A Dual-Objective-Based Tornado Design Philosophy[1]

John W. van de Lindt[2], M. ASCE, Shiling Pei[3], M. ASCE, Thang Dao[4], A.M. ASCE, Andrew Graettinger[5], M. ASCE, David O. Prevatt[6], M. ASCE, Rakesh Gupta[7], M. ASCE, and William Coulbourne[8], M. ASCE

ABSTRACT

Tornadoes represent a unique natural hazard because of the very low probability of occurrence, short warning times (on the order of only a few minutes), and the intense and destructive forces imposed on engineered and non-engineered buildings. The very low-probability very high-consequence nature of a tornado strike makes designing for survival and reducing damage under typical financial constraints a substantial challenge. On April 27, 2011 an EF4 tornado devastated a 0.8 km (1/2 mile) wide path almost 10 km (5.9 miles) long through the city of Tuscaloosa, Alabama continuing on the ground for 130 km (80 miles). This paper presents the design concept that resulted following a week-long data reconnaissance deployment throughout the city of Tuscaloosa by the authors. The dual-objective philosophy proposed herein is intended to focus on both building damage and loss reduction in low to moderate tornado windspeeds and building occupant life safety in more damaging wind speed events such as EF4 and EF5 tornadoes. The philosophy articulates a design methodology that is the basis upon which

---

[1] Submitted to the *ASCE Journal of Structural Engineering,* September 2011; Revised version submitted, January 2012.

[2]**[Contact Author]** Professor and Garry Neil Drummond Endowed Chair in Civil Engineering, Department of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL, USA. Email: jwvandelindt@eng.ua.edu

[3]Assistant Professor, Department of Civil and Environmental Engineering, South Dakota State University, Brookings, SD, USA. Email: shiling.pei@sdstate.edu

[4]Post Doctoral Scholar, Department of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL.

[5]Associate Professor, Department of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL.

[6] Assistant Professor, Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL.

[7]Professor, Wood Science and Engineering, Oregon State University, Corvallis, OR.

[8] Director, Wind and Flood Program, Applied Technology Council, Rehoboth Beach, DE.

structural engineering was formed, namely provide life safety and control damage, but focused at separate tornado intensity levels.

Key Words: Tornado; residential building; natural hazard; design method

INTRODUCTION

Tornadoes, like all natural hazards, possess a full range of intensities from Enhanced Fujita (EF) 0 that removes shingles from houses to EF5 that causes total destruction. Currently in structural engineering light-frame design, tornado forces are not considered because of their very low probability of occurrence. This is the case even though the consequences of a tornado strike are severe, usually resulting in a range of damage and often fatalities. Structural engineering research studies related to tornadoes over the last four decades has consisted of studies on tornado dynamics (e.g. Davies-Jones, 1986; Lee and Wurman, 2005), wind pressure distributions (e.g. Lewellen et al, 1980; Kosiba et al, 2008; Kosiba and Wurman, 2010; and Karstens et al, 2010), and missile risk analysis (e.g. Dunn and Twisdale, 1979; Twisdale et al, 1979). Some early studies also focused on Forensics and design of structures to tornadoes (e.g. Minor et al, 1972; 1976; McDonald et al, 1974) as well as damage prediction for buildings in tornadoes (e.g. Mehta et al, 1981; Minor et al, 1978). Studies that utilized damage to buildings in the path of a tornado to develop wind speed maps and/or assessments have also been performed (e.g. Coulbourne, 1999; 2008; Prevatt et al, 2011). A substantial amount of tornado research has been done in the field of meteorology on the occurrence and formation of tornadoes (e.g. Forbes, 2006) but is not expanded on here.

Recently, Haan et al (2010) used the tornado generator at Iowa State University to compute pressure coefficients on a small-scale model of a one-story rectangular building. They determined that the side (transverse) wind pressures on the building in simulated tornadoes were 1.8 to 3.2 times those of a straight line wind, e.g. hurricane, with the same wind velocity. Components and cladding tornado-induced pressures are between 1.4 and 2.4 times that of a straight line wind with the same velocity, mainly due to the vertical suction imposed by low pressure within a tornado (these values will be used to compare failure probabilities for a basic rectangular building later in this paper). These unique characteristics, together with the localized extremely high wind speed over 200 mph, have historically made the design of building structures against tornadoes difficult to rationalize. In this study, it is proposed based on a recent damage survey of the 2011 Tuscaloosa Tornado that the design against tornado hazard should be based on dual level limit states, namely damage control for low wind speeds and life safety for high wind speeds.

BACKGROUND

April 27th, 2011 saw one of the largest outbreaks of severe weather in US history with 53 confirmed tornados in Alabama (NOAA, 2011). The supercell that spawned the Tuscaloosa tornado traveled over 480 km (300 miles) through four states, while the tornado itself was on the ground for approximately 130 km (80 miles), starting north of Union, Alabama and traveling north-east to Fultondale, Alabama. The path cut across Tuscaloosa County and the study area is as shown on the locator maps in Figure 1. The

City of Tuscaloosa was in the direct path and was bisected in a south-west to north-east direction as shown in Figure 2. The 0.8 km (1/2 mile) wide by 10 km (5.9 mile) long buffer around the center of the tornado path became the study area.

The City of Tuscaloosa has a population of approximately 93,000. This southeastern university town is primarily made up of single-story, single-family homes and light commercial structures. The tornado's path cut through neighborhoods consisting of off-campus student housing, single-family homes, two- and three-story wood-frame apartment buildings, and light commercial buildings. The majority of neighborhoods that were in the path of the tornado were post-World War II construction dating from the 1950s to the 1970s. Intermingled in these neighborhoods are newer homes and some newer multi-story, wood-frame apartment buildings.

Over 7,000 homes in Tuscaloosa County received some level of damage as a result of the tornado. Of those 7,000 homes, approximately 4,700 homes were destroyed or received major damage. Ninety-five percent of the destroyed or damaged housing units were single-family homes (Morton, 2011).

FIELD INVESTIGATION

In the days following the Tuscaloosa tornado, a team of researchers from academia and industry assembled in Tuscaloosa to collect perishable data associated primarily with wood-framed structures. Field data collection activities were conducted from May 2 through May 5, 2011. Approximately 0.8 km (1/2 mile) long transects across the path of the tornado, spaced approximately 0.8 km (1/2 mile) apart, were studied and building damage ranging from no-damage to total destruction was recorded in the form of geo-referenced photographs and detailed case studies.

Data collection activities began each day by synchronizing cameras and video equipment with Global Positioning System (GPS) units. Transects across the tornado path were then investigated throughout the day. Each evening the photos and GPS tracks were downloaded from field equipment and processed to create a nightly progress map. A custom software program developed at The University of Alabama automatically created a Geographic Information System (GIS) ready file of photo locations from the daily GPS tracks and photo times. The photo locations were then displayed as points and overlaid on a basemap of Tuscaloosa and the photos were hyperlinked to their locations. Individual building damage was rated on an EF scale based on photo evidence and specific buildings were identified for detailed case study investigations.

A map showing EF categories for buildings is shown in Figure 3 and available on the web at http://esridev.caps.ua.edu/tuscaloosa_tornado/. The degree of damage observed and documented in Tuscaloosa ranged from no building damage to damage associated with EF4 level wind speeds. As expected, it can be seen from Figure 3 that higher EF wind speeds (reds) tend to be located along the center line of the tornado, while lower EF wind speeds (greens) tend to be along the edges of the tornado path. A contour map of the EF wind speeds developed from observed building damage is shown in Figure 4. As expected, the contours in Figure 4 show that the majority of buildings in Tuscaloosa received no building damage. The area of each EF wind speed (in acres) is shown in the legend in Figure 4. It was observed that the vast majority (86%) of the affected area was at the EF2 category or lower (wind speeds below 135 mph).

