DRAFT

Final Report for Project Entitled:

Feasibility Study for In-Home Storm Shelters in Florida Residential Homes

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by

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Executive Summary

The majority of Florida's 19 million residents live at or near to our 1,200 mile-long hurricane-prone coastlines, and their homes can be subject to damaging winds, wind-borne debris and storm surges. In addition, Florida annually experiences its fair share of tornadoes (approximately 50 per year, which can also cause building failures, injuries and death. It is well established that the Florida Building Code provides appropriate hurricane-resistant design guidelines for new buildings (FBC 2010). However over 80% of the existing inventory of residential structures, 7.2 million homes, (US Census 2010), were built before 2001, when wind-resistant design provisions were first included in the Florida Building Code. Further, as yet there are no tornado-resistant design guidelines available for typical structures.

The University of Florida is pleased to be able to conduct this research on a very important subject, on behalf of the Florida Building Commission. The building damage, injuries and loss of life are of high concern to the state of Florida. The primary focus of this project was to investigate the feasibility of building or installing in-home storm shelters in existing, pre-2001 Florida residential structures, and to recommend a research plan to establish feasible and cost-effective retrofit options for those structures. Specifically, the Florida Building Commission Staff asked us to: *Develop guidelines for strengthening a room or an area within an existing home necessary to achieve an acceptable level of protection from a severe windstorm."* Pertinent related questions included the following:

- Are the existing storm-shelter requirements appropriate for use in single-family Florida homes?
- Should in-home shelters be designed to resist tornado loads as wells as hurricane loads?
- Should Florida have a test program to evaluate tornado/hurricane resistance of in-home shelters?
- What are the cost/benefit implications to include in-home shelter design provisions in the Florida Building Code?

We reviewed existing literature on hurricane and tornado occurrence in Florida, mortality and morbidity rates related to hurricane damage, shelter design guides, and the techniques that improved hurricane forecasts and the construction of wind-resistant homes during the latter half of the 20th century. These factors have substantially reduced the loss of life and injuries from hurricanes and tornadoes in Florida. However, the potential for substantial building damage remains high particularly to vulnerable older homes, from a hurricane with the size and destructive power of the 1992 Hurricane Andrew. Tornadoes do not pose as large a threat of injury and death to the Florida population; because of their smaller size. For the most part only moderately strong, EF-2 and weaker tornadoes occur in Florida.

The studies on mortality and morbidity in tornadoes and hurricanes were insightful. While morbidity and mortality studies from hurricanes and tornadoes are limited, available reports revealed some common features and distinct differences. Persons over 60 years are at greater risk of injury and death in hurricanes and tornadoes than are persons under 20 years. Hurricanes do not increase the risk of dying but they generate a substantial increase in number of injuries, including psychiatric morbidity, (e.g. PTSD and major depression.) Flooding and storm surge are major risks of hurricane fatalities.

Tornadoes do increase the risk of deaths, usually due to head injuries, multiple fractures and arterial lacerations. The reviewed studies could not distinguish whether the injuries were due to flying debris or to building collapse. Two studies found people are at higher risk of injury when sheltering in a wood-frame building as compared with a brick-clad structure. However, persons who shelter from a tornado in a site-built home have lower risk of death and severe injury than persons in a mobile home or than persons who attempt to drive away from their home to escape a tornado.

Florida does not appear to have any state-wide policy regarding sheltering-in-place during hurricanes. Geographically, much of Florida's terrain is low-lying, less than 12 ft above mean sea level, and relatively flat. 33 of 67 counties have a coastal border, and so structures near the coasts are at risk of storm surges and flooding. The greatest threat to life and limb from hurricanes is the potential for storm surge, which can inundate large inland areas by storm surge heights exceeding 7-12 ft and in some cases by 25 ft or more. Sheltering-in-place is not an option for storm-surge prone areas. By statute, the Florida Division of Emergency Management is responsible for preparing a Statewide Emergency Shelter Plan that is a guide

for local emergency planning (FDEM 2012).

Improved hurricane forecast tracking has enabled hurricane warnings to be issued well in advance (48-72 hours) of landfall and so it provides sufficient time for an evacuation to occur. In 2014, the NHC will unveil a storm surge forecast map that indicates potential level of storm surge. If a building is structurally adequate to resist wind loads, and located outside of a storm surge and/or flood evacuation zone, there is no reason for its occupants to evacuate. For many older homes, this is not likely the case. Florida does not have a well-articulated policy on sheltering-in-place because most of the coastal areas are potentially in a storm surge zone. However for several interior counties shelter-in-place options may be appropriate. Occupants who choose this option must rely upon the strength of the homes or a safe room within the structure for protection.

The study did not find a compelling reason to undertake experimental testing of in-home storm shelters – there are several versions and design guides available today that provide “near-absolute protection” for protection during a 250 mph wind speed tornado with 15 lb wood board wind-borne debris traveling at 100 mph. However, there is some evidence that a lower design standard for Florida may be appropriate. Although our rate of tornado occurrence is equivalent to other Tornado Alley states, rarely has Florida seen an EF4 tornado (only 3 in the past 50 years).

Major Recommendation

The major recommendation of this study going forward is a proposal for Phase II experimental testing to develop design criteria for improving the fastening schedules for wall corners and Tee-joint intersections (between exterior wall and interior partition). The authors found no engineering support for the current fastening guidelines for wall corners that are in the Florida code. Further it was felt that by improving these connections, (which can be an inexpensive change and a reasonably inexpensive retrofit), the overall robustness of the house can be improved so that complete wall collapse is avoided. If the building walls remain standing, the loss of life and injuries occurring within single-family houses will be reduced.

1. Introduction

The majority of Florida's 19 million residents live at or near a hurricane-prone coastline, and their homes are susceptible to damage from severe winds. Houses along Florida's 1200-mile coastline are vulnerable to storm surges as well as high winds. Florida also experiences tornadoes throughout the year, which can cause building failures, injuries and deaths. Even houses located in the interior of the state are not immune from hurricane impacts. It is important to protect the population during the passage of a hurricane or tornado from high winds. Current forecasts can predict a hurricane track with reasonable certainty within 72 hours prior to landfall. While it is expected for people in low-lying, storm-surge prone areas to evacuate, it has become more common practice for the people to evacuate regardless whether or not their home is at risk of storm surge or flooding. The uncertainty regarding the capacity of the structural system and building envelope to resist the extreme winds is likely a factor in the decision of many to evacuate.

Of the 9 million single-family homes in Florida, 80% of these structures (or 7.2 million homes) were constructed before 2001 – the year in Florida adopted a building code statewide with upgraded wind-resistant construction details. Therefore, it is reasonable to expect that majority of our houses in the current inventory have inadequate connections and structural systems and bear high vulnerability to wind loads. The primary focus of this project is to investigate the feasibility of installing in-home storm shelters in existing pre-2001 Florida residential structures, and recommend a research plan to establish feasible and cost-effective retrofit options for those structures.

In their study Cugnoni and Whitworth (1992) found that wind-related injuries is proportional to (wind speed)^2, resulting in pronounced increase in risk of injuries above a 70 mph threshold wind speed. On average, over 1,500 tornado-related injuries and 80 hurricane-related injuries will occur in the United States annually, along with 80 fatalities from tornadoes and 17 hurricane-related fatalities.

1.1. Motivation

The Florida Building Commission Staff raised issues regarding designing or construction of in-home shelters, as follows: What are existing requirements (if any) for storm shelters, and are they appropriate for use in single-family Florida homes? Should in-home shelters be designed to resist tornado loads in addition to hurricane strength loads? What testing is required to evaluate the tornado and/or hurricane resistance of an in-home shelter? What are the costs and benefits of implementing a program to install in-home shelters in Florida homes?

1.2. Scope of Work

The University of Florida was tasked to: *Develop guidelines for strengthening a room or an area within an existing home necessary to achieve an acceptable level of protection from a severe windstorm."*

The original scope of work is listed below.

1) Review available design guides, reports and recommended practice on storm shelters, and methods for retrofitting of existing houses.
2) Summarize shelter-in-place options, retrofit solutions and present their advantages and disadvantages.
3) Synthesize knowledge and develop selection criteria for suitability of a house to have shelter-in-place hardened areas within existing light-framed wood and masonry residential structures.
4) Summarize and present recent knowledge on geographical variations of severe windstorm risks (hurricanes and tornadoes) in Florida, and develop an in-home shelter load model.
5) Recommend in-home shelter design options, including schematic renderings for an existing residential structure considering the cost, size and practicality of design and impact of Florida's mixed (hurricane and tornado) climatology.
6) Develop outline scope of work for Phase II – Detailed Engineering and Testing of Structural Components for a Hardened Shelter-in-place Room in an Existing House.

1.3. Structure of Report

This is the structure of the report. It states briefly what is in each chapter and how they relate to the whole.

Section 2. Extreme Wind Climatology of Florida

Hurricanes and tornadoes produce severe wind speeds and wind-borne debris that cause significant damage to buildings and place their occupants at risk for injuries or even death. Florida’s peninsular shape and location in the Gulf of Mexico make it particularly susceptible to both hurricanes and tornadoes. This chapter summarizes Florida’s hurricane and tornado climatology, including a historical perspective on significant wind events in Florida’s history and analyzes Florida’s statistical wind speed risk.

Section 3. Mortality and Morbidity studies for Hurricanes and Tornados

The numbers of fatalities and injuries occurring is an often-reported statistic along with hurricanes and tornadoes. This chapter provides a perspective regarding where such injuries occur in order to understand the need for in-home storm shelter protection.

Section 4. Literature Review of In-Home Shelter Design Guidelines

In post-disaster investigations after tornados, it was observed that in a few houses that lost their roof and exterior walls, small interior rooms such as closets or bathrooms remained standing. This chapter discusses the background of tornado shelters and the rationale for current design criteria. Recent in-home shelter research, design guidelines, and retrofit practices are discussed in regards to their application to a Florida specific shelter design.

Section 5. Shelter – in – place Options

This chapter presents the shelter in place options for Florida residents and proposes a recommended design philosophy. The recommendations provided in this report were selected based on cost, ease of installation and suitability for mixed wind event climatology of Florida.

Section 6. Phase II Projects

The objective of this Phase II research proposal chapter is to develop low-cost strategies to prevent the collapse of the walls of a single-family house when the roof fails in high winds. The motivation for this work is to reduce the risk of injury and deaths in existing Florida homes.

2. Extreme Wind Climatology of Florida

The need for in-home shelters is predicated on the potential for severe weather events, specifically hurricanes and tornadoes. These hazards produce severe wind speeds and wind-borne debris that cause significant damage to buildings and place their occupants at risk for injuries or even death. Florida's peninsular shape and location in the Gulf of Mexico make it particularly susceptible to both hurricanes and tornadoes. This section summarizes Florida's hurricane and tornado climatology, including a historical perspective on significant wind events in Florida's history.

2.1. Hurricane Climatology

From 1950 to 2013, 91 hurricanes have made landfall on the continental United States. The location of each hurricane strike is shown in Figure 1. Of those 91 hurricanes 31, or 34%, have struck Florida.

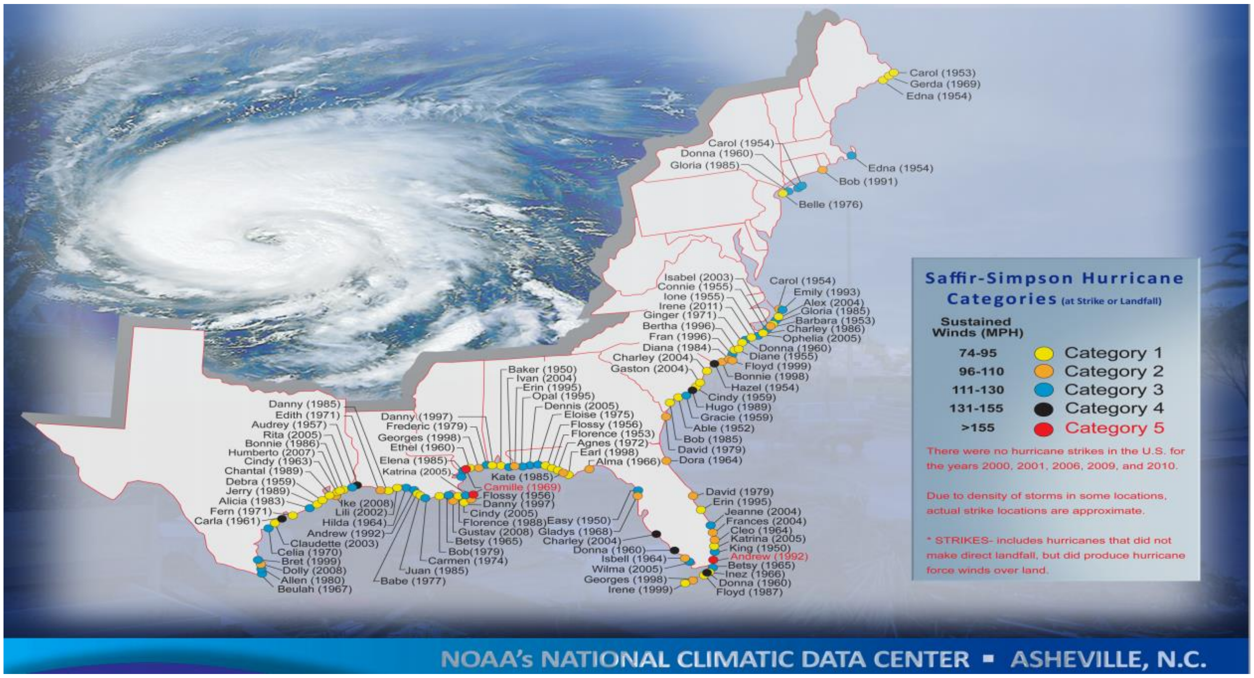

Figure 1: Continental United States Hurricane Strikes from 1950 – 2011. Image courtesy of NOAA's National Climatic Data Center, Asheville, NC.

Hurricane winds are the basis for the design wind speeds in Florida given by ASCE 7-10.. The wind speeds are based on a complete analysis of hurricane characteristics by Vickery et al (2009). Contours represent the wind speeds associated with a consistent risk factor, which differs by the building importance. Residential structures are considered Risk Category II structures, for which the design wind speeds represent a 700 year Mean Reoccurrence Interval (MRI), or Annual Exceedance Probability of 0.00143. The design wind speeds for a Risk Category II structure (which would typically include residential structures) are shown in Figure 2.

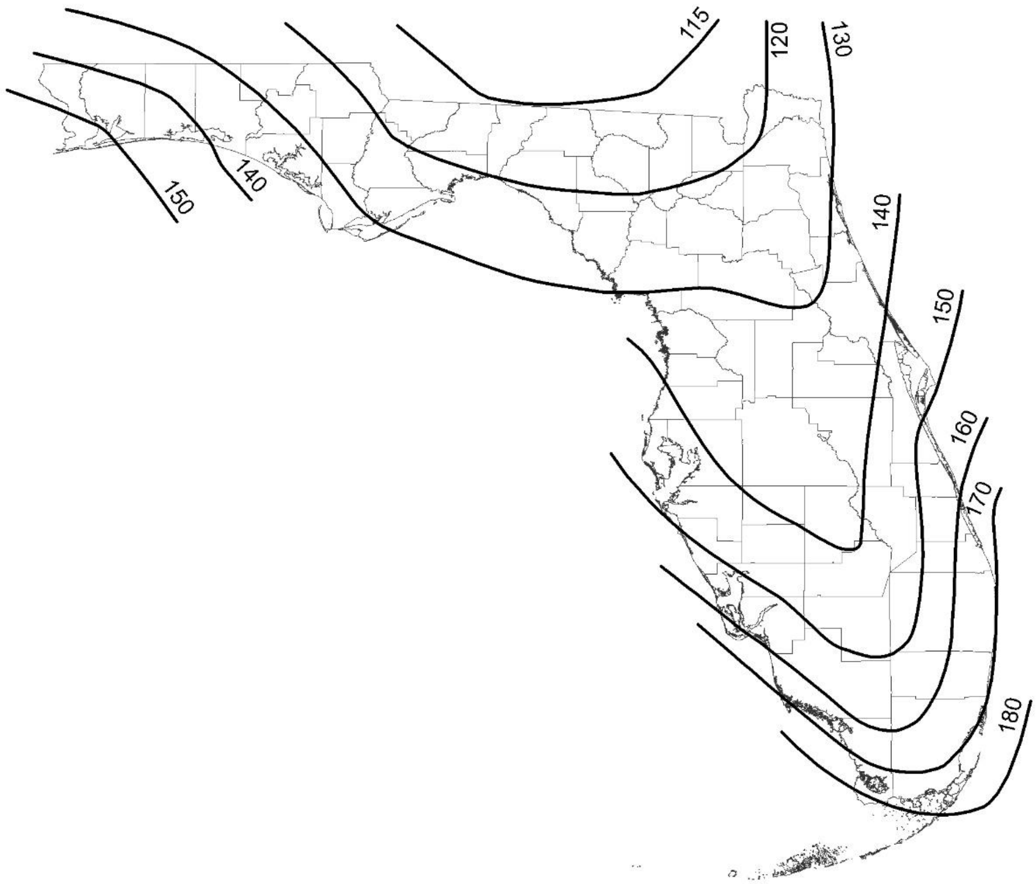

Figure 2: Design Wind Speeds (3-second gust at 33 ft above ground) for Risk Category II Structures from ASCE 7-10. Values are in miles per hour.

2.2. Significant Hurricane Events in Florida

Hurricane Andrew made landfall in South Florida 24 years ago, becoming one of the most costly and damaging hurricanes ever. With the second highest recorded sustained wind speed of 167 mph, Andrew was a category 5 hurricane at landfall in Dade County. It caused $26.5 billion in damages, 23 fatalities and 445 injuries. At least 160,000 people were left homeless, and 28,000 homes totally destroyed. There was massive evacuation in advance of landfall, 71% of people evacuated from the Category 1 surge zone, 63% from Category 2 and 3, 33% from Category 4 and 5 surge zones. In addition 13% of the inland population with the hurricane track also chose to evacuate (FEMA 1993).

The 2004 hurricane season was economically one of the worst seasons in Florida's history, with four major hurricanes (Charley, Frances, Jeanne and Ivan), causing at least 47 deaths and some $45 billion in damages Figure 3. Rappaport (2014) estimated that about 8% of the fatalities in tropical storms were caused by non-tornadic winds. Smith and McCarty (2006) estimated that 2.6 million homes sustained at least minor damage, and as many as 1.7 million people had to find temporary shelter, including more than 30% of the populations in some counties (Smith and McCarty 2006). In 2004, 40,000 homes were damaged or destroyed, and 2.8 million people participated in the largest hurricane-related evacuation in Florida in advance of Hurricane Frances (Jacobitz 2005). In that year, nearly 10 million residents were forced to evacuate from their homes. A summary of the significant hurricane impacts to Florida are provided in Table 1.

