tests were performed using a 2x4 in. 15 lb missile. The missile speed was 50 mph for wall assemblies and 34 mph for roof assemblies. Tests were also performed according to SBC large missile impact test criteria on wall and roof assemblies. A 2x4 in. 9 lb missile was used for these tests. A few tests were performed on roof assemblies using a 2x4 in. 15 lb missile impacted with varying speeds.

Miami-Dade Building Code Compliance Office (2003) approved a number of wall and roof assemblies for use on buildings in Miami-Dade County. These wall and roof assemblies satisfy the missile impact test based on FBC (2001).

The Florida Department of Education (2003) lists a number of approved roof assemblies that may be used as roof decks on Public Hurricane Shelters. According to the Florida Department of Education (2003), all roof deck systems that satisfy the missile impact and rain resistance criteria must function as an assembly. It is not the deck alone that fulfills the above requirements, but rather the entire assembly including the roof membrane. Hence the entire assembly is required to be tested successfully in a laboratory for compliance with SSTD 12 (1999). The department thus requires that all roof deck systems used on public hurricane shelters, except as described in the two items below, be tested as an assembly. The following roof deck
assemblies listed in FBC (2001) section 423.25.4.2 are approved for use on public hurricane shelters:

1. Cast-in-place concrete deck, minimum 4 in. thick. Deck must be waterproof, or have insulation and watertight roofing membrane above.

2. Precast, prestressed concrete deck, minimum 4 in. thick. Deck must be waterproof, or have insulation and watertight roofing membrane above.

Wall and roof assemblies previously tested at TTU and UF, approved by the Miami-Dade Building Code Compliance Office and the Florida Department of Education are provided in Appendix A (Tables A.1 – A.6). Table A.1 presents the wall and roof assemblies that passed the enhanced large missile impact test using a 2x4 in. 15 lb missile impacting at 50 mph speed, similar to the DOE and EOC criteria. Wall and roof assemblies that failed in the enhanced large missile impact test are listed in Table A.2. Tables A.3 and A.4 summarize the wall and roof assemblies that passed and failed the basic FBC large missile impact test using a 2x4 in. 9 lb missile impacting at 34 mph, respectively. Some test missiles used in the UF and TTU tests did not conform to either the basic FBC or the enhanced DOE test criteria. The passing and failing results from these tests, in which either missile weight and/or the speed varied from the standards, are presented in Tables A.5 and A.6, respectively.