DUAL DESIGN PHILOSOPHY

In this paper, a dual objective-based tornado engineering design philosophy is explained that has the simultaneous objectives of (1) reducing monetary losses due to damage (D); and (2) reducing loss of human life (L). While these objectives may seem an obvious goal for any design code related to natural hazards, an acceptable solution for light-frame buildings has not been put into practice by the design community. Consider that at the center of a tornado swath for a large EF4 or EF5 tornado there is substantial damage, potentially slabs swept clean of the residential building that once stood there, corresponding to a degree of damage (DOD) of level 10. Moving out perpendicular to the direction of travel of the tornado the DOD reduces at some gradient to a DOD of level 1, which is the threshold of visible damage (WSEC, 2006). It should be noted that the DOD's are not intended to be mutually exclusive nor absolute, i.e. they can overlap significantly.

There are two considerations or design objectives for a new tornado design philosophy: damage (D) and life safety (L). This dual design approach can be achieved using three philosophies, as shown in Table 1 and explained here: (1) Damage can be controlled at lower levels of the Enhanced Fujita scale wind speeds, i.e. EF0 and EF1, through the use of engineered connectors, design ensuring continuous vertical uplift load paths, horizontal load distribution and load paths, as well as better shingles and reinforced garage doors. This is handled typically at the component (C) design level, i.e. connectors, single load paths. (2) For wind speeds currently corresponding to EF2 and EF3, both component and system-level loading must be considered to enable better performance. System level (S) performance is related to load sharing amongst wall lines and distribution of the lateral load path as a whole throughout the building as a structure is racked by wind and amplified further by windborne debris. (3) In tornadoes with wind speeds currently corresponding to EF4 and EF5, the major issue becomes system effects and other alternatives (A) to provide life safety to the building occupants. These alternatives are safe rooms, underground shelters, and often basements, most of which assumes total devastation of the main structure. Table 1 presents the concept of design objectives and the philosophy aligning with each of the two objectives. It is important to note that the dual objectives must be used simultaneously in building design, and therefore so should the three philosophies that drive the design toward the objectives. This will ensure minimization of financial losses when possible and protection of life safety for building occupants in the worst case. No effort was made in this paper to identify what wind speeds can be reasonably (i.e. financially viable) designed for in practice beyond conceptual discussion.

DESIGN OBJECTIVES

Consider the first of the dual objectives described above, namely reducing monetary losses from tornadoes. Engineering design can reduce and in many instances eliminate the damage as described in Table 2. Each of the examples in Table 2 is linked to one of the two proposed design objectives and best addressed using either: 1) a component level (C) design philosophy, 2) a system level (S) design philosophy, or 3) an alternative (A) philosophy. Specifically, an engineering solution typically focuses at either the component level such as a connection or single wall, or at the system such as the lateral force resistance for a building. Additionally, as one can see from inspection of Table 2, an alternative approach for life safety must be considered at the high EF3 to EF5 wind speeds. Since there is obviously no way of knowing where in the swath of a large tornado the design building will be located, the three philosophies are applied at the same time to achieve the dual objectives.

A survey on the performance of existing residential structures in the 2011 Tuscaloosa tornado indicated a lack of continuous load path consistent with older construction practices and conventional construction. It is envisioned that by employing the dual-objective design philosophy, a portion of the damage that occurred due to EF2 and below wind speeds will be reduced thus resulting in a "shift" of building performance from current observation. There is a wind speed limit for which engineers rationally conclude the alternative philosophy will be a more practical solution and monetary losses are unavoidable for economically viable housing. A reduction in damage can be realized for many buildings that have historically suffered significant damage at the outer edges of large tornadoes or in smaller tornadoes. Consequently, the implementation of this dual-objective approach will result in a reduction of the width of extensive damage along the tornado path. Although the center of large tornados will still experience EF4 or EF5 level damage, there would be a steeper gradient in damage reduction to EF1 or below after moving outside the high wind speed region. In other words, an explicitly articulated dual-objective design philosophy will reduce the losses for wind speeds below some threshold while providing life safety at wind speeds exceeding that threshold. Figure 5 shows on the left a hypothetical tornado damage swath path and the performance of current residential buildings and on the right the improved swath due to the implementation of the dual-objective design achieved by applying all three philosophies, namely component, system, and alternative.

In the following section, selected photos from the Tuscaloosa tornado damage assessment are presented to illustrate several critical damage states outlined in Table 2. As illustrative examples, design and construction features that may help to shift the damage to a lower degree are discussed for each case and linked to the three design philosophies described earlier, as well as the potential level of difficulty in addressing these problems with engineering design. The potential level of difficulty in implementation is provided because one of the most significant challenges in residential construction is altering convention even when it may provide a performance improvement.

DOD2: Loss of roof covering: Loss of roof covering may be due to aging of roofing material or improper fastener schedule. With high wind-rated roof shingles and correct installation details, damage shown in Figure 6a could be reduced or eliminated. The potential difficulty of implementing this component level change is low.

DOD2: Loss of vinyl/metal siding: Siding materials are often torn off by strong wind due to geometry and improper installation details. An example of observed siding damage is shown in Figure 6b. The space between the siding and sheathing behind it often makes siding one of the first components to be damaged in strong wind, particularly siding on roof gables. Hurricane rated siding installed with fastener penetration into studs and sheathing material, can significantly increase the capacity of siding. The potential difficulty of implementing this component level change is medium.

<u>DOD3: Broken glass in doors and windows:</u> The damage to door glass and windows, examples of which are shown in Figure 7, is difficult to design against due to the high debris content within a tornado. There is no economical way to strengthen the glass components of a building envelope to prevent missile intrusion, however, the use of storm shutters may reduce windborne debris penetration for lower wind speeds, but likely not for wind speeds in excess of 140 mph. The potential difficulty of implementing this component level change is high.

<u>DOD4: Uplift of roof deck and loss of significant roof covering material:</u> Roof coverings are typically not designed for significant internal pressure. High internal building pressure is common in high wind due to breaches in a windward wall as a result of window breakage, and the same phenomenon is assumed to occur in a tornado. Significant roof damage can occur as shown in Figure 8a. Specifying a design limit state in which internal pressure is considered, and ensuring a continuous vertical load path, are mitigation strategies. The potential difficulty of implementing this component/system level change is medium.

<u>DOD4: Garage door blown inward:</u> Garage doors are a very commonly observed weak link in residential building envelopes, as shown in Figure 8b. Once a garage door fails, further breaching of the main portion of the house can occur because attached garages are often frame back into the main house. With proper detail in bracing design and use of

wind-rated garage door systems, garage door failure can be mitigated. The potential difficulty of implementing this component level change is low.

DOD4: Failure of porch or carport: A porch or carport is often an under designed extension of the roof system that creates a weak link at the interface with the main structure, i.e. where the porch or carport frames back into the main roof system. Poles supporting porches and carports are often inadequately connected to the foundation allowing for uplift and failure as seen in Figure 8c. Once these weak interfaces are designed properly, extended roofs for porches and carports will withstand wind speeds beyond 90 mph, perhaps even as high as 140 to 150 mph. The potential difficulty of implementing this component level change is low.

DOD4: Collapse of chimney: With proper lateral load design, the performance of chimneys in tornadoes can be significantly improved. Brick chimneys in old construction are typically stacked bricks or unreinforced masonry and are susceptible to collapse in tornado force winds as shown in Figure 8d. Designing for lateral loads on chimneys can be addressed relatively easily in new construction. Making chimneys part of a strong "core" for an entire wood frame building is also suggested. The potential difficulty of implementing this component level change is medium.

DOD5: House shifts off foundation: Significant wind speeds are required to shift an entire building off a foundation, even if the building is poorly anchored to the foundation. An observed example of a building shifting off a foundation is shown in Figure 9. Although engineering design can address the foundation slippage relatively easily, the level of lateral force may just damage the other structural components if the foundation holds. The design of the foundation and anchors must be done in coordination with structural lateral force resisting systems similar to earthquake systems. The potential difficulty of implementing this system level change is medium.