Table 1: Major Hurricane Impacts on Florida from 1992 – 2004 (NOAA.gov)

Hurricane	Year	Peak Wind Velocity (mph)	Category	Storm Surge (ft)	Economic Loss ($)	Fatalities	Injuries
Andrew	1992	177	5	17	26.5 Billion	23	445
Charley	2004	150	4	<7	11.2 Billion	24	792
Frances	2004	110-120	2	6	8.9 Billion	7	
Ivan	2004	120	3	10-15	4.5 Billion	14	16
Jeanne	2004	115-120	3	6	6.9 Billion	5	

2.3. Storm Surge

While not a wind event in itself, storm surge accompanies hurricanes and can cause significant damage. Storm surge is the abnormal rise of ocean water on land due to strong winds. The height of storm surge is influenced by several factors, including wind speed, central pressure, size, direction and forward speed of the hurricane. Storm surge is a much greater threat to lives and property than are winds from hurricanes and tropical storms. For the period 1963 through 2012, Rappaport (2014) found that storm surge flooding directly accounts for about half of the 2,544 deaths associated with tropical cyclones (which includes 1,100 during Katrina). For coastal communities in Florida it is imperative to know the storm surge height predicted for a hurricane and to evacuate to higher ground well in advance. Storm surge has important implications for storm shelters, as sheltering in place should not be done in regions at risk for flooding.

The National Hurricane Center (NHC) recently developed a storm surge risk that enables individuals to determine the forecast peak water level from a high-resolution map, presented as height above ground (i.e. inundation). The product will be tested during the current hurricane season. It is anticipated that the National Weather Service will provide U.S. storm-surge warnings by 2015. Storm surge warnings would be provided at locations and timing that often may differ from hurricane warnings based on wind speed.
The Florida Division of Emergency Management provides information on storm surge heights, classified into six zones (Tropical storm, Zones 1 through 5) (FDEM 2014). Potential storm surge heights range depending on location from 6-9 ft for Zone 1, up to 28-42 ft in Zone 5 (FDEM 2010). Since the majority of our population lives near to the coast any potential for storm surge event results in a large population that needs to evacuate to higher ground. Storm surge evacuation is the priority in these zones.

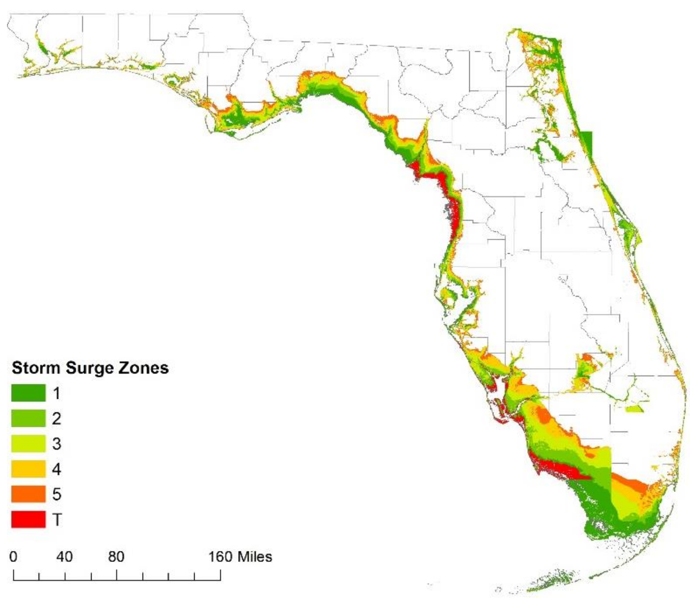

Figure 3: Florida Storm Surge Map

As an example, if a hurricane were to make landfall in Lee County, FL with a Zone 1 storm surge height of 8.7 ft, nearly 270,000 persons would be expected to evacuate. The number of persons evacuating more than doubles to 630,000 in the event of a Zone 5 storm surge (42 ft Storm Surge height). Further, Zone 5 evacuation zone would extend 22 miles inland of the coast, covering 90% of the county (Figure 4).

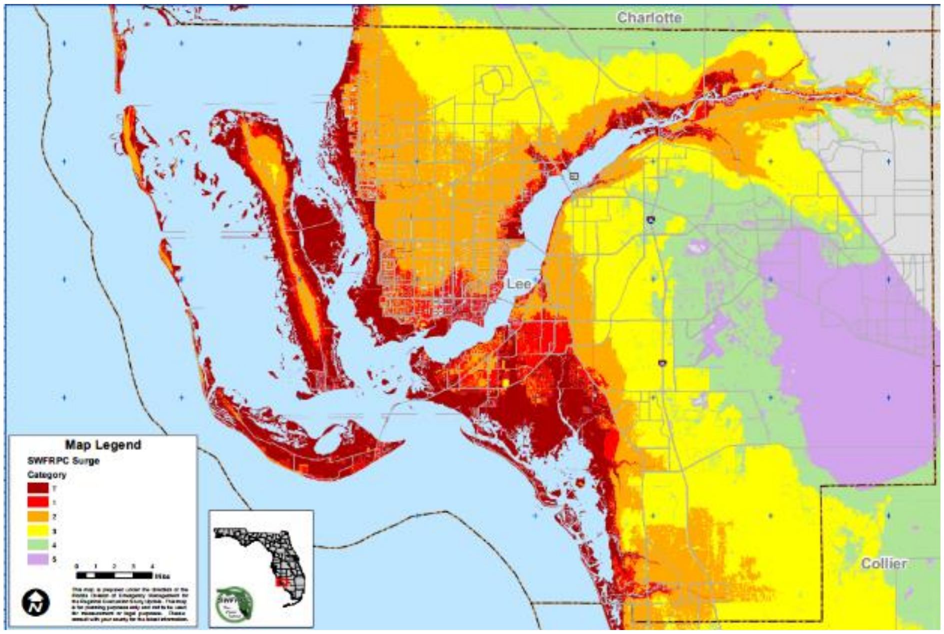

Figure 4: Lee County Hurricane Evacuation Zones ((FDEM 2010))

2.4. Tornado Climatology

On average nearly 1200 tornadoes occur in the United States each year, with a high toll in fatalities (90 fatalities per year), injuries (1,500 per year) and economic losses (approximately $4.8 billion per year) (Simmons et al. 2013). Florida annually expects about 50 tornadoes per year within the state (SPC 2014). The number of tornado-related fatalities and injuries have been steadily declining, due in large part to improvement in forecasting, tornado detection and communication of tornado warnings. In 1978, the National Weather Service could only detect 22% of tornadoes that occurred, and they provided tornado warnings with a 3-minute lead-time before a tornado impact. By 2004 the probability of detection for tornadoes was up to 75% with an average lead time of 13 min (Brotzge and Donner 2013). What is somewhat problematic now is there are relatively high numbers of false alarms (Brotzge and Donner 2013).

The majority of Florida's strongest tornadoes are associated with supercell storms, occurring from January through May, but tornadoes do occur in all months as shown in Figure 5. Approximately 11% of Florida's tornadoes are spawned by or otherwise associated with land falling hurricane (Truchelut 2014). Florida is the most active state for tornadoes per 10,000 mi^2, but Florida tornados have rarely exceeded EF-2 – since 1950, only 39 EF3 and higher tornadoes were observed in Florida (SPC 2014). By comparison, Oklahoma has seen 273 EF3 or higher tornadoes over the same time period. A comparison between the occurrence rates of tornado intensities in Florida and Oklahoma is provided in Table 2. Despite the relatively low number of strong tornadoes, Florida leads the country in deaths per mile of tornado track (Konrad and Kovach, 2014). Florida has a higher percentage of nocturnal tornadoes than occurs in Midwest (Hagemeyer et al. 2010). A summary of the EF-Scale and how it is used to classify tornadoes is provided in Appendix B.

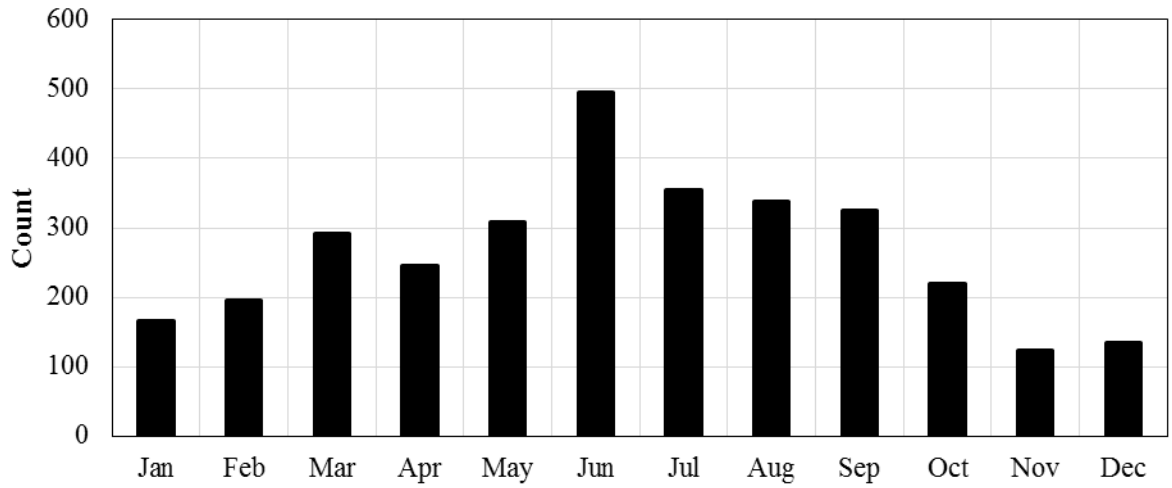

Figure 5: Total Number of Florida Tornadoes by Month (1950 – 2013)

Table 2: Occurrence rates by tornado intensity for Florida and Oklahoma

EF-scale (mph)	Number of Tornadoes		Probability		Cumulative Probability	
	FL	OK	FL	OK	FL	OK
0 (65-85)	1916	1497	0.6018	0.415	0.6018	0.415
1 (86-109)	909	1156	0.2855	0.321	0.8872	0.736
2 (110-137)	319	678	0.1002	0.188	0.9874	0.925
3 (138-167)	37	199	0.0116	0.055	0.9991	0.980
4 (168-199)	2	63	0.0009	0.0175	1.0000	0.997
5 (200-234)	0	10	0	0.0023	-	1.000
Total	**3183**	**3603**				

2.4.1. Tornado Wind Speed Probability of Exceedance

The geographic risk of tornadoes for a region can be estimated by evaluating the probabilities of occurrence of specific wind speeds due to a tornado will exceed a specified wind speed for a given point or area. This is important for the comparison of tornado hurricane risk with regards to the selection of proper design wind speeds. This study uses a stochastic method for estimating tornado risk developed by Twisdale and Dunn (1983). This method incorporates a tornado wind field model in combination with local tornado climatology (path width, path length and intensity occurrence rates) to estimate the probability that, at a single point, the wind speed from a tornado would exceed a given wind speed.

2.4.1.1. Methodology

This study uses the tornado record maintained by the Storm Prediction Center, which includes archived information of the tornado record for the United States for 1950 – 2013 (http://www.spc.noaa.gov/wcm/). For each tornado, the database includes the date and time of occurrence, intensity, associated fatalities or injuries, GPS coordinates of estimated touchdown and uplift points, path length, path width and a county code number (the Federal Information Processing Standards (FIPS)). An example of the relevant data included in the SPC database is provided in Table 3.

The tornado characteristics used to determine the wind field model, are the diameter (radius) of the tornado vortex, length and width of tornado paths, centerline wind speed, and a decay function to describe the relationship between the wind speed and the distance away from the centerline.

Table 3: Example Data for SPC Tornado Database (SPC 2014)

Date	EF scale	Injuries	Fatalities	Lat	Long	Length (mi)	Width (yds)	County Code
4/15/1958	4	7	0	27.67	-82.62	0.1	300	105
4/4/1966	4	530	11	27.92	-82.8	135.8	300	103
10/3/1992	3	75	3	27.83	-82.7	2.6	500	103
12/31/1975	3	26	1	29.08	-82.17	2	200	83

Tornado wind fields vary significantly from tornado to tornado, and as a result any tornado wind field model will depend upon a number of different parameters. Some, like path length, path width, and maximum wind speed, can be estimated from physical observations and so are found in the historical records. Others, like boundary layer depth and the wind speed decay coefficient, are not typically recorded, but estimates have been given in published literature (Twisdale and Dunn, 1983). In order to obtain accurate results despite the variability of the different input parameters, a commonly used method is a Monte Carlo simulation, which *iteratively* evaluates a deterministic model using sets of random numbers as inputs. The inputs are randomly generated from *probability distributions* of each factor (path length and width, tornado intensity, wind speed, etc.) to simulate the process of sampling from an actual *population*. This requires that accurate probability distributions are developed for the parameters dependent upon local tornado climatology, specifically path length, path width, and tornado intensity distribution.

The probability distribution for tornado intensity in Florida was developed by simply using the occurrence rates given above as a discrete probability mass function. For example, a random number is generated from a uniform distribution. If it falls between 0 and 0.6018, a F0 tornado would be selected.

Tornado path lengths and widths are typically fit to Weibull distributions (Banik et al, 2007), and this distribution function is also used in this study. The known path lengths (miles) and widths (yards) from the historical records of tornadoes in Florida were fit to Weibull distributions, giving the following fit and shape parameters for a Weibull distribution provided in Table 4. The SPC tornado data contained 693 tornadoes with unknown path dimensions in the state of Florida. In the record handling process, unknown width and length values are assigned constant values of 10 yards and 0.1 mile respectively. In order to determine the sensitivity of the analysis to the unknown path parameters the process was run with and without these values. There was no significant difference between the results so only the results with default values are reported. Only three EF4 tornadoes have occurred in Florida, therefore records from the neighboring state of Georgia, which included 34 EF4 tornadoes, were combined to provide a more reliable statistical analysis. A similar procedure was used by Banik et al (2007). Plots of the resulting fits are shown in Appendix C, with the goodness of the fit illustrated by the linearity of the empirical data.

Table 4: Weibull Distribution Parameters for Path Lengths and Path Widths without Defaults

EF-scale	Path Length		Path Width	
	a	*b*	*a*	*b*
0	1.0308	0.7309	40.8975	1.3156
1	2.1952	0.7546	66.0440	0.9950
2	5.2390	0.6824	120.1168	1.0866
3	9.5090	1.2737	248.4463	1.4826
4	26.516	0.806	667.712	1.592

To estimate the tornado hazard for point locations in Florida, design wind speeds were chosen beginning at 80 mph and increasing by intervals of 10 mph up to 250 mph. For each incremented wind speed, 100,000 tornadoes were simulated, for a total of 1,800,000. A sensitivity analysis was conducted to establish the appropraite number of evaluations required.
Each simulation consisted of the following steps:

1. Sample tornado intensity (EF-scale) using probability of occurrence (Table 2).

2. Sample path length and path width from appropriate Weibull probability distributions as described above.
3. Sample tornado wind field parameters from Twisdale and Dunn (1983).
4. Fit tornado wind field to parameters samples in 1-3.
5. Find area within the tornado wind field in which V $\geq$ v, where V is the tornado wind speed at a given distance from the tornado center and v is the design wind speed of interest (Figure 6).

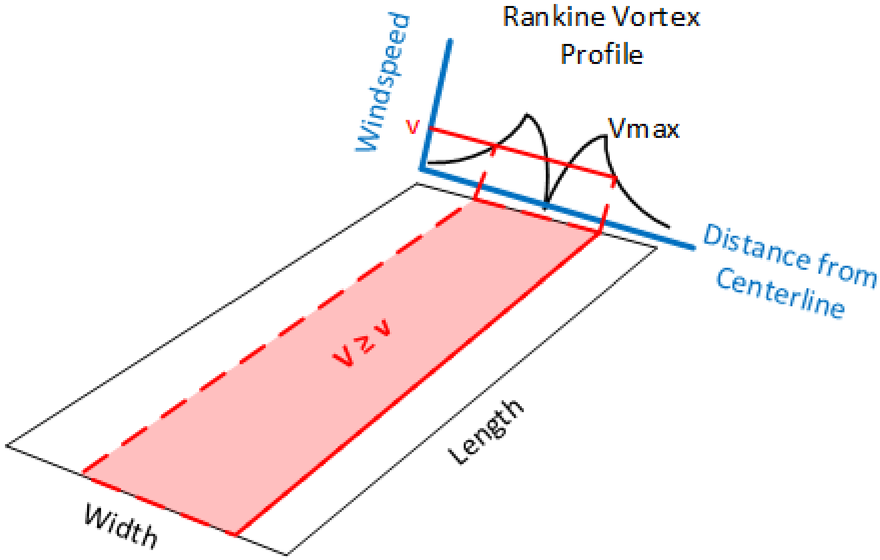

Figure 6: Simulated Tornado Path for Monte Carlo Simulation

Once the area of V $\geq$ v has been calculated for each of the 100,000 tornadoes, the probability of a certain design velocity, v, being exceeded at a site by the velocity within a single random tornado, V is then defined according to:

$$P(V > v) = \sum_{i=0}^{n_{max}} \{1 - \exp[-\gamma_i P(V > v|Fi)T]\} \quad \text{EQN 1}$$

Where γ_i is the occurrence rate (in tornadoes per year) of a tornado with intensity Fi, n_{max} represents the F-scale intensity of interest (EF4) , T is the time period of interest (63 years), and *P(V > v|Fi)* is determined as:

$$P(V > v|Fi) = \min(1, \frac{E(A_i)}{S}) \quad \text{EQN 2}$$

where E(A*i*) is the expected area within a tornado of intensity *i* in which V > v, and S is the area of the region of interest (in this study, S is the area of Florida which is 53,625 sq. mi. (US Census, 2010)).

The same method is performed using data on tornadoes in Oklahoma and plotted for comparison.

Figure 7 shows probabilities of wind speed exceedance due to a tornado are significantly lower in whole state of Florida than in Oklahoma. The difference in probabilities is consistently a factor of about ten. This is due to the increased likelihood for larger tornadoes in Oklahoma, which results in larger areas with wind speeds greater than the design wind speed. The agreement provides validation for the simulation model used in this study.

2.4.2. Results of Tornado Wind Speed Probability of Exceedance Analysis

The Probabilities of exceedance seen in Figure 7 suggest that the residential shelter design wind speed of 250 mph recommended by the current shelter standards used in Florida are overly conservative if only tornadoes are considered.

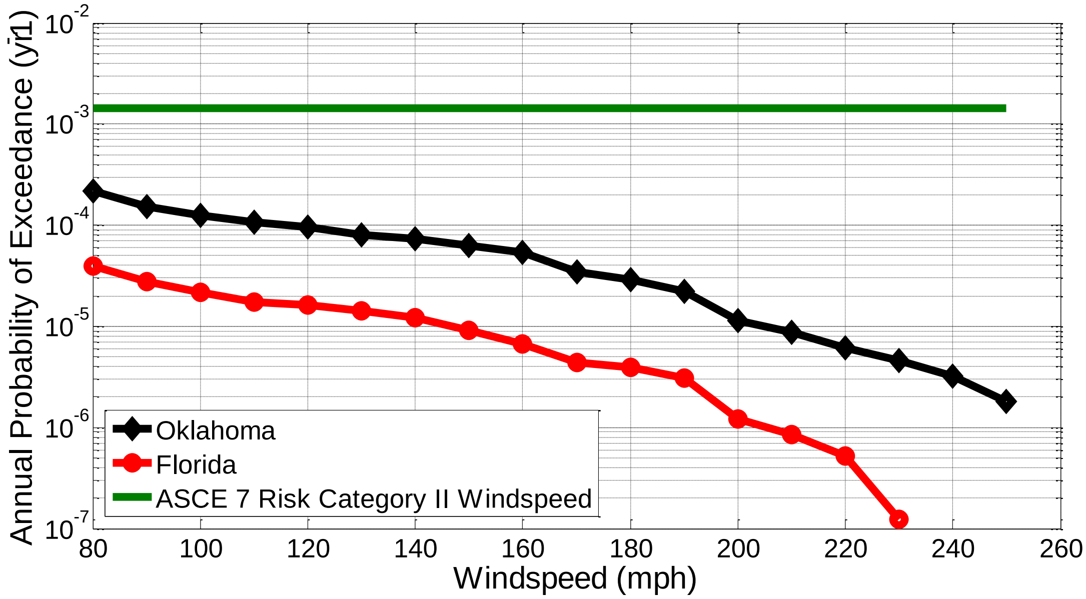

Figure 7: Annual Probability of Wind Speed Exceedance due to Tornadoes (Note: ASCE 7 Windspeed POE is based on geographic location (i.e. contour lines) and the tornado POE are for the entire state.)

However Florida is susceptible to both hurricane and tornado winds, so a joint probability of exceedance model should be considered. Hurricane design wind speeds are provided in ASCE 7-10 for Risk Category II structures (Asce 2010). The wind speed contours represent 700 year mean reoccurrence intervals having an annual exceedance probability of 0.00143. This probability is 71.4 times greater than the highest probability of exceedance for an EF2 (115 mph) or greater tornado occurrence in Florida. In order to determine whether the risk of stronger tornadoes should be accounted for when determining an ultimate design wind speed the joint POE for tornadoes and hurricanes was determined according to**Error! Reference source not found.**:

$$\left(1-\frac{1}{R_c}\right)=\left(1-\frac{1}{R_T}\right)\left(1-\frac{1}{R_H}\right) \quad \text{EQN 3}$$

Where Rc is the combined return period for a given extreme wind speed due to winds from storm types 1 and 2 (R1 and R2) (Holmes 2001). For a risk category II building in Florida the return period for a 115 mph ultimate design windspeed, the lowest stipulated design windspeed, from a hurricane event is 700 years with an annual POE of $1.43 * 10^{-3}$ (Asce 2010). The return period of a tornado having the same design windspeed of 115 mph in Florida is 66666 years with an annual POE of $1.5 * 10^{-5}$ (Figure 7). Thus, the joint probability of return period is 693 years and an annual POE of $1.44 * 10^{-3}$. It is observed that the return period is reduced by 1% from 700 years 693 years. Therefore, the inclusion of the tornado windspeed risk minimally affects the POE of hurricane data alone and the current risk category II design wind speeds found in ASCE (2010) are sufficient.

2.4.3. Kernel Density Estimation of Spatial Tornado Distribution for Florida

The tornado hazard for Florida is shown geographically using maps of the locations of all reported tornado touchdowns by F-scale, using the data from the SPC database (SPC 2011). The reported touchdown location only is plotted rather than the entire track length due to the lack of long track tornadoes in the database. With the vast majority of the reported tornadoes having lengths less than 10 miles, the touchdown point is adequate for representing geographic distributions in Florida.

2.4.3.1. Methodology

A Kernel Density Estimator (KDE) is a useful tool to visualize the spatial distribution of tornado occurrences is through the use of kernel density estimators.

The general process is as follows:

1. Obtain tornado origin points from SPC tornado database
2. Define a search area (e.g. 10 mi^2) and divide up Florida map into square search areas.
3. Determine the number of tornadoes occurring within each search area over entire period of data.
4. Fit the tornado occurrences to a spatial distribution function using Kernel Density function (Silverman 1986).
5. Normalize the results to annual occurrences.
6. Calculate mean return interval (MRI) for each search area
7. Generate contour map of the MRI using user inputted contour ranges (i.e. 700 yr, 100 yr) as seen in Figure 8**Error! Reference source not found.**.

2.4.3.2. Results

This method is used in Figure 8 for all Florida. This plot shows that the occurrence of tornadoes in Florida is not geographically uniform – regions in the central and panhandle portions of the state are much more susceptible to tornadoes than others. The highest probability of tornado occurrence is in a region near Tampa and St. Petersburg. The kernel density estimator does show that the Probability of Exceedance results could have been skewed by the tornado data used. When comparing to the population density of Florida (Figure 9) it can be seen that the SPC tornado occurrence data does seem to be biased to the more heavily populated areas. This is most likely due to the unlikelihood of someone witnessing a tornado in an unpopulated region. Elsner et al. (2013) and Widen et al. (2013) suggest that tornadoes are under-reported in unpopulated areas and have developed methodologies to account for the bias in tornado records. This methodology is not easily translated to Florida's tornado records due to the presence of Hurricane induced tornadoes (HIT), but should be a topic of future research. Kernel density estimators for HIT and non-HIT are provided in Figure 10. The analysis suggests that the propensity for tornado strikes in Florida differs slightly between HIT and non-HIT. While non-HIT are more likely in West-Central Florida, HIT are almost equally likely in East-Central Florida, the Miami region and portions of the Florida panhandle.

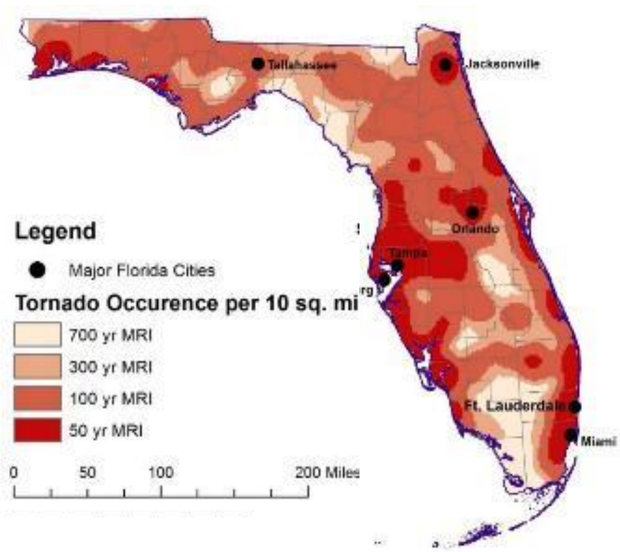

Figure 8: Kernel density estimate for all Florida tornadoes. MRI represents the Mean Reoccurrence Interval.

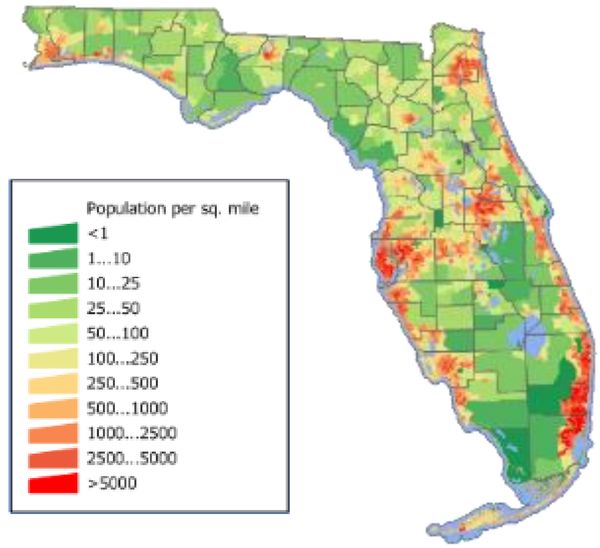

Figure 9: Florida Population Density (US Census Bureau 2010)

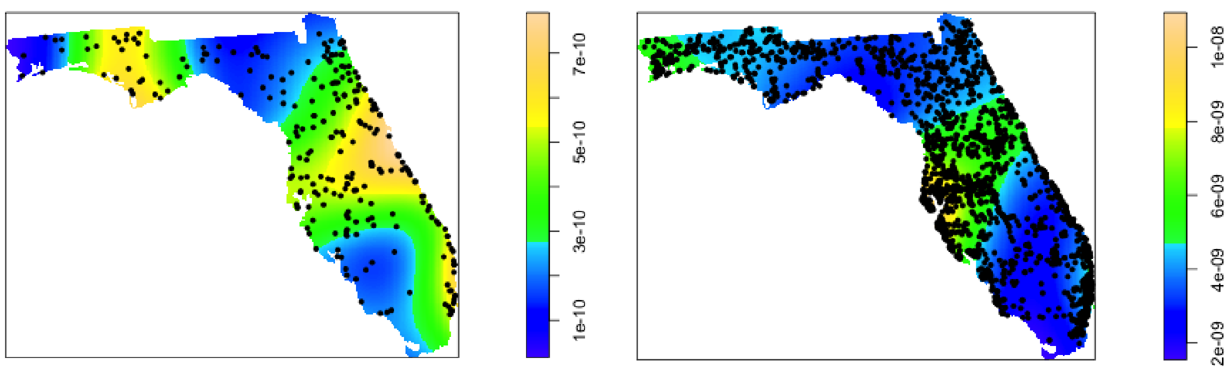

Figure 10: Hurricane-induced tornadoes in Florida (left) non Hurricane-induced tornadoes in Florida (right). Color ramps represent the density of tornado strikes in tornadoes/m2. Figures courtesy of Ryan Truchelut (Truchelut, 2014).

2.5. Significant Tornado Events in Florida

Table 5 summarizes some tornado data from a few significant tornadoes or tornado outbreaks in Florida's history. The two most significant tornado events were the F4 tornado in 1966 that nearly crossed the entire Florida peninsula and the 1998 central Florida tornado outbreak. Together these two events account for 53 of the 207 tornado deaths documented in Florida since 1882 (Hagemeyer, 2013), over 25%. Beginning in 2012, the Wind Hazard Damage Assessment Team (WHDAT) at the University of Florida has begun documenting the impacts of certain Florida tornadoes. Florida tornadoes that have been surveyed by the WHDA team are also included in Table 5.

Table 5: Tornado Events in Florida

Date	Location (County)	Length/ Width mi /yd	Rating	Damage ($)	Deaths	Injuries	Homes Destroy / Damage	Source
4/5/1966	Hillsborough	100 / 300	F4	50 Mil	11	3500	280	NOAA
2/22/1998	Sumter/Lake/ Volusia/Brevard	80 / 100	3 – F3 2 – F2	100 Mil	42	260	700/ 3000	NOAA
2/2/2007	Sumter/Lake/ Volusia	70 /100	2 – EF3 1 – EF1 1 – EF0	218 Mil	21	76	400 /1725	NOAA
6/24/2012*	Highlands	5 / 100	EF1	60,000	0	0	-	UF
8/27/2012*	Indian River	1.6 / 180	EF0	500,000	0	0	104 / NA	UF

* Survey conducted by Wind Hazard Damage Assessment Team at the University of Florida

Figure 11: (*Left*) A destroyed concrete block and stucco home in Kissimmee, FL during 1998 F3 tornado (http://www.srh.noaa.gov/mlb/?n=kissimmeepics), (*Right*) Damaged homes in Lakeside subdivision in Kissimmee, Florida. The 1998 F3 tornado moved from the upper right to the lower left, narrowly missing a school. (http://www.nws.noaa.gov/os/assessments/pdfs/cntrlfl.pdf)

Figure 12: Post-2012 Lake Placid (Highland County) tornado damage showing EF2 damage (*left*) Post-2012 Vero Beach (Indian River County) tornado damage showing EF1 damage (*right*)

3. Mortality AND Morbidity Studies for Hurricanes and Tornados

The numbers of fatalities and injuries occurring is an often-reported statistic along with hurricanes and tornadoes. This section provides a perspective regarding where such injuries occur in order to understand the need for in-home storm shelter protection.

One of the welcome trends that defined the 20th century has been the substantial reductions in global death rates from natural hazard events. Goklany (2007) reports that global death rates from natural hazards peaked in the decade of the 1920s at 242 persons per million and then the rate progressively reduced to just 3 deaths per million, or 22,000 per year in the 2000-2006 period. Putting the number of weather-related deaths in perspective, on a global scale, communicable diseases accounted for 18.3 million deaths in 2002, when extreme weather events caused just 19,868 deaths, or just 0.03% of the total.

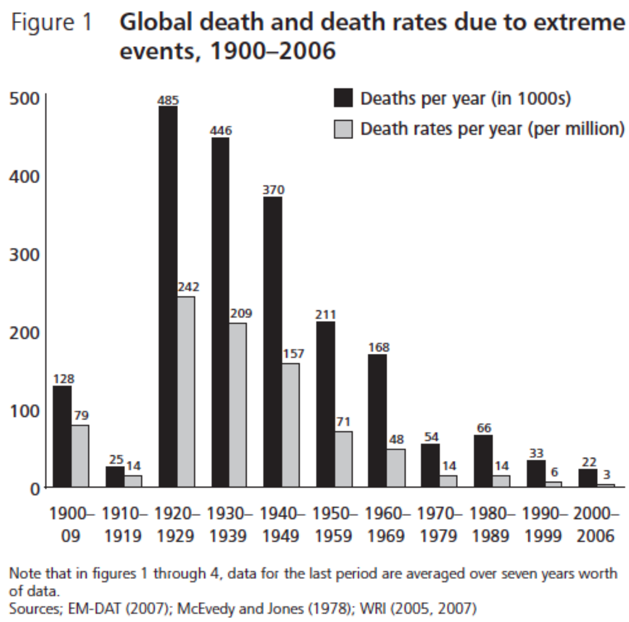

Figure 13: Global death rates due to extreme events excerpted from Goklany (2007)

By far, most natural hazards caused deaths in the 20th century were due to droughts, averaging 130,000 per year from 1900 through 1989. However, there was a remarkable reduction in drought related deaths over the period 1990-2006 to just 185 per year! On the other hand, the global annual death rates from windstorms, which averaged 10,856 per year for 90 years (1900- 1989), actually increased 26% to 13,650 per year for the 1990 – 2006 period.

In the United States, death rates from windstorms declined in the first half of the 20th century but the cumulative number of deaths from hurricanes, tornadoes, lightning and floods has remained relatively stable at 300 – 325 per year since 1959.

3.1. Morbidity and Mortality Studies on Hurricanes

The mortality studies on hurricanes consistently show that flooding and storm surge cause the most numbers of deaths. Hurricane Floyd made landfall in North Carolina on September 16, 1999 producing 20 inches of rain and flooding in coastal counties. Of the 52 deaths associated directly with the storm, 69% (38 deaths) were due to drowning. In addition, 33% of the emergency department visits after the storm was related to injuries. Comparing the first week following Hurricane Floyd with the first week of September one year earlier revealed significant increases in suicide attempts (relative risk [RR] = 5.0), and dog bites, (RR= 4.1). Although Hurricane Floyd was not a design-level wind event, it produced 20 inches of rain, causing extensive flash flooding in North Carolina. Most of the 52 fatalities were from drowning (69%), and motor vehicle car crashes (13%). Only one fatality (also by drowning) occurred in a house. Hurricane Floyd was unique for inland hurricanes, as most mortality and morbidity caused by them have been attributable to high winds (Centers for Disease Control and Prevention 2000).

3.2. Injuries Related to High Wind Speeds

Cugnoni and Whitworth (1992) reported on the number of wind-related injuries from the Great Storm of 1987 in Great Britain that over a 10-day period caused 49 fatalities and 150 million pounds sterling in insurance losses. The storm produced moderately strong winds, gusting up to 63 knots. While most of the injuries seen were minor in nature, some were serious enough to justify warnings to the public that it would be safer to stay at home on certain windy days. The results of the study suggest that wind gust speeds in excess of 60 knots (69 mph) represent more of a risk to individual personal safety. The majority of patients were either hit by flying debris or falling masonry (36%) or were blown over by the wind (33%).

Hurricane-related wind injuries are more significant. Hendrickson et al. (1997) showed that while there was not a significant increase in the risk of dying of Kauai residents in the 12 months following the Hurricane Iniki disaster in 1992, the number of injuries (1,584) treated in the post-Iniki period was nearly a 7-fold increase injuries treated (231) in the pre-Iniki period. Hendrickson et al. (1997) also found that persons 65 years and older had nearly 3-time higher risk of being injured that persons younger than 20 years. Interestingly, injury incidence rates remained significantly high 6 months following Hurricane Iniki for males in the 20–44-year age group.

Hurricanes are liable to produce psychological injury as well as physical stress and injuries. David et al. (1996) found that following a natural hazard disaster of the magnitude of Hurricane Andrew, psychiatric morbidity, including but not limited to post-traumatic stress disorder (PTSD), major depression and general anxiety disorder are common among individuals living in areas of high exposure (David et al., 1996). Due to the limited sample size (N =61), the authors considered this a preliminary assessment of risk factors, they concluded that "severe damage of buildings" was most significantly associated with outcome, possibly due to causing greater disruption of routines, persistence of disaster-related reminders, and lengthier and more difficult rebuilding processes. Further, persons with extensive reminders and arduous rebuilding tasks appear to be most at risk.

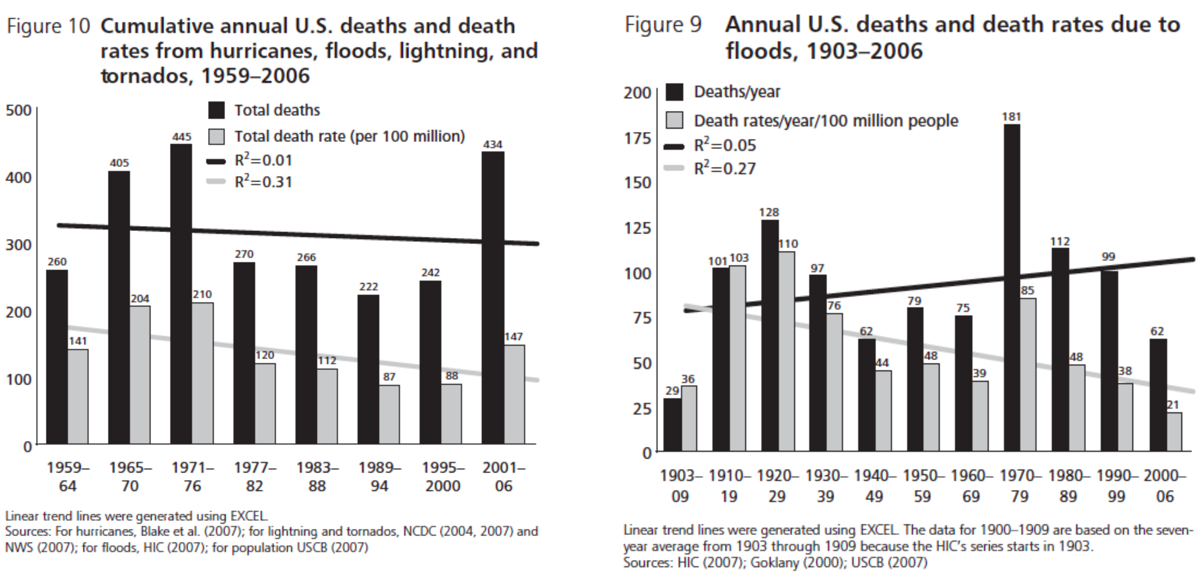

Figure 14: Death Rates from floods and wind events Goklany (2007)

3.3. Tornado-Related Injuries and Deaths

Tornado morbidity statistics show a different pattern from hurricanes, particularly with the most violent EF-4 and EF-5 tornadoes. The damage potential of extreme violent EF4/EF5 tornadoes, well exceeds the strengths observed in tornadoes. Buildings may fail in several ways: sliding, overturning, or racking. In addition, individual components or connection failures (i.e. fracture of a truss or wall stud) may also occur. Tornado shelters are designed based on best knowledge to remain intact within a structure that is completely destroyed.