DOD6: Large sections of roof structure removed: Failure of the majority of the roof structure, examples of which are shown in Figure 10, may be mitigated through the use of connection hardware and non-conventional member sizes for roof trusses. This may be a good practice for custom designed or specific buildings. The potential difficulty of implementing this system level change is medium.

DOD7: Exterior walls collapsed: A safe room or shelter is the best means of protecting the lives of the occupants in the event of wind speeds in excess of 160 mph (e.g. DOD7-DOD10). The majority of exterior walls of a wood framed structure will collapse in wind with speeds in excess of 160 mph. An observed example of a building where the exterior walls collapsed is shown in Figure 11. The potential difficulty of implementing this system level and alternative method change is high.

DOD8: Most walls collapsed: An observed example of a building where most of the walls collapsed is shown in Figure 12.

DOD10: Slab swept clean:An example of an entire building blown away, leaving only the slab, is shown in Figure 13. The building in Figure 13 was a newly constructed apartment complex built in 2010. Note that even the linoleum on the floor was pealed up from the tornado.

From the discussion on DOD levels observed during the Tuscaloosa investigation it is clear that there are design measures one can take to reduce or eliminate certain levels of tornado damage on the outside edge of a tornado path. It is believed by the authors that a residential building at the center of a strong tornado cannot be designed economically to withstand tornado loads. The authors strongly believe that this does not justify ignoring the engineering measures that can be taken to reduce tornado damage for regions under certain threshold level, e.g. 135 mph, which is the vast majority of the tornado affected region, according to the survey results from the Tuscaloosa tornado.

ILLUSTRATIVE FRAGILITIES

In order to illustrate the potential effectiveness of one retrofit or mitigation technique that is commonly used in hurricane prone regions of the U.S., fragilities for two simple scenarios are developed. The first compares two different roof nail patterns where one is representative of standard coastal construction and one represents poor construction in which some field nails were missed underscoring the need for quality. The second compares the failure probability of a single and dual hurricane clip in both a hurricane and a tornado to typical toe-nailing. The house used in this example is intended solely for illustration and included four basic rooms. The plan and dimensions of the house are shown in Figure 14. The house roof is sheathed with 1.22m x 2.44m (4ft×8ft) oriented strand board (OSB) with a thickness of 12mm (15/32 inches). The roof-sheathing panels are attached to two truss members by 8d-box nails (6cm [2.375 in]) long, 0.287cm [0.113 in] in diameter). Two roof-sheathing nail patterns were investigated in this example within the context of tornado and hurricane winds: 15cm/30cm (6”/12”) (6 inches between edge nails and 12 inches between field nails) and 15cm/61cm (6”/24”). The latter of these is used here to represent poorer construction where not all roof sheathing nails hit the truss. Roof trusses are placed at 60 cm (24 inches) on center and connected to the walls by H2.5 hurricane clips.

In order to compare the probability of failure for roof-sheathing panels or roof-to-wall connections (hurricane clip) between a hurricane and a tornado, a fragility analysis was conducted in this example. In general, the failure probabilitycan be defined through the expression of the following limit state function:

$$P[G(X)<0]=\sum_{y} P[G(X)<0|D=y]P[D=y] \tag{1}$$

where D is the random variable representing the demand on the system (e.g., 3-sec gust wind speed) and $P[D=y]$ is the natural hazard probability, $P[G(X)<0|D=y]$ is the conditional limit state probability, and denotes the so-called fragility (Ellingwood et al, 2004).

The limit state describing roof panel uplift failure involves wind load and dead load and is expressed as (Ellingwood et al., 2004):

$$G(R,W,D)=R-(W-D) \tag{2}$$

where R is the resistance of the roof panel or hurricane clip to uplift (Table 3), W is the uplift wind load and D is the dead load on the panel. The wind load applied on low-rise building components and cladding can be computed as:

$$W=q_h\left[GC_p-GC_{pi}\right] \tag{3}$$

where q_h is velocity pressure evaluated at mean roof height, G is gust factor, C_p is external pressure coefficient and C_{pi} is internal pressure coefficient. Equation (3) is used to calculate the wind load induced by hurricane wind. In order to approximate tornado wind, the total pressure coefficient is scaled by a factor H to account for the increase in vertical wind velocity pressure:

$$W = q_h H \lfloor GC_p - GC_{pi} \rfloor \tag{4}$$

In this example, the factor H is treated as a random variable and its density function is assumed to be uniformly distributed over a range [1.4, 2.4] for components and cladding and [1.8, 3.2] for the main uplift wind resisting system based on the work by Haan et al, (2010). It should be noted that the pressure coefficient on the components and cladding is still larger than the main wind force resisting system even when the factor H is applied. The velocity pressure is calculated following ASCE-7 (2010) as:

$$q_h = 0.00256 K_h . K_{zt} . K_d . V^2 \tag{5}$$

where K_h is the exposure factor, K_{zt} is the topographic factor (taken equal to unity so as not to make the results dependent on local topography surrounding the building); and K_d is the directional factor (it is assumed that the wind direction is known and K_d is set to unity); and V is basic wind speed. R, D, GC_p, GC_{pi}, and K_h are taken as random variables in reliability analysis. The mean value of GC_p was evaluated by wind tunnel tests (Datin and Prevatt 2009). Statistics of random variables for wind load and dead load are presented in Table 4. It is observed from the wind tunnel test data that the largest wind pressure coefficient occurs on the roof at panel B (Figure 15) with wind direction

$\alpha_{wind} = 45^o$ (C$_p$ = 2.3). For wind direction $\alpha_{wind} = 0^o$, the largest wind pressure coefficient is at the panel A (C$_p$ = 1.47).

Figure 15 shows the fragility curves of the two panels with different nail patterns under the wind load induced by hurricane wind and the approximate tornado wind loading. It can be seen from Figure 15 that the lowest risk of failure is for panel A, nail pattern 15cm/30cm (6"/12") under the hurricane wind (the far-end curve on the right). If this panel is subjected to the approximated tornado wind, the fragility shifts to the left and is indicated by the large bold curve. Comparing these two curves, one can see that panel A with nail pattern 15cm/30cm (6"/12") almost has zero probability of failure at hurricane wind V = 224 kph (140 mph), but this panel has a probability of failure of 30% if it is under a tornado wind with the same wind velocity. The worst case is panel B with a nail pattern of 15cm/61cm (6"/24") under tornado wind, whose fragility curve is represented by the curve on the far-left end. One can see that this panel has less than 10% failure probability under hurricane wind velocity 150 kph (93 mph), but 63% probability of failure if the house is subjected to a tornado with the same wind velocity (approximately an EF1 tornado wind speed).

A fragility analysis was also used to illustrate the failure of the roof-to-wall connection. This roof-to-wall connection is close to the location where the largest wind pressure occurs and is shown in the inset images in Figure 16a and 16b. The wind direction used in the calculation is 45^o,which is the same as the wind direction that induces the maximum wind pressure on the roof. Again, the fragility curves for a single hurricane clip, double clip, and toe nailing under the wind load from a hurricane is shown in Figure

16a. Note that toe nails have a 67% probability of failing at 160 kph (100 mph) but that simply replacing them with a single H2.5 hurricane clip virtually eliminates the likelihood of failure. In a tornado, recall from the earlier discussion that the uplift and other pressures are higher than a straight line wind and thus the amplification factor was modeled as a uniformly distributed random variable based on the range given by Haan et al (2010). Although this is approximate and clearly additional work is needed, it is applied here to help introduce the additional uncertainty associated with tornado wind loading into the resulting fragilities. It can be seen that if the roof truss is connected to the wall with a H2.5 hurricane clip, the probability of failure for the hurricane clip is about 49% to 89% if loaded by an EF2 tornado (expected wind speed range of 111 – 135 mph). If two H2.5 hurricane clips are used, and assuming the wood truss can develop the full force in the connectors, there is only approximately a 2% to 18% failure probability in an EF2 tornado. This illustrates the damage reduction possibility for a single damage mechanism through the use of hardware. Finally, it should be noted that in the tornado pressure calculations the building was assumed to have been breached whereas the envelope was assumed to remain intact in the hurricane pressure analysis.