Following the 3 May 1999 Oklahoma tornado, Brown et al. (2002) analyzed data on tornado-related deaths and injuries. A total of 690 persons were either treated in a hospital or killed. Forty-five persons (7%) died, including 42 from injuries and 3 from cardiac conditions. Twenty-nine persons died at the scene and 16 at a hospital. Among the 645 survivors, 33 were not injured but were treated for other medical conditions. Pertinent facts regarding tornado-related injuries are presented below:

- The majority of direct tornado deaths are immediate, occurring at the scene (Bohonos and Hogan 1999; Carter et al. 1989; May et al. 2000)
- Direct tornado deaths result from multiple injuries, head injuries, chest injuries, crush injuries, asphyxia, and heart attacks (Bohonos and Hogan 1999; Centers for Disease Control and 1997; Centers for Disease Control and 1997; Glass et al. 1980; May et al. 2000)
- Soft-tissue wounds are among the most common kind of injuries resulting from tornadoes, and, frequently, the wounds are contaminated with debris and bacteria and require irrigation and delayed closure (Bohonos and Hogan 1999; Brenner and Noji 1992).
- Among seriously injured persons, fractures, brain injuries, and deep wounds are common, particularly fractures and wounds of the extremities (Carter et al. 1989; Glass et al. 1980; May et al. 2000).
- Indirect tornado injuries and deaths occur as a result of the rescue and recovery process and the disaster aftermath. Cleanup-related electrocutions, burns, puncture wounds, strains/sprains, sunburn, and heat exposures have been documented in various reports (Bohonos and Hogan 1999; Centers for Disease Control and 1997; Centers for Disease Control and 2000)
- Most patients receiving major abrasions and lacerations had not covered themselves with blankets, pillow or mattresses (Glass et al. 1980).
- Brenner and Noji (1993) reported that persons 60 years of age and older are more likely to be injured than are people younger than 20 years.
- People have greater risk of death and severe injury, if they attempt to drive away from their homes to escape a tornado, as do occupants of mobile homes (Glass et al., 1980).

Studies also showed the degree of building failure is highly correlated with the risk of death or injury, and further there appears to be some, albeit self-reported association, of fewer injuries for people inside brick homes as compared with light-framed wood homes. This latter was not independently confirmed. Thus far, no studies were able to determine whether injuries were due to high-velocity projectiles or to the collapse of structures.

3.4. Mortality Rates in the 25-28 April 2011 Tornado Outbreaks

Casey-Lockyer et al. (2012) described the fatalities of the April 25-28 2011 southeast tornado outbreak by demographic characteristics, type of shelter used, cause of death, and tornado severity and location. It was reported that 95% of the deaths from the outbreak were caused by trauma. Flying or falling debris is most often the cause of trauma during a windstorm event. Of the 338 deaths, 44% of the bodies were recovered from inside their private home and 47% of the 332 injuries were inside single-family homes. Therefore, it is necessary to protect residents from flying debris to ensure life safety.

3.5. Summary

Globally, the death rate related to windstorms is low but it has increased through 2007. In the U.S., morbidity and mortality studies from hurricanes and tornadoes are limited, but it is clear wind-related deaths occur less often than storm-surge related fatalities. The risks of storm surge in coastal areas in Florida pose a threat and the NWS is undertaking new tools to enable coastal communities to know whether they need to evacuate. There are some common features and distinct differences between hurricane and tornado deaths. Hurricanes do not increase the risk of dying but they generate a substantial increase in number of injuries, due to building component failures and flying debris. PTSD and major depression are two outcomes from hurricane disasters, which are strongly related to building damage. Head injuries abrasions and arterial lacerations are common injuries causing deaths in tornadoes. However, studies have not clearly shown whether this is due to flying objects or building collapse. Persons who shelter from a tornado in a site-built home have lower risk of death and severe injury than persons in a mobile home or than persons who attempt to drive away from their home to escape a tornado.

4. Literature Review of In-Home Shelter Design Guidelines

Above-ground in–home shelters were first proposed in Kiesling and Goolsby (1974). The rationale was motivated by observations that small interior rooms can survive a direct tornado hit as reported in a comprehensive report by Texas Tech University (Mehta 1971). In the post-disaster investigations after that tornado, it was observed that in a few houses that lost their roof and exterior walls, small interior rooms such as closets or bathrooms remained standing. Kiesling and Goolsby proposed that these rooms could be reinforced to resist tornado loads and provide protection of human life and prevent injuries. The primary design consideration is structural integrity to withstand direct wind forces and the secondary forces imposed by the collapse of the building onto the house.

Kiesling and Goolsby proposed that direct wind surface pressures could be up to 140 psf, and in addition the walls, doors and ceiling should also be able to resist penetration by wind-borne debris. The energy at impact was the criteria related to penetrating power of the missile, and the mass, ductility and shear strength were criteria defining the resistance of the shelter. The proposed design missile was a 2 in. by 4 in. wood weighing 17 lb and travelling 100 mph, but the rationale for this level is not clear.

In their proposal, the shelter door was a critical component, the storm shelter was developed with two doors, one swinging door for normal use, and a structural sliding door provided for use when the room is used as a storm shelter. Design guidelines were provided to build a storm shelter using “ordinary” building materials at a competitive cost relative to basement construction. In 1976 FEMA published TR-83A *Interim Guidelines for Building Occupant Protection From Tornadoes and Extreme Winds* (McDonald et al. 1980) that provided guidelines for reinforcing interior rooms within public buildings and other high-occupancy structures.

McDonald (1990) determined that conventional residential wall sections plywood and wood stud, and concrete masonry unit (CMU) wall sections are unable to withstand the impact of windborne debris in tornado strength winds. Impetus for in-home shelters occurred after the 1997 Jarrell, Texas tornado, directly hit the Double Creek Estates residential subdivision and completed destroyed 40 homes. This disaster was featured on national television in a National Broadcasting Company (NBC) documentary titled “In the Eye of the Tornado”. The feature showed video of testing of impact-resistant walls at Texas Tech University, the NBC documentary program, demonstrating that tornado-resistant structures rooms can be built (Rideaux 1997).

4.1. FEMA 320/361 and NSSA/ICC 500

In 1998, Federal Emergency Management Agency (FEMA) published the first edition of FEMA 320 *Taking Shelter from the Storm: Building a Safe Room Inside Your House*. This document presented prescriptive design and construction details for a concrete masonry in-home storm shelter, capable of accommodating up to 16 people. In June 2000, FEMA published FEMA 361, *Design and Construction Guidance for community Shelters (First Edition)* that provides technical guidance for the design and construction of community safe rooms to accommodate 16 or more persons.

The design philosophy behind FEMA 320 and FEMA 361, was to provide “near-absolute protection” within an above-ground tornado shelter. Near absolute protection is defined as providing a very high probability to shelter occupants of being protected from injury or death, based on current knowledge of tornadoes and hurricanes (FEMA 2008). The shelter is required to provide protection to its occupants with sufficient structural resistance for surface pressures generated by a 250 mph wind velocity and also to resist without failure, the direct impact of a 15 lb 2 in. by 4 in. wood member travelling at 100 mph at any location of the shelter, door and door hardware. Other criteria in storm shelters include the following:

- The structural resistance of the walls and doors were evaluated experimentally.
- Structure is independent of the rest of the building
- Door locks are specially designed. Doors can open inwards or outwards.
- Shelter is anchored to a foundation that has sufficient weight to resist uplift loads.
- Ventilation provided

- ADA compliant construction
- Emergency power requirements.
- Wood Shelter Details
    - Shelter foundation: Anchor shelter walls to concrete foundation using ½" anchor bolts through a double wood bottom plate, spaced 16" o.c., minimum embedment length 3", and provide with 3"x3" steel washers. A minimum of 4 anchor bolts per side required.
    - The roofing wall section will consist of 2 – 2"x6" joists 19 ¼" o.c. with 2 layers of ¾" plywood and 1 layer of 14 ga. continuous steel sheathing on the non-impact (interior) side. Fasten joist to a wood double top plate with a Simpson Strong Tie HHETA16 Truss Anchor on either side of the joist.
    - The wall section consists of double 2"x4" wood studs at 16" o.c., sheathed with 2 layers of ¾" plywood and one layer of 14 ga. continuous steel sheathing. Studs are connected with 10d nails at 6" o.c. staggered on each side of stud. Secure frame to studs with #8x3" long wood deck screws at 12" o.c. around perimeter of frame. Secure studs to the top and sill plates using a Simpson Strong Tie LGT2 connector and 2 SPH4 connectors respectively. In addition, provide 2 16d nails to fasten studs to the top and sill plates.

The National Storm Shelter Association (NSSA) in collaboration with the International Code Council (ICC) published the *ICC/NSSA Standard for the Design and Construction of Storm Shelters* (ICC-500) in 2008 (ICC 2008). FEMA 320 and FEMA 361 were used as the basis for developing the new ICC/NSSA standard. FEMA continues to support the development of consensus codes and standards that establish minimum acceptable requirements for the design and construction of hazard resistant buildings. ICC-500 updated the design and performance criteria presented in the earlier FEMA documents, and codified them through the consensus standard process. ICC-500 uses the same design wind speed maps, and other similar criteria, but still there are important differences between it and the FEMA documents, delineated in Table 6.

Table 6: Differences in design criteria between FEMA 320/361 and the ICC 500

FEMA 320/361	ICC-500 / NSSA
Use Exposure C only	Use Exposure C, with some Exposure B
Use partially enclosed design coefficients for residential safe rooms	Enclosed or partially enclosed design coefficients may be used for residential storm shelters
Hurricane debris impact criteria 0.5 x safe room design speed	Hurricane debris impact criteria 0.4 x shelter design speed
Flood design criteria restricts placement of safe rooms in designated flood zones	Flood design criteria allows placement of shelters anywhere
Peer review triggered at 50 occupants	Peer review triggered at 300 occupants

The design wind speed used in storm shelter standards are based upon the strength of a tornado design event based upon historical records (1950- present) Figure 15. The map uses four wind speed zones, 250 mph along Tornado Alley, and an annular region of 200 mph that includes Florida. The New England states and a group of centrally located states have a tornado design wind speed of 160 mph, and the remaining western states the design wind speed is 130 mph (SPC 2014). FEMA 320 uses these zones to help a homeowner assess their risk, but it provides a single structural design option regardless of the location. Additionally, FEMA 320 states that if you live in a hurricane susceptible region, your risk is considered high, even though the worksheet indicates only a moderate or low risk. FEMA 361 uses these zones for community safe room design wind speeds, but specifies the design wind speed for residential storm shelters as 250 mph, regardless of its geographical location. ICC 500 uses these zones in order to determine the wind loads on any type of shelter, and structural design is based on the wind speed.

Figure 15: Wind zones from FEMA 320 based on ASCE 7-05 criteria. These same zones are also used in FEMA 361 and ICC 500 (Source: FEMA 320)

4.2. Previous FEMA/ICC Shelter Performance

Following the 2011 tornado season, FEMA (2012) presented a study of safe rooms, hardened areas, and tornado refuge areas in residential structures. All of the safe rooms that they observed were built before the adoption of the 2009 International Building Code and IRC, which codified the requirements of ICC 500. Many storm shelters had at least one of the following deficiencies: doors and door hardware not designed or constructed to meet known wind and wind-borne debris impact criteria for life-safety protection (Figure 16), inadequate anchorage, and inadequate ventilation. There were numerous accounts of homeowners seeking shelter in basements, interior rooms or hallways which were not a safe option.

Figure 16: A hardened room in a residence Tuscaloosa, AL whose door failed in the April 27, 2011 tornado (source: FEMA (2012))

4.3. Impact Resistance Testing

Carter (1998) conducted research to quantify the impact resistance of appropriate structural wall systems for use in storm shelters. He investigated the impact resistance of 30 wood framed and three masonry composite wall systems (small specimen ≈ 24" x 30"), tested using a 15 lb 2x4 in. missile over 100 mph, which is now the accepted standard design missile for tornado resistance for regions where the Design wind speed is 250 mph (Table 7). A wood framed wall consisting of two sheets of ¾" plywood and one sheet of 16 ga. sheet metal can prevent missile from penetrating to the interior. On this basis, the so-called "near-absolute protection" storm shelter design was established.

Table 7: ICC-500 Physical Missile Criteria for Tornado Shelters

Design Wind Speed (mph)	Missile Dimensions (in)	Missile Weight (lb)	Missile Speed (mph)
130	2 x 4	15	80
160	2 x 4	15	84
200	2 x 4	15	90
250	2 x 4	15	100

Clemson University conducted a study for FEMA (Clemson University 2000) that proposed wall systems to provide Enhanced Protection from Severe Storms. The objective of this study was to design guides for wood-framed walls that improve protection of conventional light-framed wood construction. Mainly focusing on impact penetration of wall systems, several levels of construction were proposed that provided a defined percentage of the impact resistance that is provided in a near-absolute protection storm shelter. The study found that impact resistance of a composite wall is related to the resistance of the individual layers used, and so they proposed that total impact resistance, defined as highest linear momentum of the missile that the wall section resists from through-penetration, can be determined by adding up the impact resistance (as tested) of each layer. The study concluded that using common construction materials, it is possible to produce a well-anchored storm shelter, which achieves 20%, 40% and 60% of the debris impact resistance specified in the FEMA 320 guidelines.

The level of protection provided by any wall siding material can be compared with that prescribed by the ICC500 /NSSA guidelines. Figure 17, excerpted from the Clemson University report, presents the relative protection afforded by several wall materials versus that of a FEMA near-absolute protection storm shelter wall section.

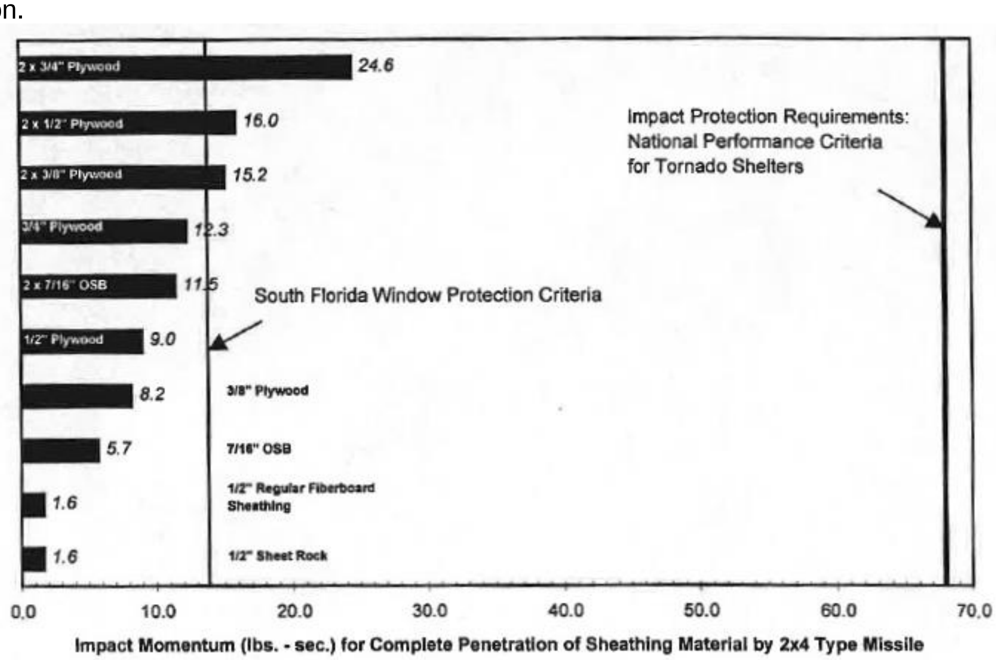

Figure 17: Impact Momentum for a 2x4 Wood Member Missile to Penetrate Common Sheathing Materials (impact perpendicular to sheathing surface) from Clemson University, 2000.

A FEMA 320 residential shelter must be capable to withstand debris impact equivalent to a 15 lb 2x4 traveling at 100 mph, or impact momentum of 68.8 lb-s. The impact resistance of conventional walls that use a ½" fiberboard sheet and ½" sheet rock was shown to be very low, (less than 5%) of that provided by a FEMA near-absolute protection storm shelter. Further, using the additive linear momentum model for impact resistance, existing conventional walls can be strengthened to meet specific impact resistance levels by incorporating additional layers of protection by retrofitting existing wall systems in a house (Clemson University 2000; Reinhold et al. 2002). A single ¾ in. plywood sheathing provides approximately one-fifth (18%) of FEMA-specified resistance. Each additional ¾ in. plywood sheathing provide an additional 18% of FEMA impact standards. Table 8 summarizes the impact resistance of several wall configurations and their comparative strengths relative to FEMA 320 storm shelter requirement. Appendix D lists some of the wall sections that were tested and their impact resistances.

A recent study by the U.S. Forest Service, Forest Products Laboratory (FPL), examined the effectiveness of various materials and wall designs for use in storm shelters. Wall systems were tested using an air cannon capable of firing 2-in. by 4-in. lumber missiles into wall sections at 100 miles per hour (Bridwell et al. (2013)). The testing mimicked the retrofitting of existing building structures to provide increased impact resistance, and it included tests on 30 panels made using oriented strand board (OSB), plywood, hardwood paneling, fiber-laminated hardboard, cross laminated timber (CLT), or bamboo composite panels. This research is in the early stages and research results are not yet available.

Table 8: Wall Debris Impact Resistance as a percentage of FEMA standards (Clemson University 2000)

Impact Resistance	**Source**	**Wall Description**
100%	FEMA 320	*100% : Linear momentum resistance = 68.8 lb-s* 2 ¾" sheets of plywood and on sheet of 16 ga. steel
	Bridwell (2013)	*102%: Linear momentum resistance = 70.6 lb-s* *5 ply Douglas-fir CLT panel*
	Carter(1998)	*100%: Linear momentum resistance = 68.8 lb-s ** 2 ¾" sheets of plywood and on sheet of 16 ga. steel
60%	Clemson (2000)	*Test Wall #34: 60%: : Linear momentum resistance = 43 lb-s ** ½" Reg. Fiberboard Sheathing, and 16 Ga. Corrugated Steel, ½" Sheet Rock
		*Test Wall #35: 58%: Linear momentum resistance = 40 lb-s ** 7/16" OSB, 2" x 8" Cavity Fill w/ 2" x 4" Blocking, and ½" plywood, ½" Sheet Rock
	Yazdani (2006)	*59%: Linear momentum resistance = 40 lb-s *** *1 sheet of 14 ga. steel*
40%	Clemson (2000)	*Test #30 40: Linear momentum resistance = 27 lb-s* ½" sheet rock and armor screen, and ½" plywood
		Test #9 - 44%: Linear momentum resistance = 30 lb-s ½" plywood and Kevlar cloth, and ½" plywood
	Yazdani (2006)	*36%: Linear momentum resistance = 24.6 lb-s *** *2 x ¾" plywood sheathing*
20%	Clemson (2000)	*Test #3 20%: Linear momentum resistance = 14 lb-s* ¾" plywood and ½" sheet rock
		Test #6 24: Linear momentum resistance = 17 lb-s ½" plywood and ½" plywood

**Did not fail*
***Did not test*

It should be noted that the impact tests addressed wall strength as limit state of impact resistance only. So far, there have been no studies to verify the wind resistance overall stability and strengths via full-scale tests. It is our opinion such tests would be required for modifying design from the FEMA and

NSSA/ICC standards.

A study by Lin et al. (2007) that investigated the trajectories of rod-like wind-borne debris, appears to question the rationale for using a design missile debris with a 100 mph upper limit (for a 15 lb 2x4). They concluded that the ratio of horizontal debris speed to wind gust speed is primarily a function of the horizontal distance traveled by the debris as it accelerates toward the tornado gust wind speed. Thus given sufficient distance of travel, a 2 by 4 linear object in flight should as a minimum approach the 3-second gust wind speed of the wind flow itself. There is limited evidence from recent tornado storm chaser data, that wind-borne debris speeds can be at least as high as 180 mph (Elsner 2014). Thus, if damaging wind-borne debris emerged only from close or adjacent structures in a sub-division and it only traveled a short distance before impact, the current theory may be valid. However, if the missile was carried along with the debris cloud encircling the vortex, it could very well have travelled hundreds of yards or more, providing sufficient time for it to approach the gust wind speed. One factor that may limit maximum velocity of wind-borne debris may be the turbulent wind conditions within a tornado that would create unsteady wind speeds acting to temper the potential maximum wind speed of the object.

Ernst Kiesling, (Kiesling 2014) Executive Director of the NSSA provides the following reasons for acceptance of current missile penetration criterion that uses a 15 lb 2x4 in board traveling at 100 mph:

- The 2 x 4 is one of the most prevalent types of debris types in urban areas, generated by buildings coming apart
- There is some conservatism in assuming that the missile strikes its target perpendicular to the face of the target and that the missile is traveling without pitch or yaw. Even a small angle of incidence upon impact makes a great difference in the tendency of the missile to perforate the target as bending is introduced into the missile causing it to fracture.
- The 2 x 4 has a greater tendency to perforate than a 2 x 6 of the same length traveling at the same speed.
- For hard surfaces such as concrete the energy of the missile is reflected back into the missile upon impact, causing the missile to shatter rather than to perforate. For those surfaces, higher missile speeds are not likely result in greater tendency to perforate. Higher speeds might increase the tendency for spalling on the back surface of the target.
- Higher speed missiles might increase the tendency for concrete to spall on the back surface of the target

4.4. FEMA/ICC Storm Shelter Alternatives

The FEMA storm shelter design guides were primarily geared towards newly constructed homes and so it is quite difficult to modify an existing house to conform to the specification of the FEMA safe room. The cost to build a FEMA safe room in a new home ranges from US$6,300-$13,500 (FEMA 2008) and building a storm shelter in an existing home would probably be 20% to 30% more.

A less expensive alternative storm shelter was proposed and tested at Florida International University (Yazdani et al. (2006)), as an economical (cost $3,100 for material and labor) hurricane-proof in-home shelter for existing homes in Category 4 hurricanes (130-156 mph) and EF 2 tornadoes (110-137 mph). The authors claimed this shelter is capable of resisting 40% of the required impact momentum for a FEMA shelter and it could be installed as a hardened interior room of an existing house. The shelter is designed so that the house will fail around it before the shelter fails.

Commercial organizations now produce multiple storm shelter designs and configurations, and prices are likely to reduce as the demand increases. Innovative use of fabric reinforcing (such as Kevlar) have enabled shelters to be sold at competitive costs (DuPont 2006). It is important that rated load capacities of walls ceiling and doors be established by testing through an independent laboratory.

4.5. Enhanced Structure for Sheltering-in-Place

The advantages and disadvantages of structurally enhancing an existing structure, versus installing or building an interior storm shelter were discussed in Reinhold et al. (2002) and summarized here in Table 9.

Table 9: Pros and Cons of Strengthening a Home vs. Installing a Storm Shelter (Reinhold et al. 2002)

	Stronger House	**Storm Shelter**
Pros	• House will remain habitable after windstorm • Easier to secure windstorm insurance • Lower premiums and smaller deductibles. • Cost increase less than 3– 6% higher in new homes	• Can provide enhanced safety and protection during an extreme wind event. • Various levels of protection available to the owner depending on budget • Material cost between $500 and $1,500 (2000 US$)
Cons	• Inspection requires removal of wall sheathing or sheet rock • If serious deficiencies, expensive and difficult to resolve • Retrofit costs to exterior envelope between $5,000 and $12,000 (2000 US$).	• Not for use in flood-prone areas. • Cannot provide security for valuables not already stored in the shelter. • House may still be completely damaged. • Does not provide near-absolute protection

Effective strengthening of an existing house is feasible, but challenging. A proper inspection usually requires removal of wall coverings, windows and connections. If material deficiencies are found in hidden areas, the costs can escalate and be more expensive that originally budgeted. Sometimes and appropriate solutions are difficult to develop and require engineering input, not normally available. The cost to retrofit the envelope of an existing home has been found to be between $5,000 and $12,000 for basic envelope-related work (Reinhold et al. 2002). Current retrofit costs for a small house can easily approach $20,000.

Wood frame homes in Florida built to the latest building code provisions performed well structurally in Hurricane Charley in 2004 (ARA 2008), because the codes now require the structure to have a continuous load path for wind loads applied to the roof and walls down to move through the structural system to the foundation. Key requirements for this load path include keeping the roof structure intact and connected to the walls and keeping the walls connected together and to the foundations. Once the roof is removed there is very little lateral load support of the walls. If the walls of the structure collapse, residents in the shelter will be more vulnerable to debris impact. Interior partitions within houses are currently not used to buttress the walls for collapsing.

In their 2011 report to the Florida Division of Emergency Management, Prevatt and Gurley, (2011), documented the costs of retrofitting of two homes in Gainesville, FL. One of the houses was a 1947 wood-framed bungalow, with wood floors and set on 3 ft tall masonry piers. The other house was a 1963 concrete masonry structure on a concrete slab. Both of these houses had small plans 1,305 sf and 2,295 sf and they did not have small interior rooms that were independent of the exterior walls that could be used to create a storm shelter. Several retrofits were therefore considered for the houses themselves to enhance the level of protection provided to occupants.

Several structural retrofits that were considered for the two houses are listed below:

- Roof Covering: The older asphalt shingle roofing system is extremely vulnerable to wind damage, and studies show roofing losses is one of the largest contributors to hurricane loss.
- Secondary Water Barrier: During re-roofing, a secondary water barrier was installed to prevent water from entering the structure through joints in sheathing.
- Gable End Wall bracing: Florida Building Code now includes methods for bracing gable end walls that provides a redundant load path for lateral loads. Gable end wall failures have been documented in tornado damage surveys (Prevatt et al. 2012) as well as in hurricanes.
- Roof to wall connections: The connection between the roof truss and wall top plate is made through metal straps.
- Soffits: Previous studies at the University of Florida on behalf of the Florida Building Commission identified water entry through soffit vents as a cause of significant water damage from wind-driven

rain (Quarles et al. 2014).

- Windows and Doors: Fenestration systems are vulnerable to wind damage and they are prone to water leakage in strong wind events. Window protection (shutters) can be provided that protect the glazing and help minimize water intrusion (Fernandez et al. 2010) .
- Garage Door Retrofit: Due to their large area and flexible connection supports garage doors are liable to fail in strong winds. Failure of a garage door can initiate progressive failures of other building components by suddenly increasing the internal pressure acting on the roof and walls.
- Structural anchors: The wall anchorage systems must be evaluated to ensure the building is adequately fastened to the ground, usually with steel anchor rods set into concrete, and large steel washers and nuts.

The retrofit costs of the two houses were $8100 and $10,470 respectively, and state-licensed residential contractors and roofers carried out the work after a selective bidding process. The University of Florida project managed the work. It was clear to the researchers that retrofit of existing houses is not an easy or straightforward, particularly when a house is occupied at the time. Contractors that include retrofit as a large portion of their business eventually would develop skills and knowledge and efficiencies, but general residential contractors are not set up to do retrofit work. The retrofits that structurally enhanced the roof to wall connections were relatively easy to install because the components were not hidden by construction or interior finishes. However, some details such as anchoring the building to the ground were beyond the budget of the project, which had an arbitrarily set limit of not to exceed 20% of the market value of the house. Intuitively it is assumed that by constructing or retrofitting existing houses with hardened building envelopes ultimately will reduce the damage caused in future wind events. Every house that remains intact will reduce the missile debris that would otherwise be produced from broken or disconnected studs, and truss components by the wind (Grayson et al. 2013).

5. Shelter-in-Place Options

Regardless of the wind speed risk found in Florida; there are several in-home shelter options available to existing homes.

Option 1: Install/Construct a FEMA shelter

Homeowners considering installing a FEMA shelter in an existing home may be more amenable to the costs, as an add-on renovation that increases the area of conditioned space, providing a dual purpose room (Chapman-Henderson 2010). The shelter should be approved for installation only in areas outside of known storm surge and flood zones. The structural integrity of the shelter should not depend on main structural system for support, and it should be capable of surviving even if the structure collapses upon it. Thus, it is recommended to install a roof on the shelter that is independent of the ceiling or roof of the building. One of the most critical components of the shelter is the provision of a certified storm shelter door. The storm shelter industry has noted a trend to replace certified door for the shelter with less expensive, but untested commercial doors. This decision can lead to death or injury should the door be hit during a tornado. At $900 – $1,500 per door, these are single most costly and important parts of the shelter. Recent media stories surrounding the 27 April 2014 Arkansas tornado have drawn attention to the unfortunate fatality that occurred in a tornado safe room when the door failed (NSSA 2014). This event was important as it could make the public question whether FEMA shelters in fact provide “near-absolute protection” as is stated in the FEMA 320 and 361 tornado design guides. The NSSA issued a statement advocating using certified doors following the 27 April 2014 Arkansas tornado incident and through its internal discussion, has determined that nearly 90% of all safe room doors installed may not be tested in accordance with the NSSA standards (NSSA 2014).

- This will provide near-absolute protection for residents against missile impact in winds up to 250 mph and protect occupants of the house should it collapse.
- Florida has a higher percentage of nocturnal tornadoes than occurs in Midwest (Hagemeyer et al. 2010).
- Most existing Florida homes do not have basements or other places of shelter.
- Can be marketed as a dual purpose room – shelter is a secondary purpose (Chapman-Henderson 2010).

Disadvantages

- Difficult to implement in existing homes, particularly if occupied at time of construction.
- May not be appropriate for long-term shelter required during hurricanes.
- May be difficult to find location in smaller existing homes for interior room.
- The cost to install in an existing structure ranges from $7,500-$16,000 (2014 US$) (FEMA 2008).

Option 2: Retrofit/Strengthen the building envelope and structural framing

Extreme wind damage from hurricanes and tornadoes show the houses tend to be very brittle structures. That is to say that when they are overloaded, they break apart suddenly and catastrophically. Thus a retrofit strategy is to provide stronger, more ductile connections that will have residual strength to stay together. The entire house can be retrofitted to the current building code to withstand design level winds in two levels. Level I retrofit includes all connections in the vertical load path, including at building envelope and between framing members (sheathing-to- roof, roof-to-wall, stud to wall plate, and wall-to-foundation connections) would be reinforced. Lateral load path connection retrofit would also be provided (i.e. gable end wall bracing to roof and ceiling diaphragm. Level II retrofitting includes mechanical connection of exterior all corner joints, and joints between selected interior partitions and exterior walls. Installation of shear panel (4 ft wide) within interior partitions (including mechanical anchors to slab, sheathing and metal ties to wall) provide a redundant load path that serves to buttress and support the exterior walls and prevent total collapse. Window and door protection is recommended, but optional (except in the High Velocity Hurricane Zone (HVHZ)).

Advantages

- Will substantially reduce property damage yet it may be insufficient to ensure life safety.
- Reinhold et al. (2002) determined the cost to retrofit the average building envelope system of a single-family home would range between $6,500-$15,800 (2014 US$).
- It can be seen that these building envelope modifications address easily accessible components, mainly located on the exterior of the home or within unoccupied attic space. Thus the retrofit costs are somewhat minimized.

Disadvantages

- The additional structural modifications proposed here (secure interior walls to foundation, strengthen interior to exterior wall connection, strengthen wall corner connections), could add a further $6000-$10000, which nearly doubles the cost to do the building envelope modifications. This increase is due mainly to the cost due to difficulty in reaching hidden components and labor and materials to restore interior rooms to the conditions before installation of the retrofits. The work would include refinishing and repainting the walls and ceiling of interior rooms.

Option 3: Retrofit/Strengthen the home to near-absolute protection.

A highly motivated homeowner may consider strengthening the entire house to provide near-absolute protection for its occupants. This would entail a structural design of systems to resist loads due to 250 mph wind gusts, and providing walls that can withstand a 100 mph missile impact (ICC 2008). Substantial upgrades to the building envelope would also be required, including replacement exterior doors rated for above-ground storm shelter use, impact glazing and window protection. While Option 3 could provide near absolute protection for all occupants from direct tornado impact, the structure would likely be extremely costly to build, making this option impractical for widespread application within Florida’s building stock. We recommend against this option, as the risk may not warrant the costs for such renovation.

Advantages

- Would provide near absolute protection for all occupants from direct tornado impact

Disadvantages

- Extremely costly to build, making this option impractical for widespread application within Florida’s building stock
- The risk may not warrant the costs for such renovation.
- Substantial upgrades to the building envelope would also be required, including replacement exterior doors rated for above-ground storm shelter use, impact glazing and window protection

Option 4: Retrofit/Strengthen the vulnerable connections and build a hardened interior room.

This option is a hybrid of Options 1 and 2, and it will strengthen the vulnerable components of a house to withstand design level winds while also providing a hardened interior room to provide life safety. The hardened shelter area may not provide the near-absolute protection of a storm shelter but it would use added structural sheathing in interior and exterior walls of the room to increase penetration resistance and provide shear capacity and bracing to remain standing should the structure be hit by hurricane or tornado loads. Thus reducing the need to evacuate and expediting the recovery process by allowing residents to begin clean up immediately after the storm. This option will reduce both damage to the house and protect the lives of the people – but it is the least well understood in terms of its structural capacity. Additional measures must be taken to allow the walls to detach from the shelter during a severe windstorm event. Notch the studs above the shelter roof to allow the house to fall away from shelter and not pull on the shelter walls.

Advantages

- Uses added structural sheathing in interior and exterior walls of the room to increase penetration resistance and provide shear capacity and bracing to remain standing should the structure be hit by hurricane or tornado loads
- Reduces both damage to the house and protect the lives of the people

- Expedites the recovery process by allowing residents to begin clean up immediately after the storm

Disadvantages

- May not provide the near-absolute protection of a storm shelter
- Least well understood option in terms of its structural capacity

5.1. Recommended Shelter-in-Place Design

Our recommended design methodology is Option 4 – to both harden the main structural systems while provided a protective interior space within the building. We call the “egg and egg carton philosophy” (Option 4), which has two goals of protecting occupants with building envelope structure primarily for impact resistance, and at the same time ensuring there is sufficient ductility, structural capacity and robustness in the main structure that will minimize the risk for the house to be *swept clean off its slab*. This philosophy accepts that such ultimate level failures still may occur but the path of such damage should be narrowed to just around the vortex of EF4 and EF5 tornadoes.

The structural framing system, or egg carton, will be strengthened to provide redundancy in the house design to prevent catastrophic destruction and absorb some missile energy. The hardened room, i.e. the egg, will be an interior room that is retrofitted to resist the missile impact and wind velocity pressures found in Florida to provide life safety. The advantages and disadvantages of the shelter must be clearly understood by the owners, the designer and the contractor. Owners should understand the limitations of using a shelter, provided the house is located outside storm surge zone or flood plain. The recommendations provided in this report were selected based on cost, ease of installation and suitability for mixed wind event climatology of Florida.

A shelter must be accessible by the occupants of the home to provide safe shelter during hurricanes and tornadoes. The provision of several shelters within a neighborhood may enable more residents to remain at or near to their property in wind event. This strategy has community-wide benefits because it would enable homeowners to be able to start repairs immediately after (and sometimes during) an event, which can minimize negative effects of water damage through delayed cleanup. Additionally, it has been observed that the more safe houses in a community, the more resilient that neighborhood will be (Grayson et al. 2013).

If possible, selecting a walk-in closet, bathroom, or small storage room as the location of a storm shelter they have the advantage of having a function other than providing occasional storm protection. Typically, these rooms have only one door, no windows (or small windows), which makes them well-suited for conversion to a safe room. Bathrooms have the added advantage of including a water supply and toilet.
Since hurricane risks dominate the Florida climatology, and in-home protection is likely to be used more frequently in hurricanes than in tornadoes. Therefore, it is recommended to provide amenities for a hurricane shelter, that include as a minimum 7-20 ft²/person, access to water, sewer and food storage supplies and power. The challenge will be to find sufficient space in an existing home to meet this provision.

Table 10: Comparison of needs for a tornado shelter vs. hurricane shelter

Tornado Shelter	Hurricane Shelter
• 2 hours of use • 5 ft²/person • Can be natural ventilation • Needs electricity	• 24 hours of use • 7-20 ft²/person • Need food • Need electricity • Need bathroom facilities • Mechanical ventilation

The shelter designs in FEMA 320 for residential structures are designed to resist wind pressures from 250 mph winds (FEMA 2008). ICC 500 states the design windspeed for a shelter in Oklahoma is 250 mph

(ICC 2008). Figure 7 shows that the Mean Recurrence Interval (MRI) for a 250 mph tornado in Oklahoma is 500,000 years. In Florida, the equivalent storm with a 500,000-year MRI is a 195 mph tornado. Thus, the case can be made that a 200 mph capacity shelter provides an equivalent level of safety to occupants in Florida as does a 250 mph shelter in Tornado Alley. ICC 500 provides guidelines to design a 200 mph residential shelter. However, the prescriptive guidelines in FEMA 320 require a 250 mph design wind speed for all residential shelters located within the United States.