FUTURE STEPS FOR RESIDENTIAL LIGHT-FRAME CONSTRUCTION

The low probability of tornado occurrence combined with the high consequences of a tornado strike make for a very challenging load scenario to consider in structural design. Unlike straight line winds, it is difficult to attach a specific probability to tornado wind speed at a specific building site because of the low occurrence rate. There are also studies (e.g. Haan et al, 2010) that show tornado loading has a significantly stronger vertical component than straight line winds, even when the horizontal wind speeds are the same, as illustrated in the fragility assessment presented earlier. Several critical issues need to be addressed before the structural engineering community can develop and implement a dual-objective design philosophy for tornado hazard mitigation of residential buildings. Some of the most important issues include:

<u>Issue 1:</u> Identify realistic threshold wind speeds that a light-frame wood building can resist. A systematic study needs to be conducted that focuses on the optimal threshold tornado wind speed for which engineers should be designing a system. This requires a thorough survey of possible improvements and design options that are practical and the corresponding wind speed at which these measures will be valid. A study should also be conducted on the cost-benefit ratio of these design options at various wind speeds to inform the calibration of the new dual-objective tornado design philosophy. This threshold is highly dependent on the structure type and acceptable probability of failure. For economically viable residential buildings it is likely to be in the 120~150 mph range.

<u>Issue 2:</u> Develop a better understanding of the spatial characteristics of tornado loading. The current understanding of tornado loading on structures is not comprehensive or even comparable to that for straight winds because of the high level of turbulence and debris in a tornado. This is partially due to the lack of experimental procedures to accurately represent tornado loading. Unlike widely adopted scaled wind tunnel testing for wind loading on structures and components, the spatial characteristics of the loading on buildings within a tornado path are very difficult to experimentally investigate. In addition, how the lateral wind pressure combined with suction acts on different

components of a structure is unknown, although some work has been performed in this area. Applying design methods from straight wind cases will likely improve the resistance of buildings against tornadoes; designing using realistic and quantifiable tornado loading is most desirable. Studies on tornado loadings should be focused on scaled experimental work, numerical simulation, and continued in-situ tornado data collection.

<u>Issue 3:</u> Acceptable and implementable approaches in design and construction of residential buildings to reduce tornado damage. A suite of design and retrofit measures should be developed to reduce structural and component damage up to the threshold wind speed. The measures for design and retrofit can be very different and may take many forms including adjustment factors for loading, prescriptive requirements, innovative analysis procedures, and additional load cases (such as the breached garage door case for attached garage wall and roof design). Available products on the market for residential construction must back measures that can be implemented by the current residential construction industry, possibly with minimal training. Implementing hurricane region construction practices and products in tornado prone regions is a good starting point, but not necessarily an end solution.

<u>Issue 4:</u> Shelters or safe rooms for extreme wind speeds. For wind speeds exceeding the design threshold, the alternative of a shelter or safe room can provide life safety to building occupants. The shelter must be designed to handle both wind pressure and debris impact as in the current guidelines (FEMA 320 and FEMA 361) to build safe

rooms and shelters. These can be built per FEMA recommendation and their increased use should be further enabled in more for tornado prone regions. Shelters should be included at the same time as the component and system philosophies are implemented as discussed above.

Summary and Recommendations

Tornados are very low-probability but very high-consequence natural hazard events which makes designing for survival and mitigating damage under typical financial constraints a substantial challenge. However, a dual objective-based design philosophy for residential buildings can reduce damage and save lives by focusing on separate tornado intensity levels. The performance of buildings: (1) at EF0 and EF1 wind speeds can be improved at the component level (i.e., connections), (2) at the EF2 and EF3 wind speed design can be improved at the system level (e.g., shear walls, load paths), and (3) at EF4 and EF5 wind speedlife safety can be provided using alternate means (e.g., safe rooms). The Tuscaloosa, Alabama tornado of 2011 was used as an example throughout this paper to systematically explain the concept. However, several critical issues have to be addressed before this dual-objective design philosophy for tornado hazard mitigation can be realized, e.g., identification of realistic threshold wind speeds, better understanding of the spatial characteristics of tornado loading, acceptable and implementable approaches in design and construction to reduce tornado damage, and implementation of shelters or safe rooms for extreme wind speeds.

Acknowledgements

The National Science Foundation provided partial support for damage analysis following the April 27, 2011 Tuscaloosa Tornado through RAPID Grant CMMI-1139722. The first author also acknowledges the Drummond Chair funds at the University of Alabama.Thanks also to the students from the University of Alabama and the University of Florida for their participation.

References

ASCE; “ASCE 7-10: Minimum design Loads for Buildings and Other Structures:, Am. Soc. Civil Engineers, Reston, VA

Coulbourne B. (1999). “Midwest Tornadoes of May 3, 1999: Observations, Recommendations and Technical Guidance. Building Performance Assessment.”, Federal Emergency Management Agency; Washington D.C.

Coulbourne W.L. (2008). “Wind speed analysis of greensburg, KS Tornado”. Proc. 2008 Structures Congress: Crossing Borders, April 24 - 26, 2008. Vancouver, BC, Canada: American Society of Civil Engineers; Reston, VA.

Datin, P. L.and Prevatt, D. O. (2009).“Equivalent Roof Panel Wind Loading for Full-Scale SheathingTesting.”*Paper presented at the 11th Americas Conference on Wind Engineering, Puerto Rico.*

Davies-Jones R.P. (1986). “Tornado dynamics. Thunderstorms: A Social and Technological Documentary”. Ed by Kessler E., University of Oklahoma; 197-236.

Dunn, W.L. and L.A. Twisdale. (1979). “A Synthesized Windfield Model for Tornado Missile Transport.”, *Journal of Nuclear Engineering and Design*; 52.

Ellingwood, B. R., Rosowsky, D. V., Yue, Li S., and Kim, J. H. (2004). “Fragility Assessment of Light-Frame Wood Construction Subjected to Wind and Earthquake Hazards”, *ASCE Journal of Structural Engineering*, 130(12): 1921-1930.

FEMA 320: “Taking Shelter From the Storm: Building a Safe Room For Your Home or Small Business”, Federal Emergency Management Agency, Washington D.C., 2008.

FEMA 361: “FEMA 361 - Design and Construction Guidance for Community Shelters”, Federal Emergency Management Agency, Washington D.C., 2008.

Forbes, G. (2006). “Meteorological Aspects of High-Impact Tornado Outbreaks.”, *Proc on the Challenges of Severe Convective Storms*, AMS, Atlanta, pg 1-12.

Haan, F.L.Jr, V.K. Balaramudu, and P.P. Sakar. (2010). “Tornado Induced Wind Loads on a Low-Rise Building.”,*J. of StructEngrg*, 136(1), 106-116.

ICC 600-08 “Standard for Residential Construction in High Wind Regions”, International Code Council, Washington D.C.

IRC (2009).International Residential Code for One- and Two-Family Dwellings, International Code Council, Washington D.C.

Karstens, C.D., T.M. Samaras, B.D. Lee, W.A. Gallus, Jr., and C.A. Finley. (2010). “Near-Ground Presure and Wind Measurements in tornadoes.”, Monthly Weather Review; 138; 2570-88.

Kosiba K.A., R.J. Trapp, and J. Wurman. (2005). “An analysis of the axisymmetric three-dimensional low level wind field in a tornado using mobile radar observations.” *Geophysical Research Letters*. 35.

Kosiba K.A. and J. Wurman. (2010). “The three-dimensional axisymmetric wind field structure of the Spencer, South Dakota, 1998 Tornado”. *Journal of the Atmospheric Sciences,* 67; 3074-83.

Lee W-C and Wurman J. (2005). “Diagnosing new details about tornado dynamics”. *Bulletin of the American Meteorological Society*; 86; 1547-50.