Clemson University (2000) states that the cost savings of a reinforced concrete 200 mph shelter (relative to a 250 mph shelter) may be insufficient to justify the reduced level of safety. However, they have provided a procedure for design of wall systems that have a reduced structural capacity to FEMA shelters for a fraction of the cost.

As discussed in section 4.3, Lin et al (2007) questions the rationale for using a design missile debris with a 100 mph upper limit (for a 15 lb 2x4). Still, many other factors stated by Dr. Ernst Kiesling earlier provide suitable reason to accept the 15 lb 2x4 traveling at 100 mph as the Impact loading criteria for an in-home shelter designed for 250 mph. ICC 500 suggest an impact resistant wall for a 200 mph design wind speed region such as Florida should have the capacity to resist a 15 lb 2 x 4 missile travelling at 90 mph. Impact resistant wall sections as seen in Table 11 and Appendix D should be selected for the hardened area based on this impact criteria.

Table 11: Penetration Velocity of Impact Resistance Testing

	100 mph	90 mph
Clemson (2000) (9 lb.)	7/16” OSB, 2 x 8 Cavity Fill with 2 x 4 End Blocks and ½” Plywood and Sheet Rock	Vinyl Siding, ½” Plywood, ½” Floating Plywood, Treated Landscape Timbers, and ½” Durock, ½” Sheet Rock
Carter (1998) (15 lb.)	2 x ¾” Plywood and 1 16 ga metal sheet on impact side	2 x ¾” Plywood and 1 14 ga metal sheet on non-impact side
Bridwell (2013) (15 lb.)	5 ply CLT panel	-
FEMA (2008) (15 lb.)	2 x ¾” Plywood and 1 16 ga metal sheet on impact side	-

Stedman et al. (2014) observed that wind loads apply a moment to the corners that cause them to open up. The experimental results showed that the presence of brick veneer provided a significant increase in the strength and stiffness at the corners. The brick veneer increased the rotational resistance of the corner; basically decreasing maximum displacements by up to 60%. Therefore, to ensure the corners of the building do not fail they must be retrofitted with straps to resist rotation if there is no brick cladding.

Weak wall framing at gable ends is quite common. For homes with trusses the framing members are simply the vertical members (the studs) of the last roof truss. They are often 2”x4” lumber members oriented with their wide face parallel to the wall. This is the weakest direction for these members and they can be bent by the wind pressures applied to the wall. For homes with rafters and ceiling joists, the wall structure will typically be made of 2”x4” members turned so that wind forces are applied to the narrow face of the 2”x4” (the orientation with the strongest resistance to bending of the 2”x4”) The major risk is that they may not stay in place because they are only held to the rafters and ceiling joists with toe nails, nails driven at an angle through the ends of the 2”x4”. Section 1604 of the Florida Existing Building Code provides prescriptive solutions for the retrofitting of gable end buildings (FBC 2010). Homeowners should follow these guidelines to increase the resistance of existing gable end construction for out of plane wind loads resulting from high wind events.

Stedman et al. (2014) ran full scale tests on wood frame structures under extreme wind loads and concluded that when acted upon by negative pressure, the strength of interior-to-exterior wall connections directly affects the overall capacity of the exterior wall. Increasing the capacity of these connections, say by using hurricane straps or screws, would allow larger displacements of the wall and lead to failures of structural members (instead of connections) at higher wind speeds.

Windows and doors are important features of a home that provide access, egress, light and view. They are installed in openings framed into our walls and consequently are frequently referred to as "openings" in building codes and engineering standards. During a severe windstorm there is a chance of a dominant opening occurring on the windward face due to damage from windblown debris. If this happens the internal pressure will rise, increasing the load on the roof, leeward and side wall. Dao et al. (2014) analyzed failure progression of wood frame structures in the 2013 Moore tornado and found that when a house was hit by windborne debris, the internal pressure changed causing progressive damage of the structure. If a large window or door is broken open on the wall facing into the wind, the overall uplift forces that are trying to lift the roof off your house may be doubled. Window and door protection may make the critical difference between losing your roof and keeping it on.

Installing shutters over windows and doors can protect them from the impacts of windborne debris and can keep wind pressures from building up in your house to the point where it significantly increases the uplift forces on the roof. However, it probably won't keep the doors and windows from bursting open from wind pressure if they are weak or poorly anchored to the walls of the house. If possible, select a shelter location away from large openings.

5.2. Shelter-in-Place Case Study

A traditional Florida ranch style home was selected to demonstrate the recommended egg and carton design philosophy. Figure 18 shows that this traditional floor plan does not have an interior room that does not share an exterior wall where residents can seek shelter in a severe windstorm event.

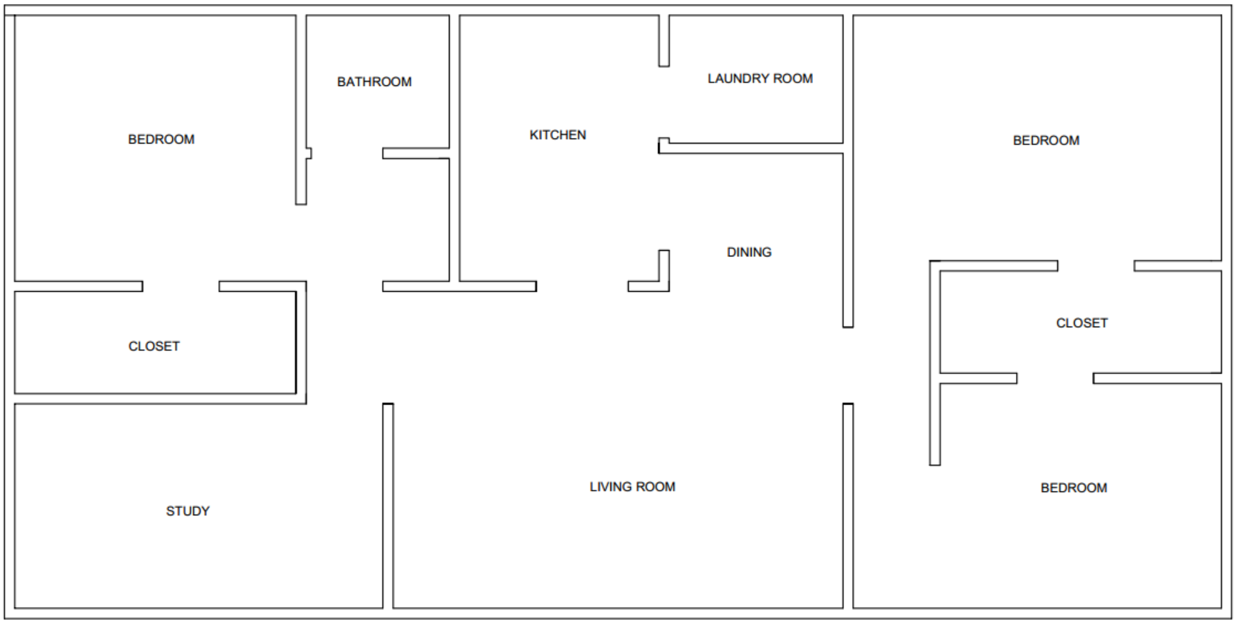

Figure 18: Ranch style home floor plan

In order to increase the structural capacity of the home and prevent complete collapse of the structure it is recommended to stiffen the interior walls at the locations specified in Figure 19. This will help resist deflection of the exterior walls and provide lateral support when the roof is removed. The corners of the house should be retrofitted to the specifications found in Appendix E in order to resist the moment forces applied to corners in a severe windstorm as seen by Stedman et al. (2014).

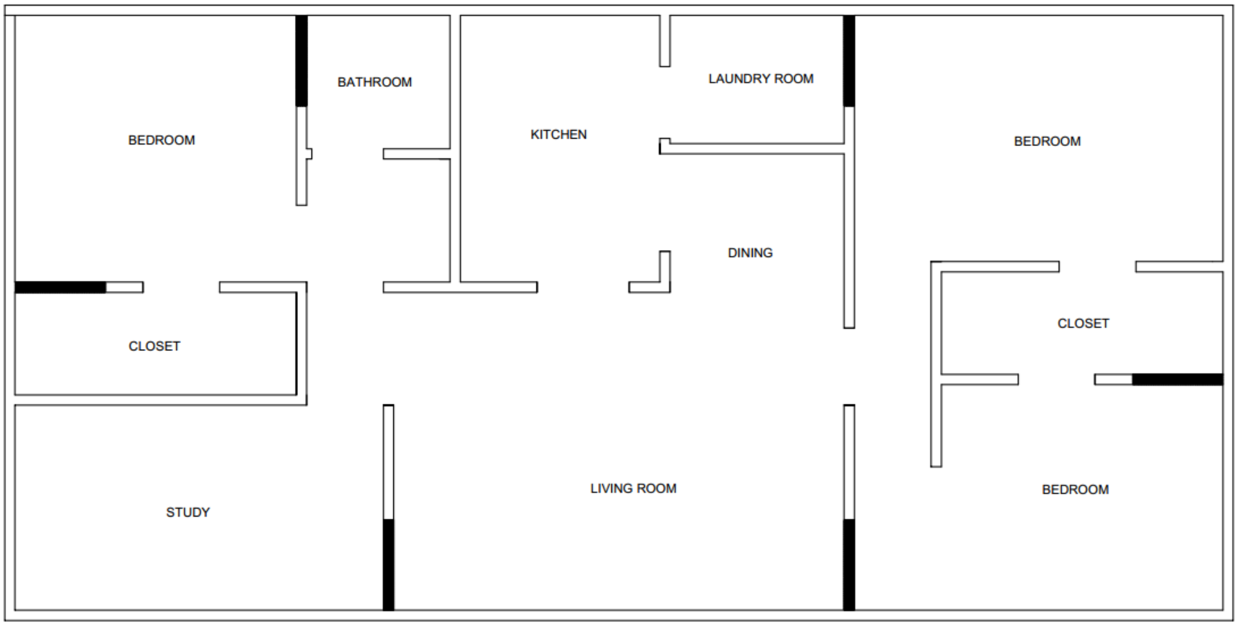

Figure 19: Floor plan with recommended location of stiffened interior walls

In order to provide life safety to the residents, it is proposed to retrofit a room in the home at one of the locations seen in Figure 20. These locations were chosen so that only a minimal area was exposed to the exterior walls to reduce risk of missile debris exposure. The size, cost, and ease of installation was must be considered when selecting a shelter location. For example, it may be useful to have water and sewage use from a bathroom during a long storm, but installing impact resistant walls around plumbing may be difficult. Shelter designs and construction details can be found in Appendix E.

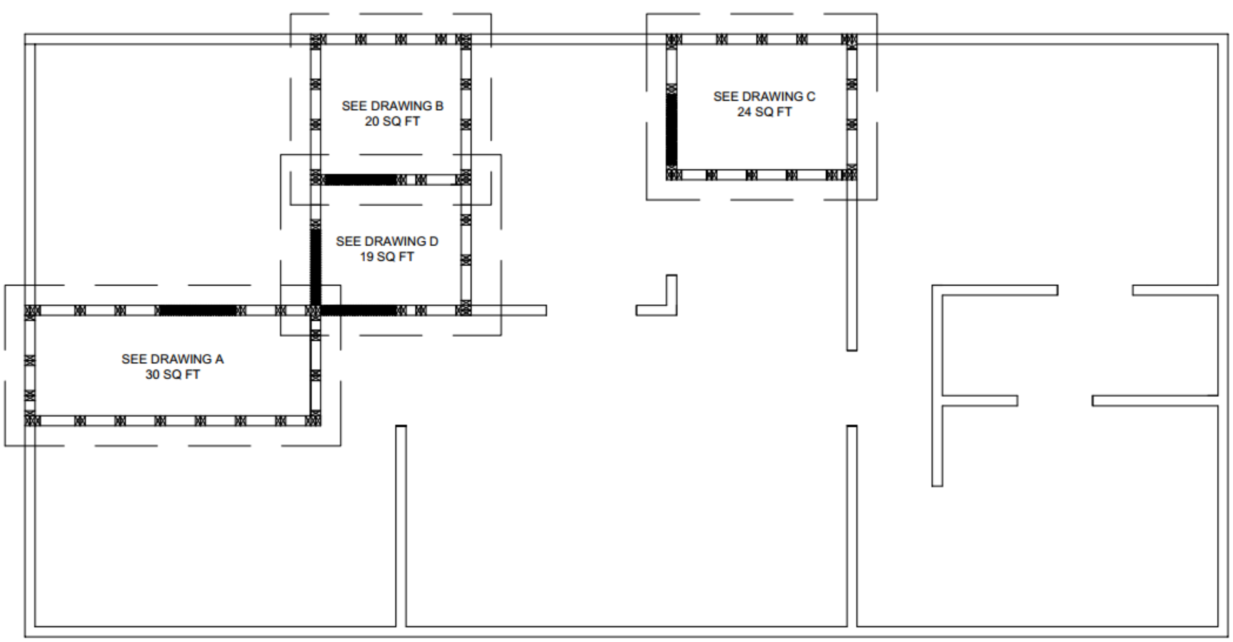

Figure 20: Storm shelter location options

6. Phase II Research: Enhanced Structural Robustness with Corner and Tee Wall Connectors

Robust Wall Corner and Intersection Details to Prevent Wall Collapse Under Wind Loads

Presented to the

Florida Building Commission
State of Florida Department of Business and Professional Regulation

by

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6.1. Issues

A literature review by the University of Florida raised the following issues about the corner and tee-joint detailing in the Florida Building Code. It appears the current approach is susceptible to disproportionate collapse once the roof structure is lost.

Problem Definition: *Evaluate strength of wall-to-wall connections and anchor details to reduce likelihood of wall collapse in single-family homes after they have lost the lateral support from the roof structure necessary to achieve an acceptable level of protection from a severe windstorm".*

6.2. Objective:

The purpose of this project is to evaluate current methods for design and construction of wall-to-wall intersections in wood-framed construction as defined by the Florida Building Code.

6.3. Relevant Sections of the Code (and related documents)

- Section R602 Wood Wall Framing (ICC 2009)
    - Table 602.3(1) Fastener Schedules for Structural Members
        - Item 7: Built-up corner studs: 10d nails at 24 in. oc.
        - Item 16: Stud to sole plate: 3-8d or 2-16d nails
        - Item 17: Top plate to stud: 2-16d nails
        - Item 18: Top plate lap at corner & intersections: 2-10d nail

6.4. Introduction

The analysis of damage investigation data from residential houses in tornadoes and hurricanes have shown a problem of a lack of robustness in the current design performance of houses subjected to high winds. Robustness as defined by Taguchi et al. (1986) is the ability of a structure to withstand (loading) events like wind or seismic forces, impact or the consequences of human error, without being <u>damaged to an extent disproportionate to the original cause</u>. In extreme wind events – Cat 3 hurricanes and above, and in EF3 to EF5 tornadoes – the loss of a roof structure can result in near complete collapse of the entire house. At its worst, a house structure may be "swept clean" from its concrete slab and foundation. One of the consequences of wall collapse when the roof is lost is that the number of fatalities and injuries significantly increase. Historically, very few deaths occur in commercial structures (European Union 1991).

Figure 21: Wall connection failures from tornado damage

It appears that while robustness as a design limit is considered in engineering design of other structures, i.e. commercial and industrial buildings, robustness is not an explicitly considered limit state for the design of houses. It is now accepted performance for houses that once the roof structure is lost for at least some or all of the exterior walls to collapse. This is a catastrophic event in itself, but this destruction is coupled with a substantially elevated risk to occupants of that building who can die or be seriously injured by collapsing walls. In the 2011 Tuscaloosa tornado, one life was lost for every 10 houses that were destroyed (Prevatt et al. 2012).

Given that the occupants have taken the best protection available within their homes, better forecasts may not significantly improve fatality rates, as nearly half of the deaths from tornadoes already occur in single-family homes. It is the catastrophic failure of the buildings that are causing fatalities. Further, it would make less of a difference for the communities in Florida, which do not traditionally have basements or cellars to provide a safe, nor are storm shelters a common feature in single-family homes.

6.5. Background on Wall Corner and Tee-Joint Construction

- Corner Framing Effect: Dolan and Heine (1997; 1997) showed that corner framing provides a hold down effect on a 40 ft long wall test.
- A small (2ft – 4ft) return can change response of a long wall, by prevented damaging cracks and separation of sheathing which reduces the load carrying capacity and stability of the house.
- Racking stiffness of walls – non-linear response to peak load, then load softening. Doudak et al. (2006). Once peak is attained progressively more displacement occurs.
- In Tuscaloosa, AL EF4 tornado there was one death for every 10 houses destroyed (Prevatt et al. 2011).
- Stedman et al. (2014) reported that large local deflections were observed in the longest unsupported wall spans of wood-frame houses. However, the length of wall at which this becomes critical is unknown, and requires further research.
- Stedman et al. (2014) also showed the strength of interior-to-exterior wall connections directly affects the overall capacity of the exterior wall. Thus placement of shear connectors between the two top plate members would increase the strength of the exterior walls.

6.6. Statement of Work – Phase 2 Testing: Corner and Tee- Joints of Exterior Walls

- Document current construction in the field of corners and tee-joints with certified residential building contractors
  - Field visits to sites to establish regional preferences for constructing exterior walls, corner stud packs and interior partition attachments to exterior walls.

  - Forensic investigation of existing home to establish historical patterns for construction (if a home can be found)
- HAPLA Pressure Tests of 8 ft by 8 ft wall sections to establish load-deflection behavior of typical and simple retrofitted connections
  - Test corner configurations with typical and retrofitted built up corner studs and sheathing connections (3 x 2 = 6 tests)
  - Test Tee-joint intersections between interior partitions and exterior wall (with typ. and retrofitted connections) (3 x 2 = 6 tests)
  - Conduct control tests on corner and Tee-joint connections with and without ceiling joist/truss in place (2 x 2 = 4 tests)
  - The simple retrofits include:
    - lag screws (versus nails),
    - metal ties at sole and top plate intersections,
    - anchor bolts for interior partition buttress panels
- Determine the ultimate resistance (wind pressure) to out-of plane wind loads of walls
- Propose design guide (code language) to specify connectors at corner and interior partition panels.
- Structural design calculation example for a typical existing building and a retrofitted one. Quantify the robustness ratio for the house
- Results of engineering analysis will be used to validate existing values or to develop recommendations for a table to replace Wall Connection details in Table R602.2(3) of the Florida Residential Building Code.
- If indicated, new values will be submitted to the Florida Building Codes as proposed code changes.

6.7. Points of Contact

- To Be Determined

6.8. Budget

Table 12. Budget (DRAFT BUDGET

Budget	Amount
Salaries	$62,662
Fringe Benefits	$18,607
Misc. (M&S, Tuition)	$20,000
Indirect cost/overhead	$15,000
TOTAL	$116,269

Research personnel time will be reported and certified using a “loaded” rate computed from the following table. Note that the indirect cost shown in Table 12 is computed from the indirect cost in Table 13 + the indirect cost associated with the travel and miscellaneous categories.

Miscellaneous costs (APPROXIMATE):

- Travel: Florida survey and select existing house layouts: $1,000
- Materials and Supplies: materials to construct structural mock-ups of in-home shelter components: $11,000
- Tuition: Graduate student tuition support: $9,000

Table 13. Breakdown of the hourly compensation rate

Person	Hours	Hourly Rate	Fringe Benefits	Tuition	IDC	Total
F. Masters	80	$70.07	$18.43	$0.00	$8.85	$97.35
D. Prevatt	180	$61.32	$16.13	$0.00	$7.74	$85.19
K. Gurley	20	$63.70	$16.75	$0.00	$8.05	$88.50
Lab Manager	180	$25.38	$8.45	$0.00	$3.54	$37.21
Admin Asst	30	$22.51	$10.24	$0.00	$3.38	$36.03
Graduate Students (1)	1500	$20.00	$14.40	$11.91	$3.28	$49.75
Undergraduate Students (0)	500	$10.00	$0.16	$0.00	$1.02	$11.18

6.9. Deliverables

- Interim report and experimental test plan by November 2014
- A summary report will be submitted to the Program Manager by June 15, 2015
- Design Guideline for Sizing and Fasteners for Corner and Tee-Joint Intersections.
- A breakdown of the number of hours or partial hours, in increments of fifteen (15) minutes, of work performed and a brief description of the work performed. The Contractor agrees to provide any additional documentation requested by the Department to satisfy audit requirements

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8. Appendix

A. SPC Tornado Dataset Sample

Tornado #	Year	Month	Day	Date	Time	Time Zone	State	FIPS #	State #	F Scale	Injuries	Fatalities	Property Loss ($)
29	1950	3	16	3/16/1950	9:15:00	3	FL	12	1	2	0	0	3
85	1950	5	8	5/8/1950	13:00:00	3	FL	12	2	1	0	0	3
105	1950	5	15	5/15/1950	11:00:00	3	FL	12	3	1	0	0	4
106	1950	5	15	5/15/1950	11:00:00	3	FL	12	4	2	0	0	4

Crop Loss ($)	Start Lat	Start Long	End Lat	End Long	Length	Width	# St's Affected	Affect other states	Tornado Segment	1 County FIPS	2 County FIPS	3 County FIPS	4 County FIPS
0	29.65	-81.22	0	0	1.5	150	1	1	1	109	0	0	0
0	29.13	-81.35	0	0	0.3	30	1	1	1	127	0	0	0
0	28.58	-81.37	0	0	0.1	10	1	1	1	95	0	0	0
0	28.5	-81.37	0	0	0.1	10	1	1	1	95	0	0	0

B. Tornado Intensity Classification

Tornadoes create complex patterns of wind flow around the vortex that have radial, tangential and vertical components. In addition, a low pressure is created at the center of the vortex, which is also believed to play a part in the damage caused by tornadoes. Due to the difficulty in predicting the locations that tornadoes will occur, there is no reliable or consistent means to pre-position wind anemometers in the path of a tornado that can measure the wind speeds that cause damage to buildings. As an alternative, tornado intensity is measured on the Enhanced Fujita Scale, which is calibrated by damage observations to estimate the wind speed producing such damage (Marshall and McDonald 2004; McDonald et al. 2009). The EF-Scale is used to estimate the peak wind speeds in a tornado by observing the damage caused to 28 so-called "damage indicators" (e.g. trees, commercial and residential buildings and other structures). Each damage indicator has a "Degree of Damage" scale that includes specific damage descriptions related to a wind speed range. Table 14 shows the difference between the EF-Scale and the previously used Fujita Scale.

Table 14: Fujita and Enhance Fujita Scale Tornado Ratings

Fujita Scale (mph)	Enhanced Fujita Scale (mph)	EF Rating
45-78	65-85	0
79-117	86-109	1
118-161	110-137	2
162-209	138-167	3
210-261	168-199	4
262-317	200-234	5

Residential structures are used as a Damage Indicator in the EF-Scale system. Designated as One or Two Family Residences (FR12), the damage indicator has 10 Degree of damage descriptions, ranging from DOD 1 (53-80 mph) to DOD 10 (165-220 mph) (Table 15) (Marshall and McDonald 2004; McDonald et al. 2009). The scale was developed to calibrate for three groups of construction quality, LB – lower bound, EXP – expected, and UB – upper bound quality. The construction quality has a direct impact on the wind speed estimates and hence EF-rating.

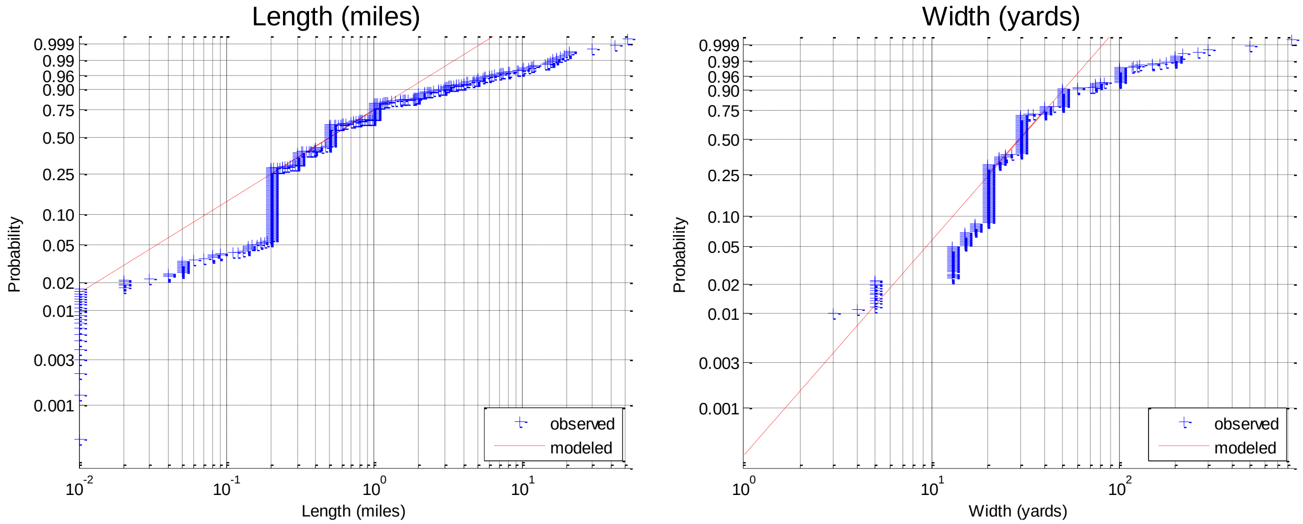
Table 15: FR12 DOD Scale

DOD	Damage Description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well-constructed residence; slab swept clean	200	165	220

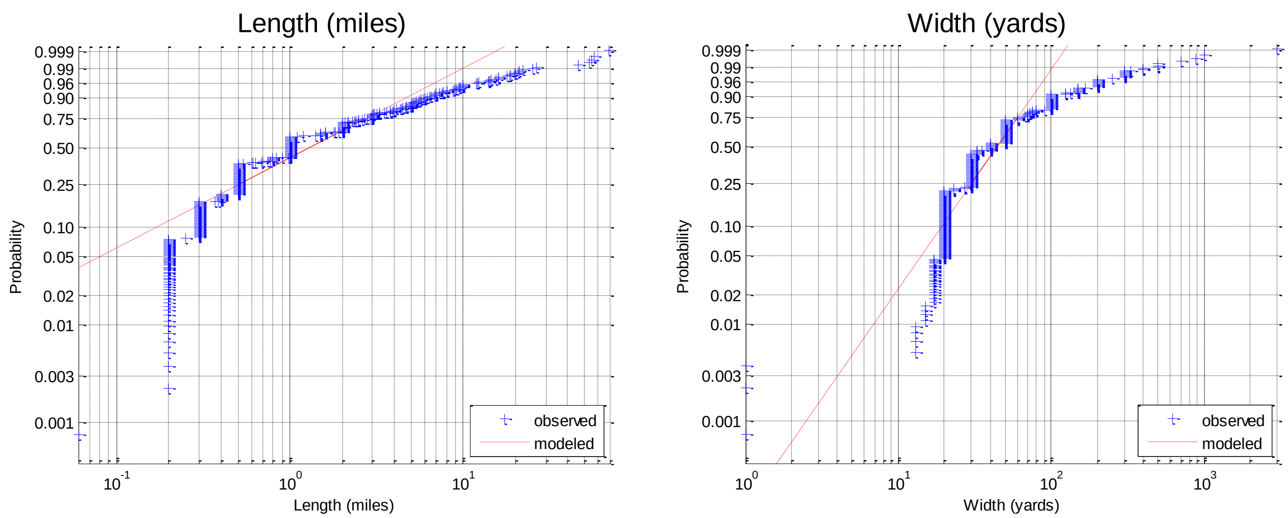
Tornadoes are ultimately rated by the highest EF-rated damage that was observed in the event (McDonald et al, 2006). In other words, when all post-tornado EF-rating values are compiled, the highest rating observed is used to classify the intensity of the tornado. Thus, an EF-3 tornado, would have at least one damage location rated at EF-3 wind speed – 138 to 167 mph.

C. Weibull Path Fit Parameters

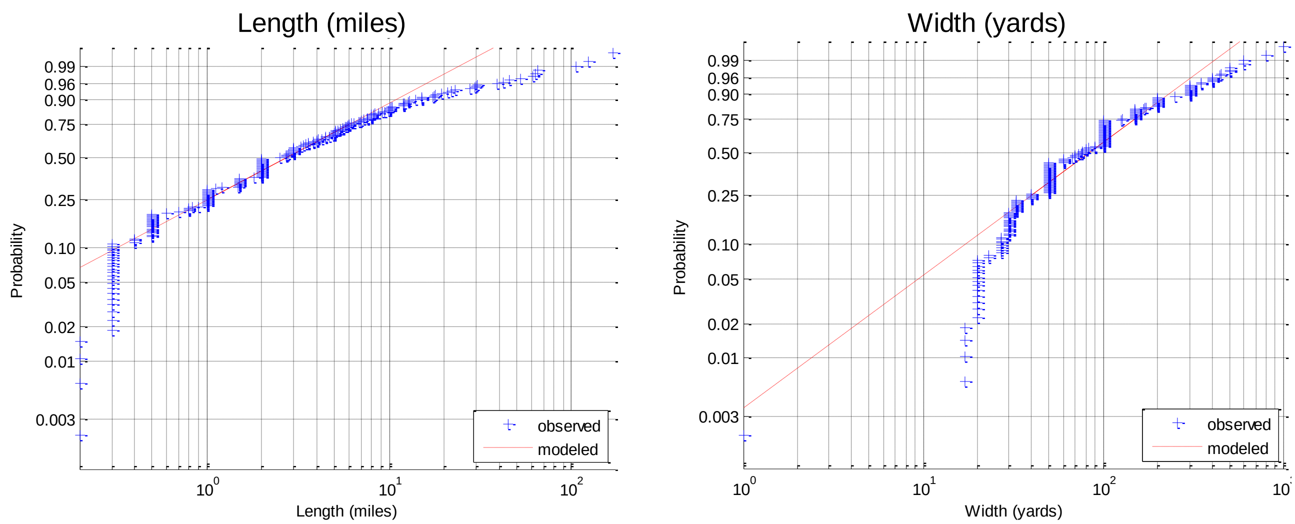
EF0



EF1



EF2



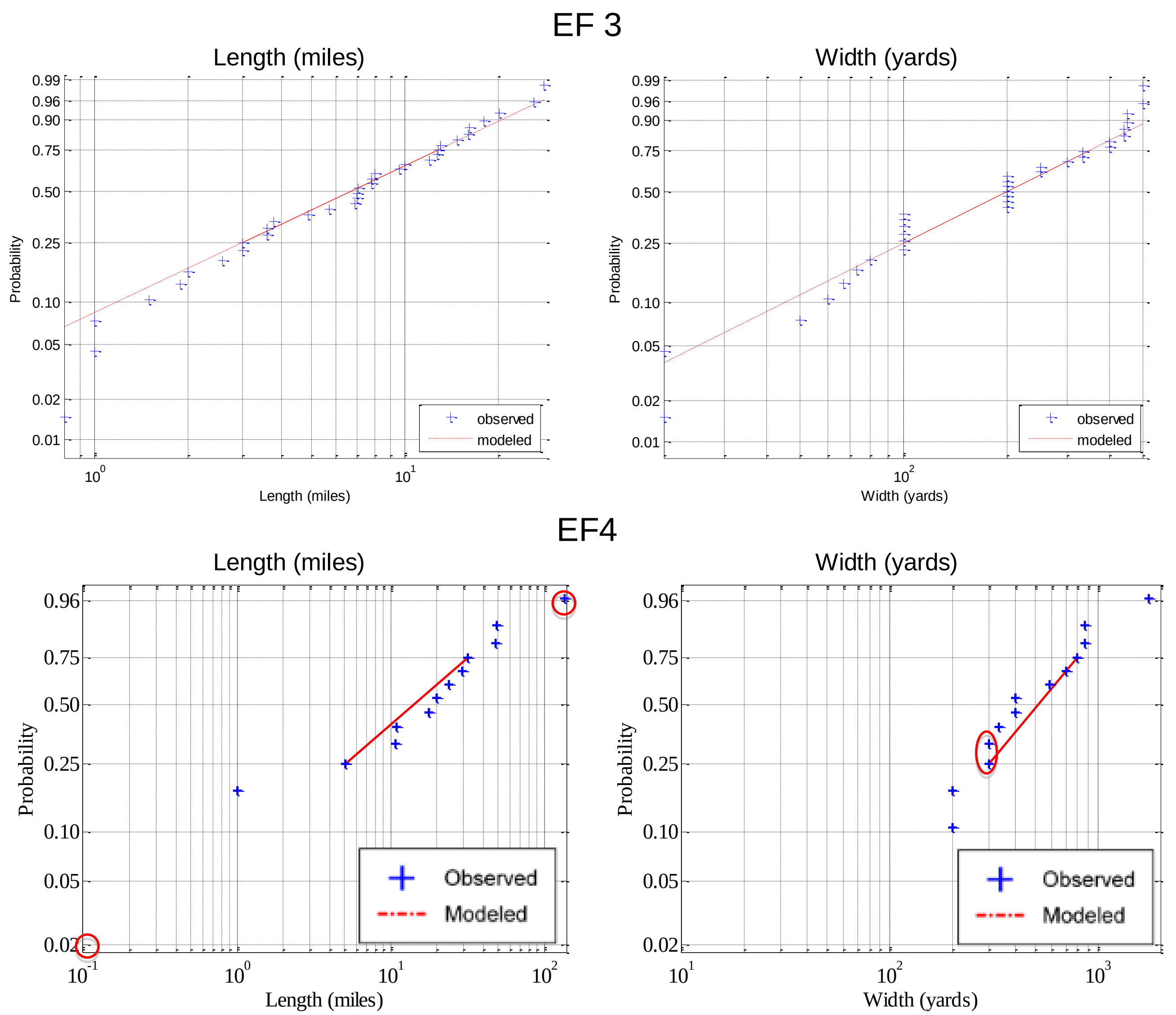
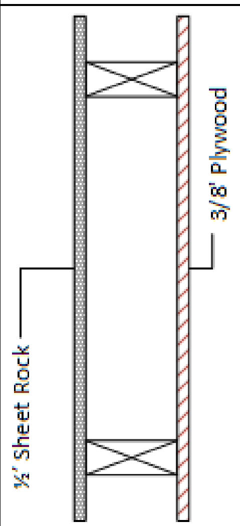
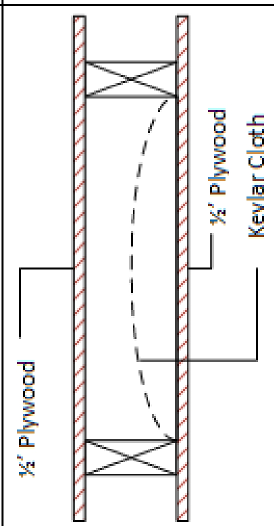
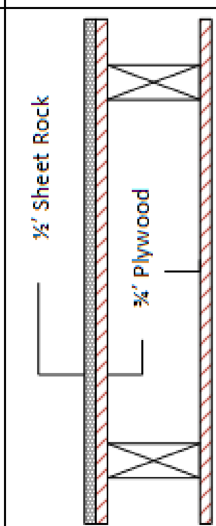
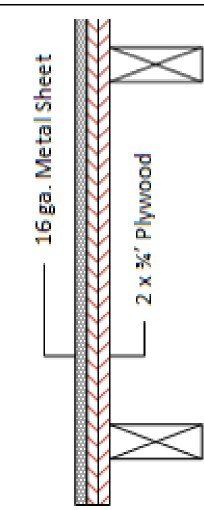
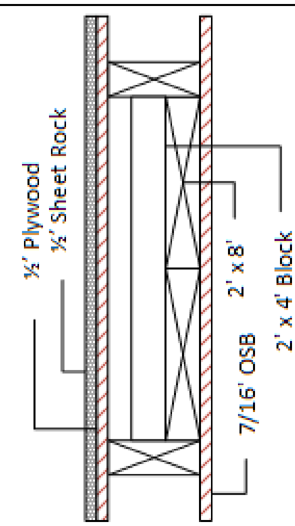
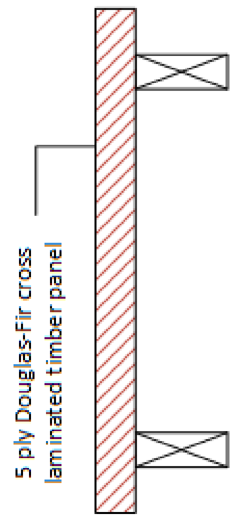
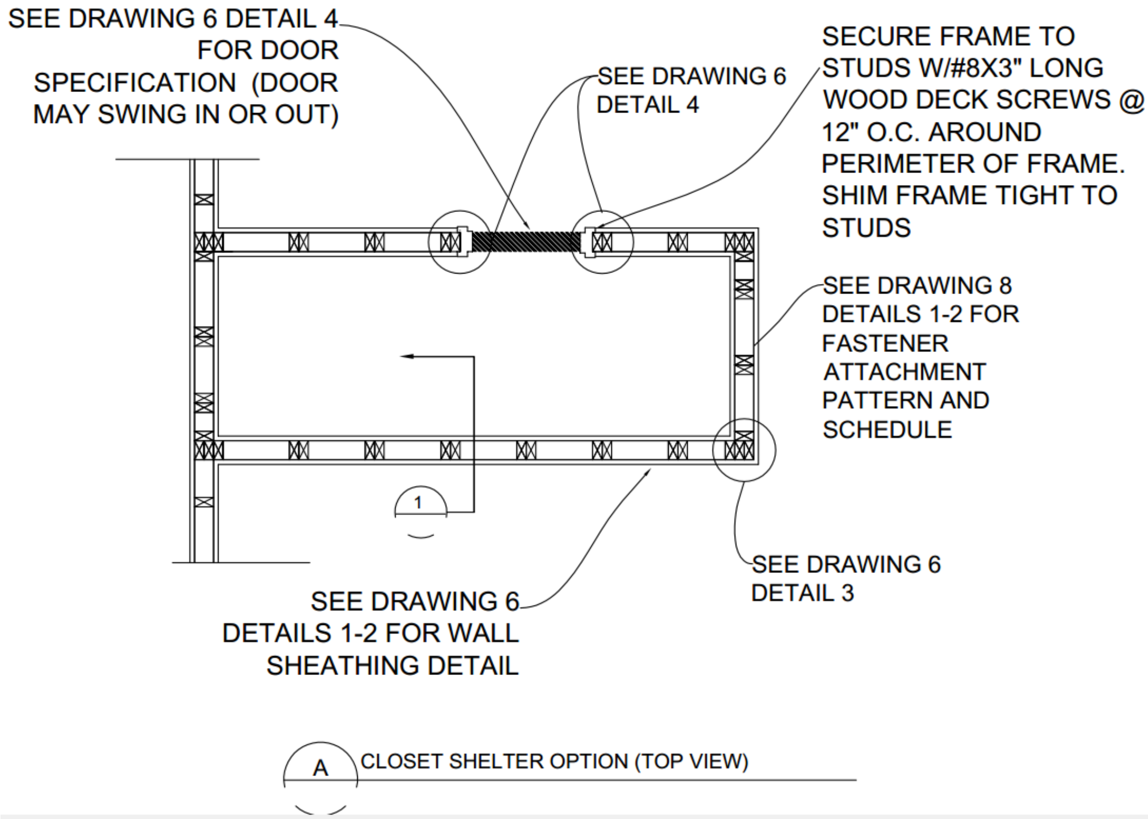