Lewellen W.S., M.E. Teske, and Y.P. Sheng. (1979). "Wind and Pressure Distributions in a Tornado". *Proc of the 5th International Conf on Wind Engineering*, Colorado State University, Fort Collins, CO.

McDonald, J.r., k.C. Mehta, and J.E. Minor. (1974). "Tornado-Resistant Design of Nuclear Power Plant Structures.", *Nuclear Safety*, 15(4), 432-439.

Mehta, K.C., J.r. McDonald, and D.A. Smith. (1981). "Procedure for Predicting Wind Damage to Buildings.", *Journal of the Structural Division*, ASCE, ST11(107); 2089-2096.

Minor, J.E., J.R. McDonald, and K.C. Mehta. (1978). "The Tornado, an Engineering-Oriented Perspective.", U.S. Dept. of Commerce, NOAA, Springfield, VA.

Minor, J.W., K.C. Mehta, and J.r. McDonald. (1972). "Failure of Structures Due to Extreme Winds.", *Journal of the Structural Division*, ASCE, 98(ST11), 2455-2472.

Minor, J.W., K.C. Mehta, and J.r. McDonald. (1972). "Air Flow around buildings as Reflected in Failure Modes.", *ASHRAE Transactions*, 82(1), 1061-1071.

Morton, J., 2011, Tuscaloosa News May 17, 2011, "Red Cross Tallies Damage Destroyed Homes," http://www.tuscaloosanews.com/article/20110517/NEWS/110519753?Title=Red-Cross-tallies-damaged-destroyed-homes

NOAA, 2011 http://www.srh.noaa.gov/bmx/?n=climo_2011torstats

Prevatt DO, van de Lindt JW, Graettinger A, Coulbourne B, Gupta R, Pei S, Hensen S and Grau D. Damage Study and Future Direction for Structural Design Following the Tuscaloosa Tornado of 2011 University of Florida 2011.

Texas Tech (2006), *A Recommendation for an Enhanced Fujita Scale*, Wind Science and Engineering Center, Texas Tech University, Lubbock, Texas.

Twisdale, L.A., W.L. Dunn, and T.L. David. (1979). "Tornado Missile Transport Analysis.", *Journal of Nuclear Engineering and Design*; 51.

van de Lindt, J.W., A. Graettinger, R. Gupta, T. Skaggs, S. Pryor, and K. Fridley. (2007). "Performance of Woodframe Structures During Hurricane Katrina."*ASCE Journal of Performance of Constructed Facilities*; 21(2); 108-116.

WFCM-01 " Wood Frame Construction Manual for One- and Two-family Dwellings," American Forest and Paper Association.

Table 1: Design Objectives and Philosophy Considered as a Function of Wind Speed

	Enhanced Fujita Scale Winds (3-sec gust)					
Methodology Proposed	EF0 (65-85)	EF1 (86-110)	EF2 (111-135)	EF3 (136-165)	EF4 (166-200)	EF5 (>200)
Design Objective Damage (D)/Life Safety (L)	D	D	D/LS	D/LS	LS	LS
Philosophy Considered Component (C)/System (S)/Alternative (A)	C	C	C/S	S	S/A	A

Table 2: Dual design objectives, philosophy, and examples of Engineering/ Construction Improvements

Proposed Design Objective	Philosophy	DOD[1]	Damage Description	Example Engineering and/or Construction Improvements
Damage Mitigation	Component	1	Threshold of visible damage	N/A
		2	Loss of roof covering	Use manufacturer recommended number and placement of fasteners for high wind shingles.
		2	Loss of vinyl/metal siding	Use high wind-rated siding and ensure fastener penetration into studs (not board of any kind).
		3	Broken glass in doors and windows	Use hurricane rated windows and doors. This is not necessarily effective against windborne debris impact, but minimizes loss of building envelope.
		4	Uplift of roof deck and loss of significant roof covering material	Use hurricane clips on both sides of truss, 2x6 trusses, heavier nail schedule on roof sheathing, add blocking for short edge nailing of roof sheathing.
		4	Collapse of chimney	Better connection to the structure.
		4	Garage door blown inward	High wind-rated garage door and track system.
	Component / System	4	Failure of porch or carport	Ensure continuous vertical load path through engineered metal connectors from roof into foundation.
		5	House shifts off foundation	Ensure adequate number and placement of anchor bolts, use steel hold downs, 2x6 sill plates with washers.
	System	6	Large sections of roof structure removed	Ensure connection between trusses/rafters to wall top plates. Space trusses at 16” oc and line them up with vertical wall studs.
Life Safety		7	Exterior walls collapsed	Closer nail schedule for shear capacity, provide full anchorage for all walls; safe room or shelter.
	Alternative	8	Most walls collapsed	Safe room or shelter.
		9	All walls collapsed	Safe room or shelter.
		10	Slab swept clean	Safe room or shelter.

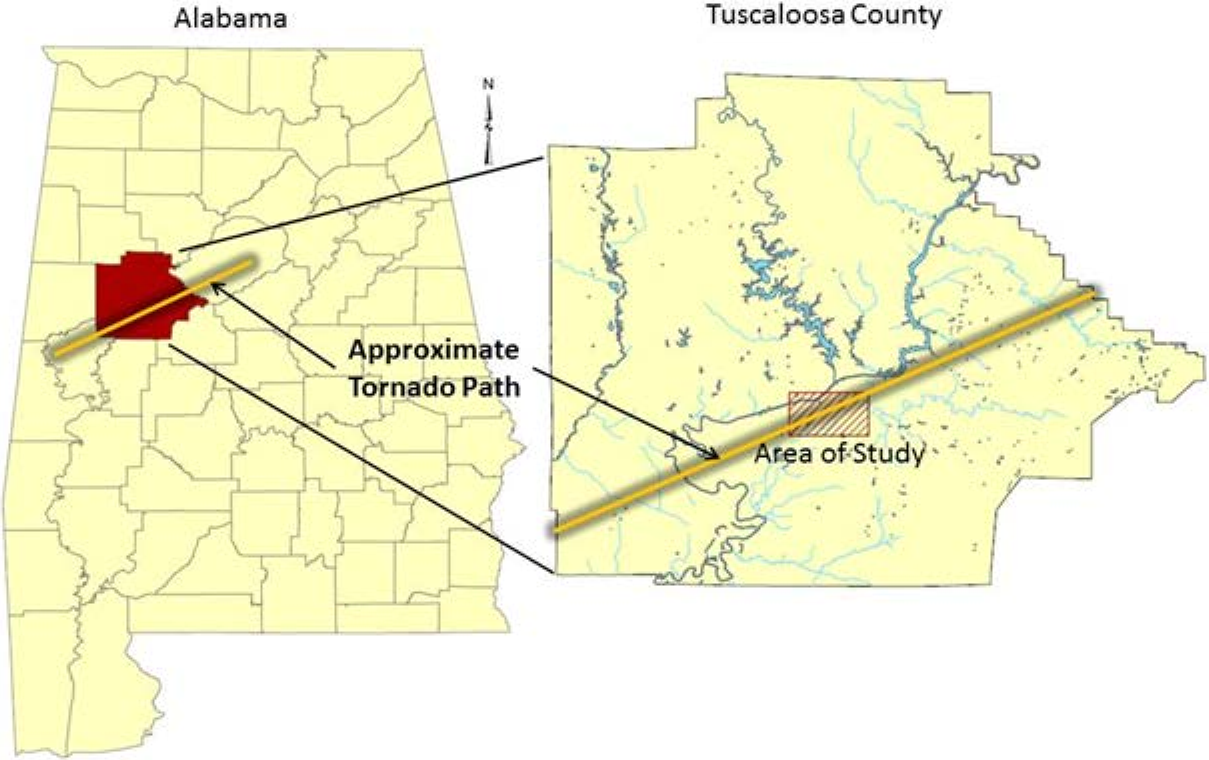
[1] A recommendation for an Enhanced Fujita Scale (2006), Wind Science and Engineering Center, Texas Tech University, Lubbock, Texas.

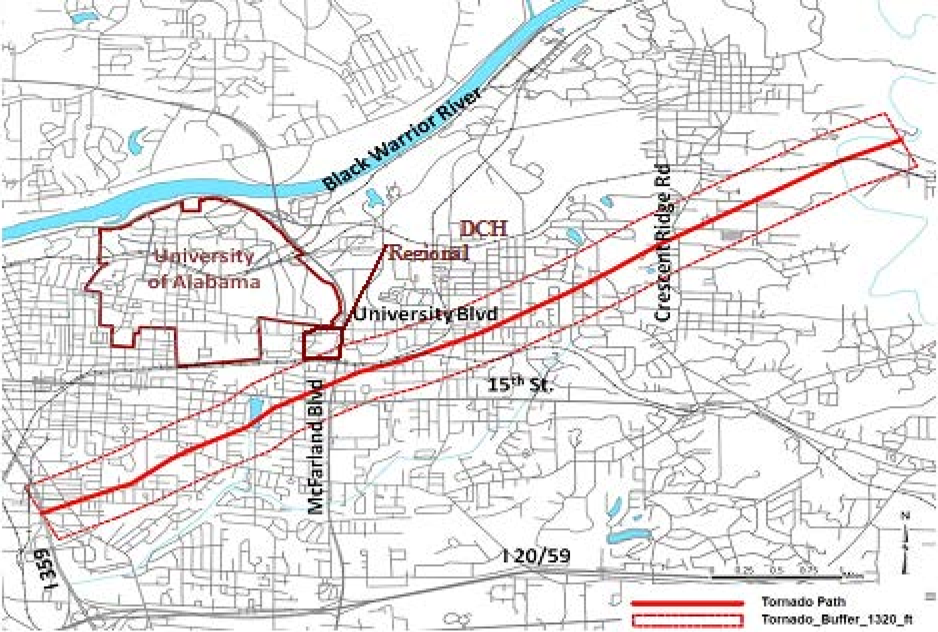
Table 3: Capacity statistics

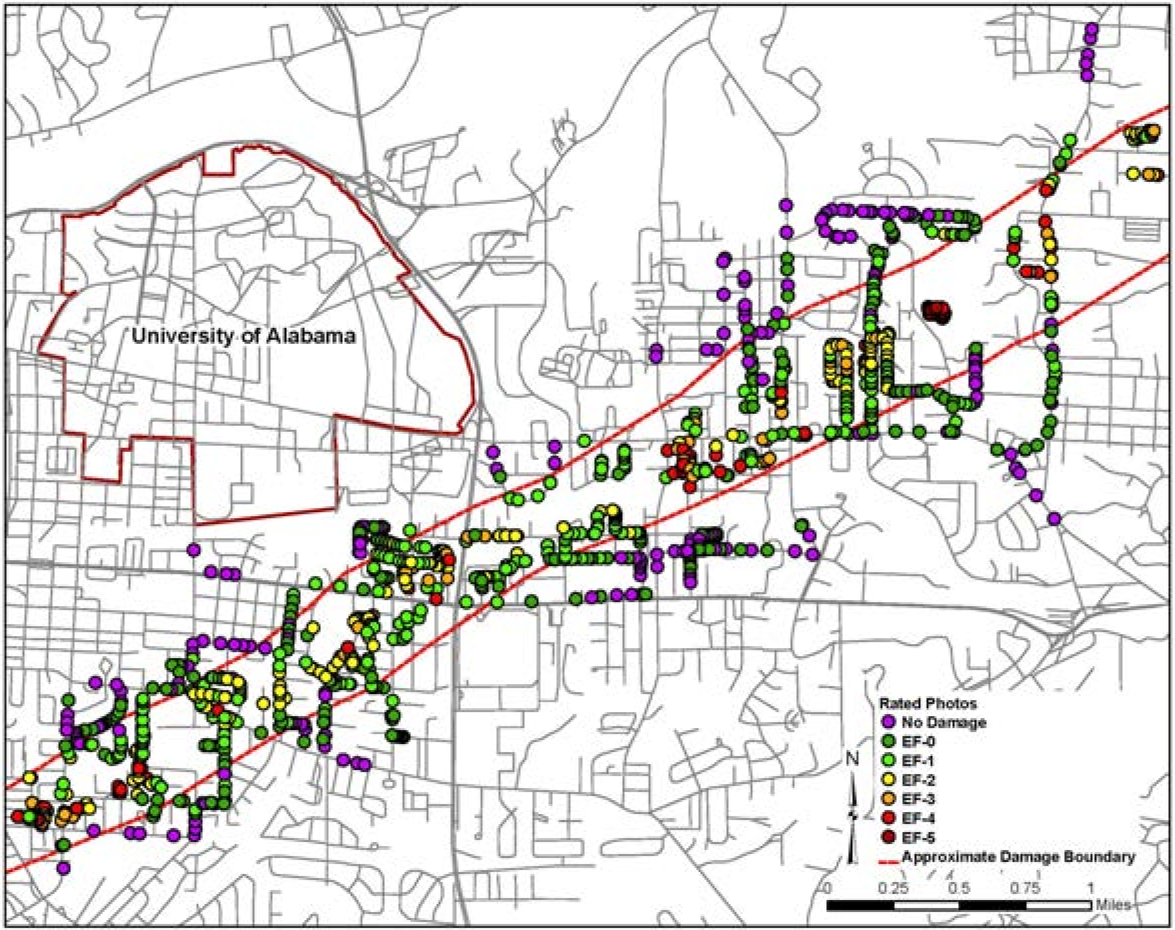
Variables	**Mean**	**(COV)**	**Distribution**
Roof sheathing panel (15cm/30cm or 6”/12”)	69 lbs/ft^2	0.22	Lognormal
Roof sheathing panel (15cm/61cm or 6”/24”)	34 lbs/ft^2	0.29	Lognormal
Hurricane clip H2.5	1312 lbs	0.12	Normal
2-16d Toe Nails	350 lbs	0.16	Normal

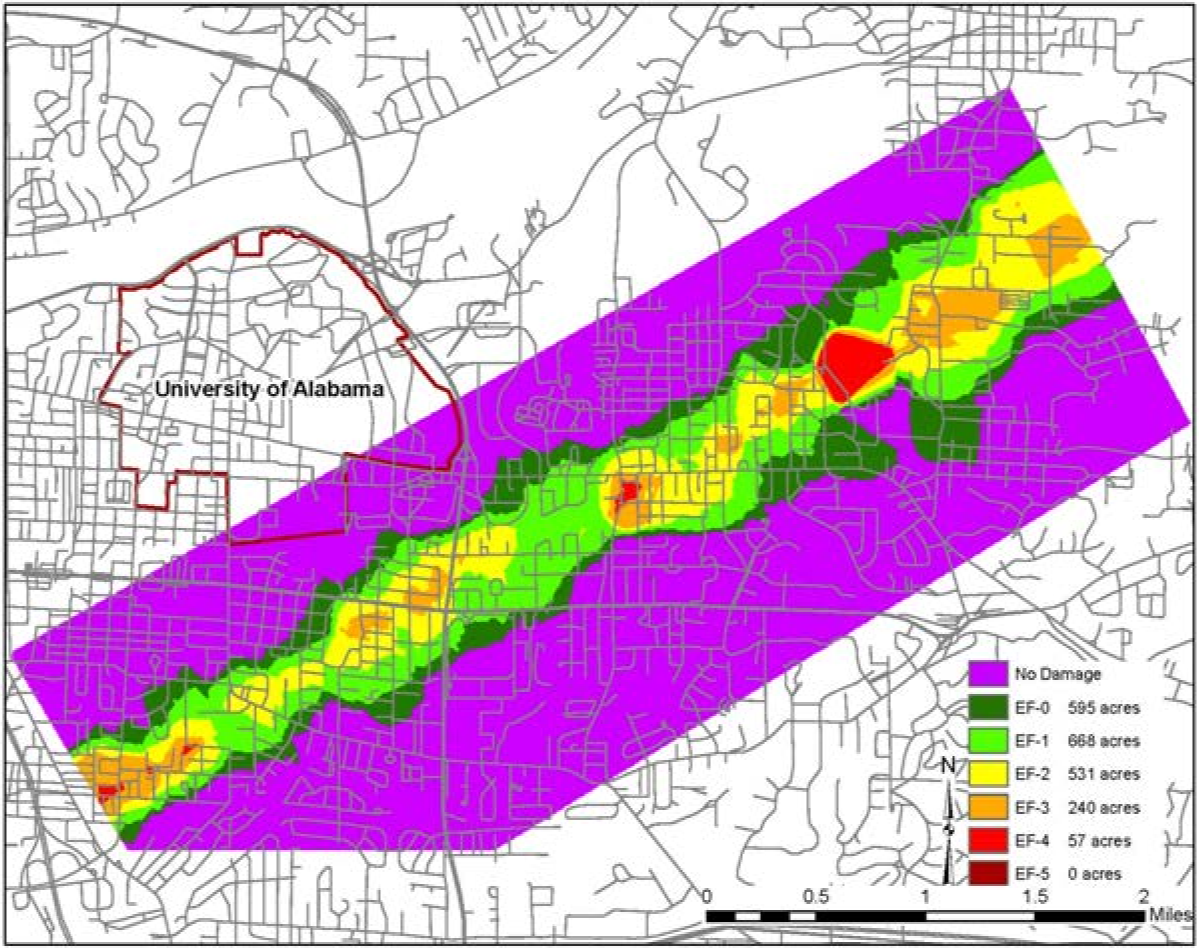
Table 4: Wind load and dead load statistics