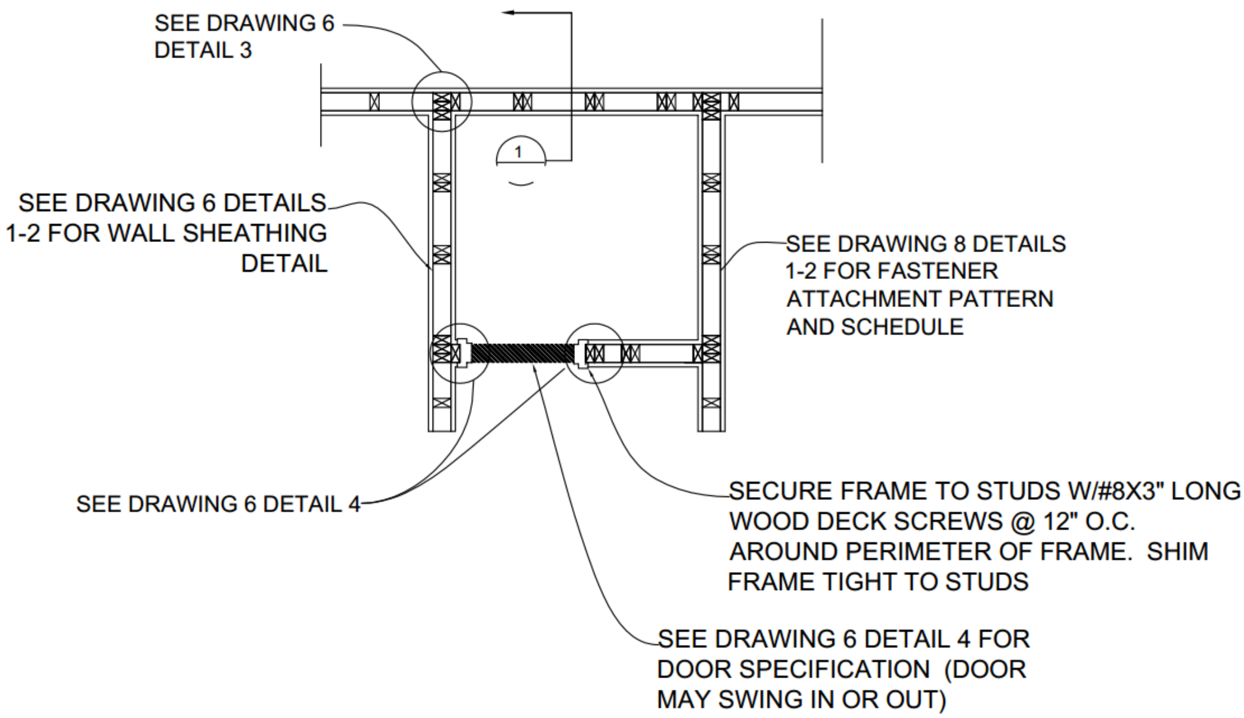
Figure 22: Path Lengths and Path Widths of Florida Tornadoes Fit to Weibull Distribution Model (Note: Since only 3 EF4 tornadoes have been recorded in Florida, tornado data for 34 EF4 tornadoes from the bordering state of Georgia was used. ○ signifies the Florida EF4 tornadoes in the database.)

D. Penetration Velocity of Various Impact Tests

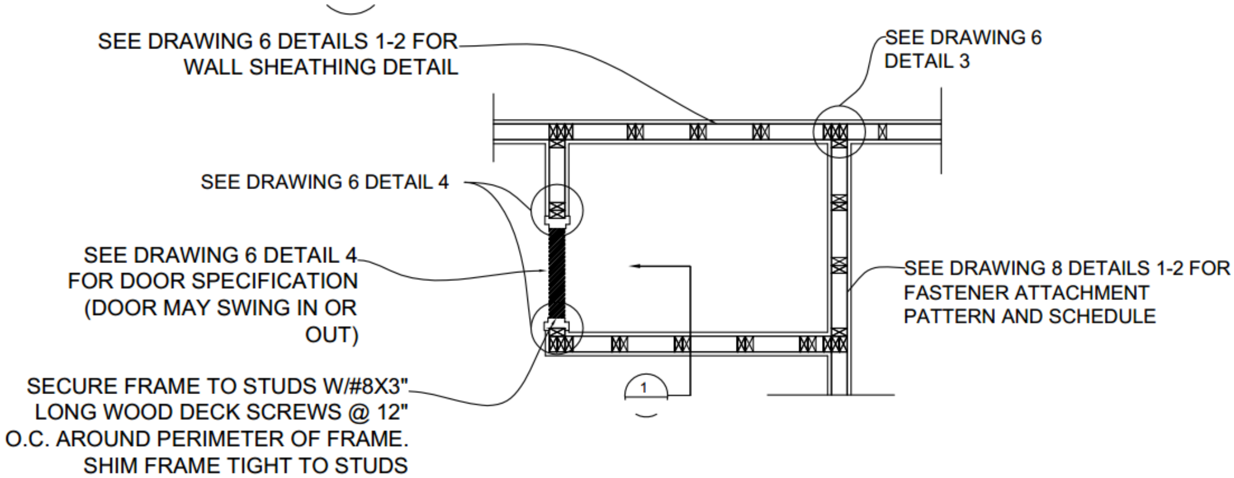
mph	Carter (1998) (15 lb 2x4 in)	Clemson (2000) (9 lb 2x4 in)	Bridwell (2013) (15 lb 2x4 in)
25			
50			
75			
100			

E. Shelter Floor plans and Construction Details

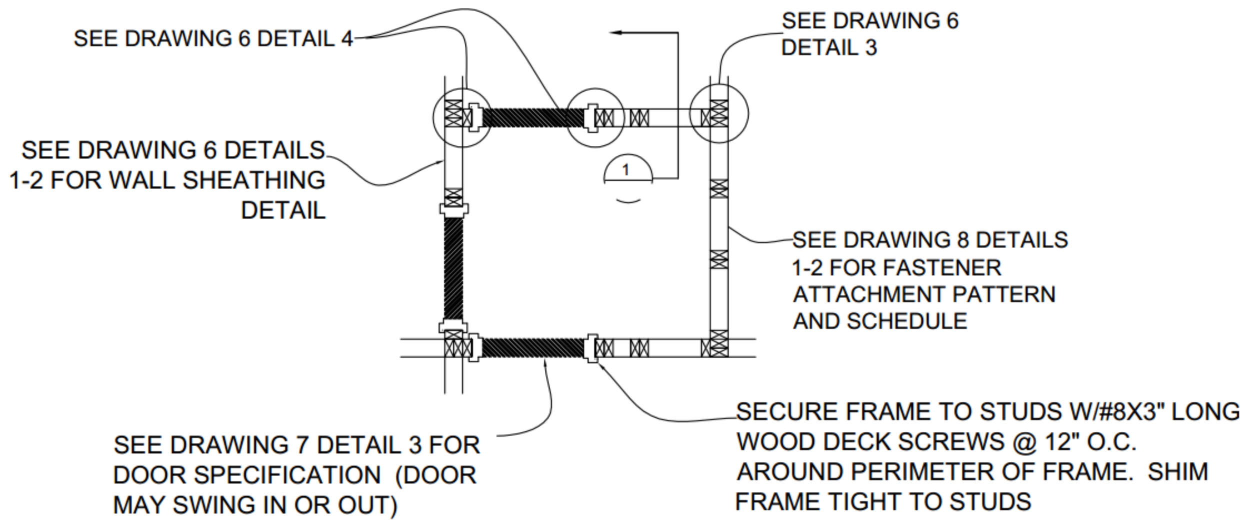




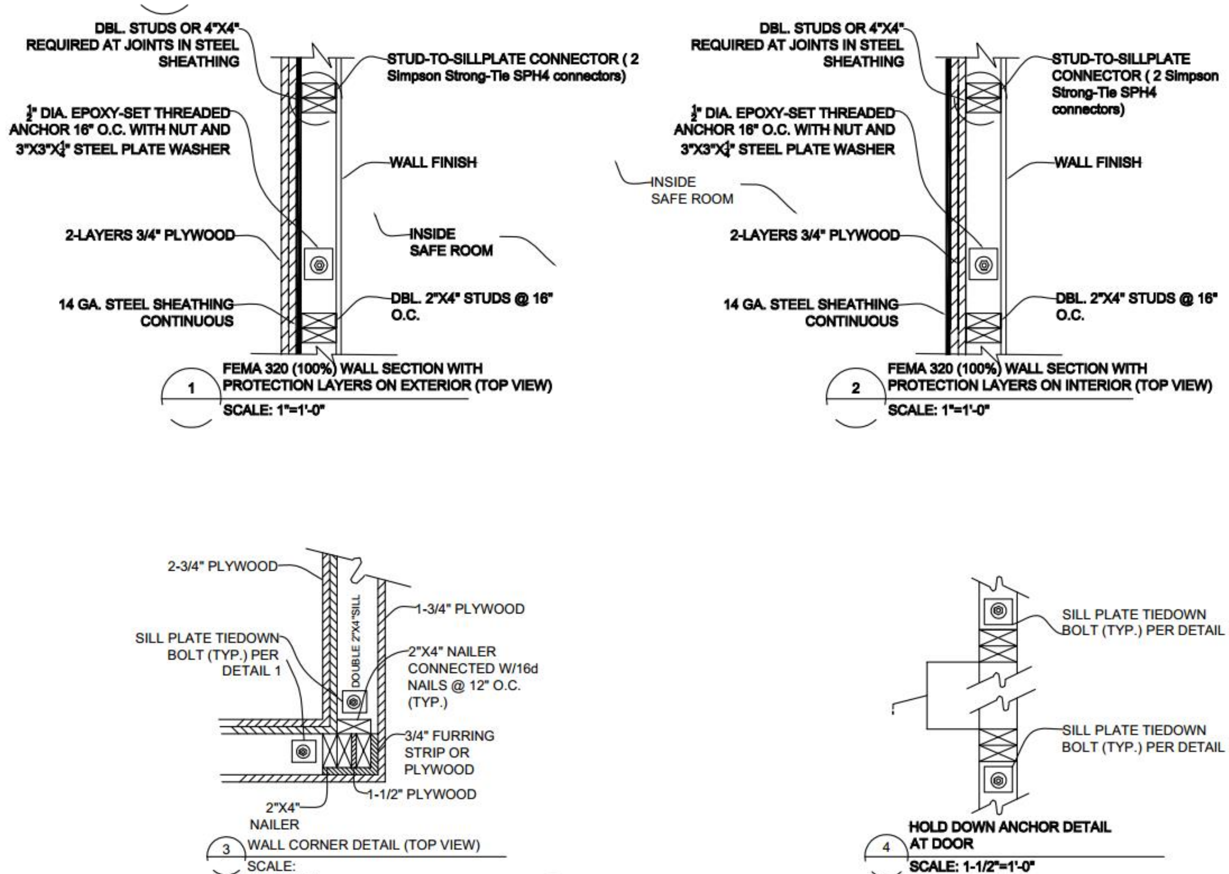
B BATHROOM SHELTER OPTION (TOP VIEW)



C LAUNDRY ROOM SHELTER OPTION (TOP VIEW)

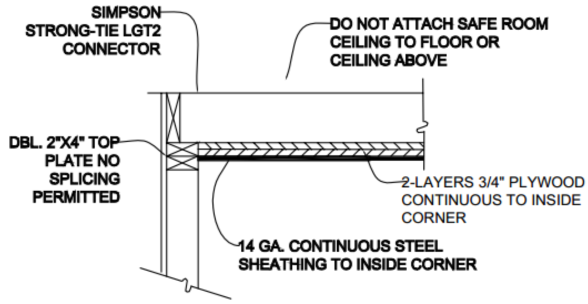


D HALLWAY SHELTER OPTION (TOP VIEW)

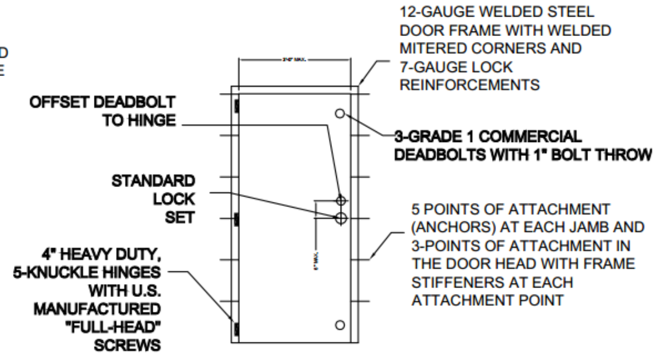


6 DRAWING 6

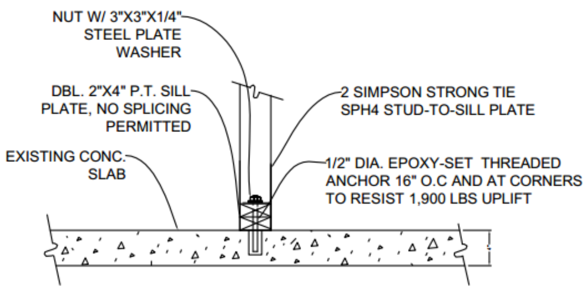
WOOD JOIST CEILING SCHEDULE	
MAX. SPAN	MAX. JOIST SPACING
8'	2-2"X6" @ 19-1/4" O.C.
14'	2-2"X10" @ 16 O.C.



1 CEILING SECTION CONNECTION

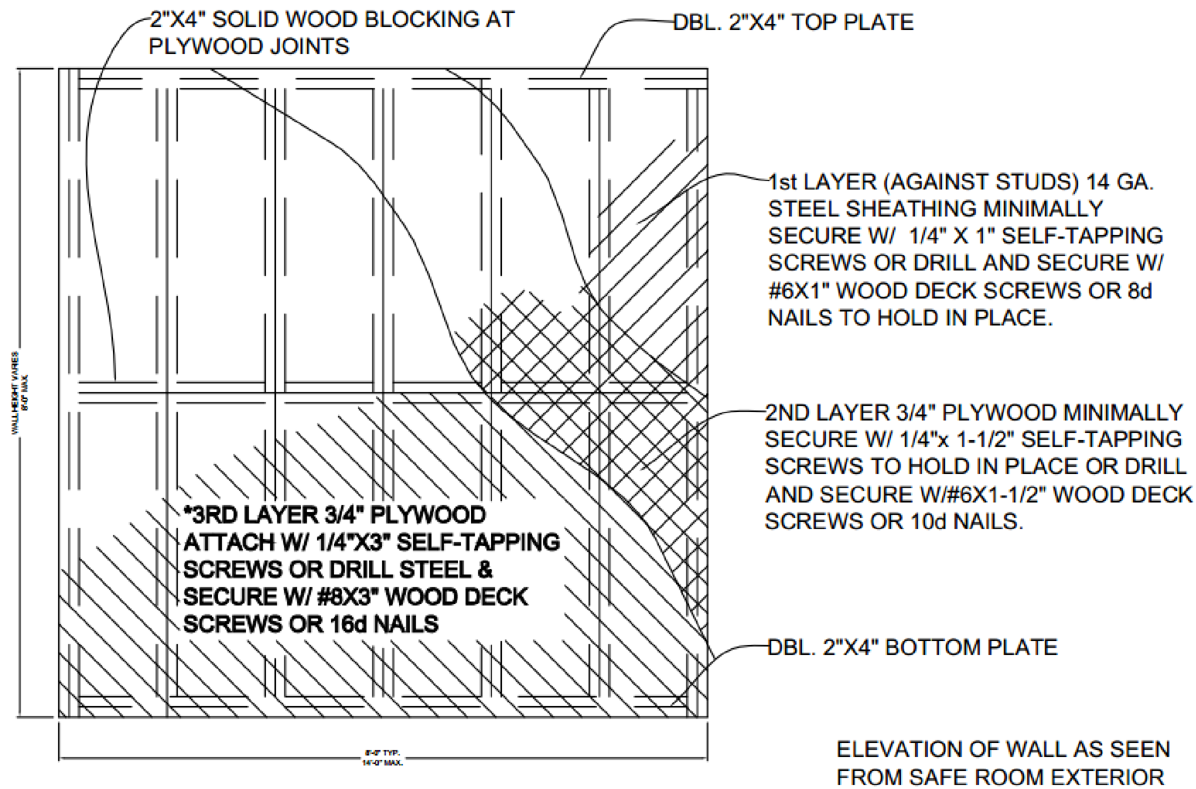


3 DOOR ATTACHMENT DETAILS (ELEVATION VIEW)



7 DRAWING 7

2 HOLD DOWN ANCHOR DETAIL
SCALE: 1"=1'-0"



1 **PLYWOOD SHEATHING ATTACHMENT PATTERN FOR SAFE ROOMS WITH PROTECTION LAYERS ON EXTERIOR**

SCALE: 1/2"=1'-0"

8 **DRAWING 8**