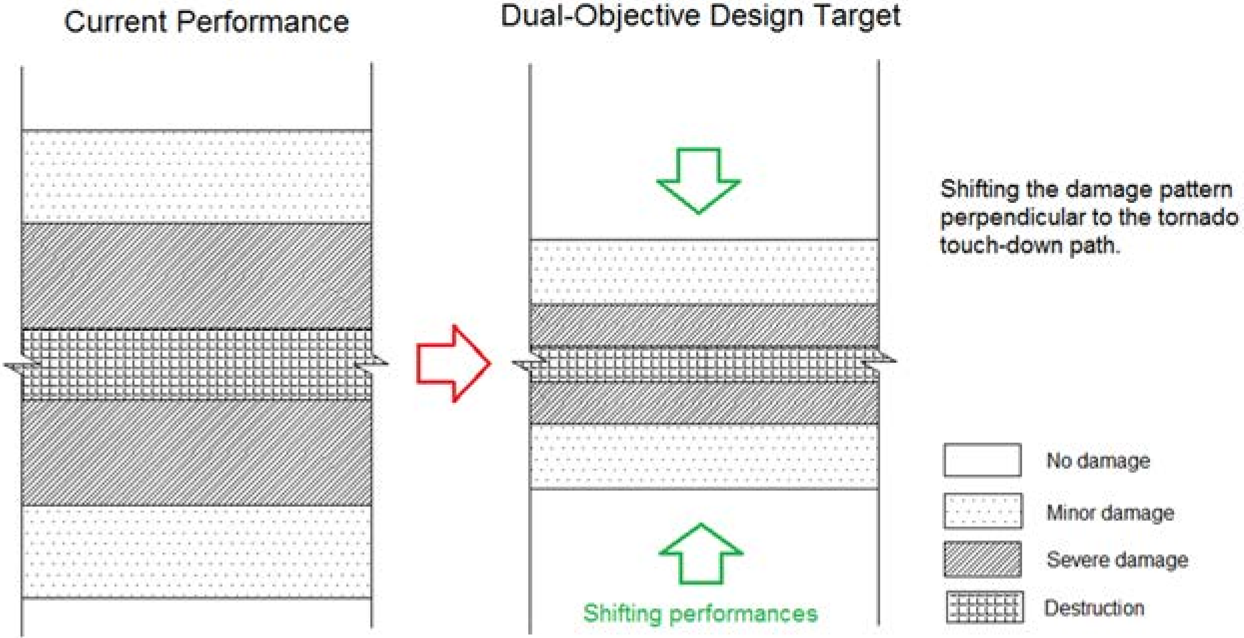
Variables	**Mean**	**Coefficient of variation (COV)**	**Distribution**
Dead Load D	1.6 psf (0.077 kPa)	0.10	Normal
K_h (exposure B)	1	0.21	Normal
GC_p (C&C)	Wind tunnel tests	0.12	Normal
GC_{pi}	0.15	0.05	Normal


Alabama
Tuscaloosa County
N
Approximate Tornado Path
Area of Study


Black Warrior River
DCH
Regional
University of Alabama
University Blvd
Crescent Ridge Rd
15th St.
McFarland Blvd
I 359
I 20/59
N
Miles
Tornado Path
Tornado_Buffer_1320_ft


University of Alabama
Rated Photos
No Damage
EF-0
EF-1
EF-2
EF-3
EF-4
EF-5
Approximate Damage Boundary
N
0
0.25
0.5
0.75
1
Miles

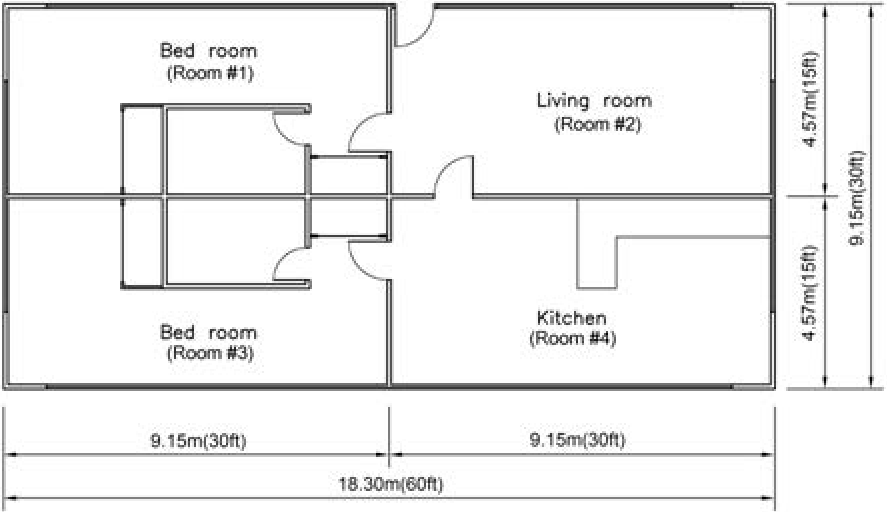

University of Alabama
No Damage
EF-0 595 acres
EF-1 668 acres
EF-2 531 acres
EF-3 240 acres
EF-4 57 acres
EF-5 0 acres
N
0
0.5
1
1.5
2
Miles

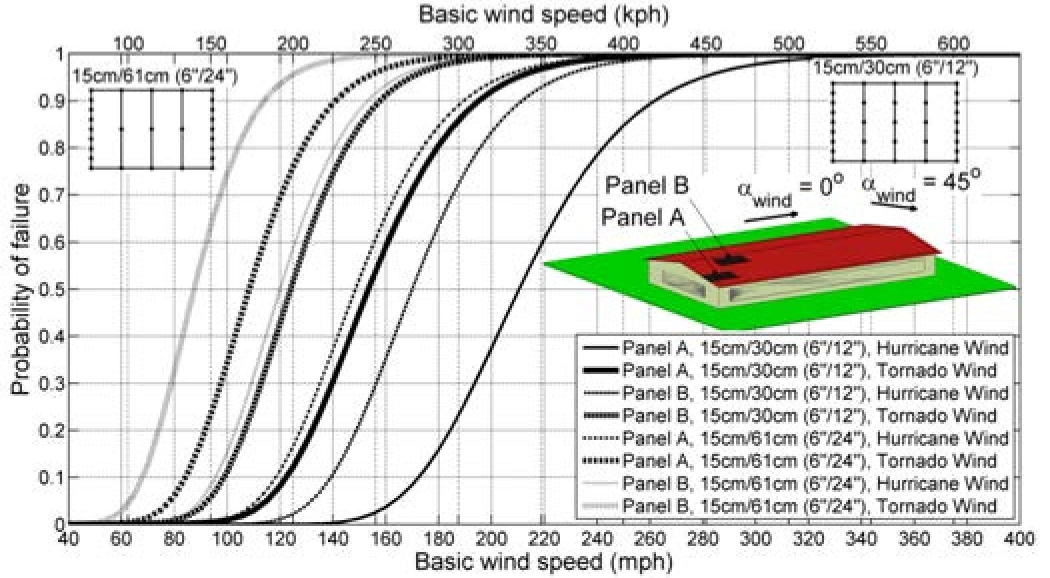


Shifting the damage pattern perpendicular to the tornado touch-down path.

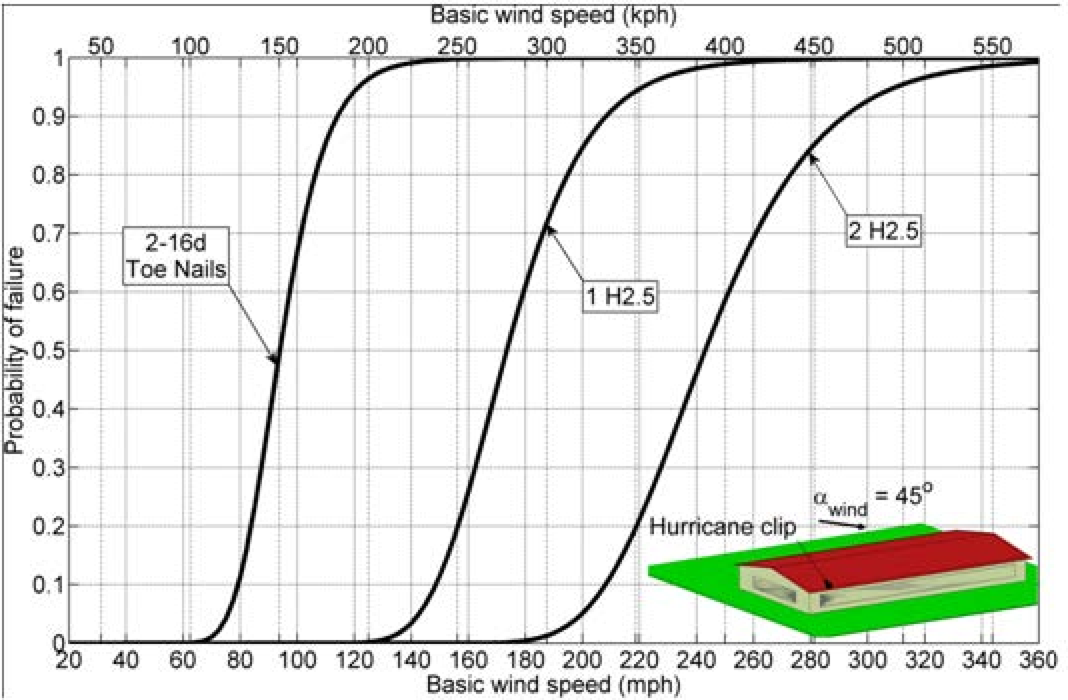

a
b

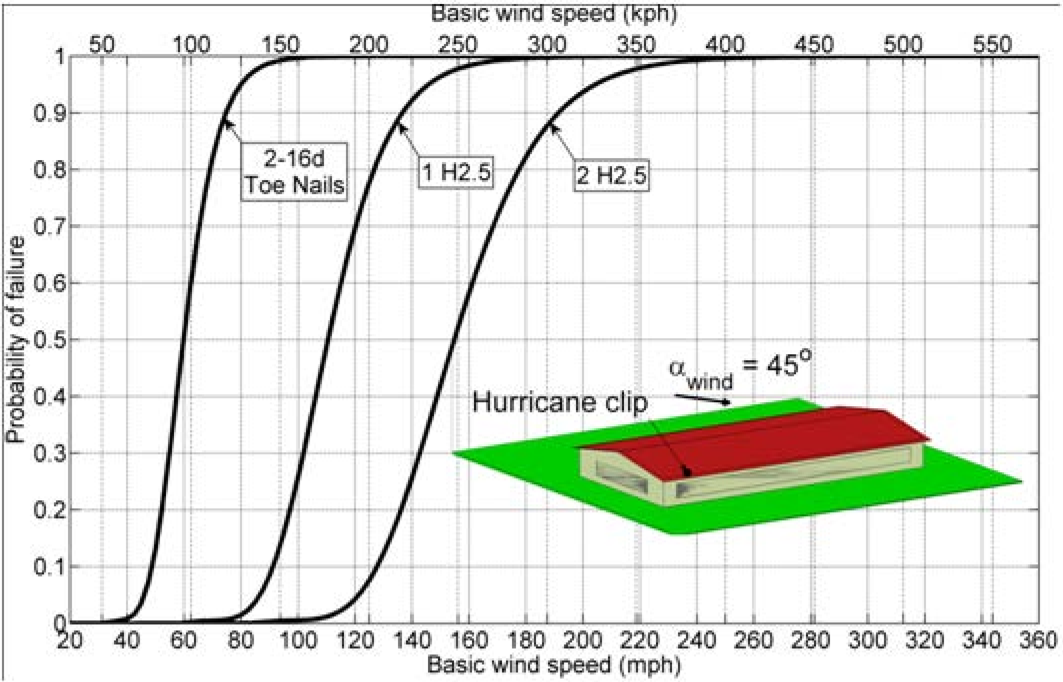

a
b
c
d


Bed room
(Room #1)
Living room
(Room #2)
Bed room
(Room #3)
Kitchen
(Room #4)
4.57m(15ft)
4.57m(15ft)
9.15m(30ft)
9.15m(30ft)
9.15m(30ft)
18.30m(60ft)



Basic wind speed (kph)
100
150
200
250
300
350
400
450
500
550
600
15cm/61cm (6"/24")
15cm/30cm (6"/12")
Panel B
Panel A
α_{wind} = 0°
α_{wind} = 45°
Probability of failure
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Panel A, 15cm/30cm (6"/12"), Hurricane Wind
Panel A, 15cm/30cm (6"/12"), Tornado Wind
Panel B, 15cm/30cm (6"/12"), Hurricane Wind
Panel B, 15cm/30cm (6"/12"), Tornado Wind
Panel A, 15cm/61cm (6"/24"), Hurricane Wind
Panel A, 15cm/61cm (6"/24"), Tornado Wind
Panel B, 15cm/61cm (6"/24"), Hurricane Wind
Panel B, 15cm/61cm (6"/24"), Tornado Wind
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
Basic wind speed (mph)


Basic wind speed (kph)
50
100
150
200
250
300
350
400
450
500
550
Probability of failure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2-16d Toe Nails
1 H2.5
2 H2.5
α_{wind} = 45°
Hurricane clip
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
Basic wind speed (mph)


Basic wind speed (kph)
50
100
150
200
250
300
350
400
450
500
550
Probability of failure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
Basic wind speed (mph)
2-16d Toe Nails
1 H2.5
2 H2.5
α_{wind} = 45°
Hurricane clip

List of Figures – STENG 1767

Figure 9: Example of observed Level 5 Degree of Damage, building shifted off of the foundation.

Figure 10: Example of observed Level 6 Degree of Damage, large sections of roof removed.

Figure 11: Example of observed Level 7 Degree of Damage, exterior walls collapsed.

Figure 12: Example of observed Level 8 Degree of Damage, most walls collapsed.

Figure 13: Example of observed Level 10 Degree of Damage, newly constructed (2010) apartment complex with slab swept clean.

Figure 14: Plan of the house used in the example

Figure 15: Fragilities for loss of roof sheathing panels

Figure 16:Fragilities for roof to wall connection failure in a (a) hurricane and (b) tornado