Dual-Objective-Based Tornado Design Philosophy

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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 nonengineered 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 enhanced Fujita (EF) 4 (EF4) tornado devastated an almost 10-km (5.9-mi) long, 0.8-km-wide (1/2-mi-wide) path, through the city of Tuscaloosa, Alabama, and continued on the ground for 130 km (80 mi). 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 wind speeds 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 structural engineering was formed—namely, provide life safety and control damage—but the new philosophy is focused at separate tornado intensity levels. **DOI: 10.1061/(ASCE)ST.1943-541X.0000622.** *© 2013 American Society of Civil Engineers.*

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Introduction

Tornadoes, like all natural hazards, possess a full range of intensities from enhanced Fujita (EF) 0 (EF0) 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 have consisted of studies on tornado dynamics (e.g., Davies-Jones 1986; Lee and Wurman 2005), wind pressure distributions (e.g., Lewellen et al. 1979; Kosiba and Wurman 2010; 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 the design of structures in relation 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. 1977). 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 related to the occurrence and formation of tornadoes (e.g., Forbes 2006); however, this 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 1-story rectangular building and determined that the side (transverse) wind pressures on the building in simulated tornadoes were 1.8–3.2 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 as a result of the vertical suction imposed by low pressure within a tornado (these values will be used subsequently to compare failure probabilities for a basic rectangular building). These unique characteristics, together with the localized extremely high wind speed over 324 k/hr (200 mi/h), have historically made the design of building structures against tornadoes difficult to rationalize. In this study, based on a recent damage survey of the 2011 Tuscaloosa tornado, it is proposed 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 27, 2011, saw one of the largest outbreaks of severe weather in U.S. history with 53 confirmed tornados in Alabama [National Weather Service (NWS) 2011]. The supercell that spawned the Tuscaloosa tornado traveled over 480 km (300 mi) through four states, while the tornado itself was on the ground for approximately 130 km (80 mi), starting north of Union, Alabama, and traveling

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northeast to Fultondale, Alabama. The path cut across Tuscaloosa County and the study area are shown in the locator maps in Fig. 1. The City of Tuscaloosa was in the direct path and was bisected in a southwest to northeast direction as shown in Fig. 2. The 0.8-km-wide (1/2-mi-wide) by 10-km-long (5.9-mi-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, 2- and 3-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 multistory, 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,

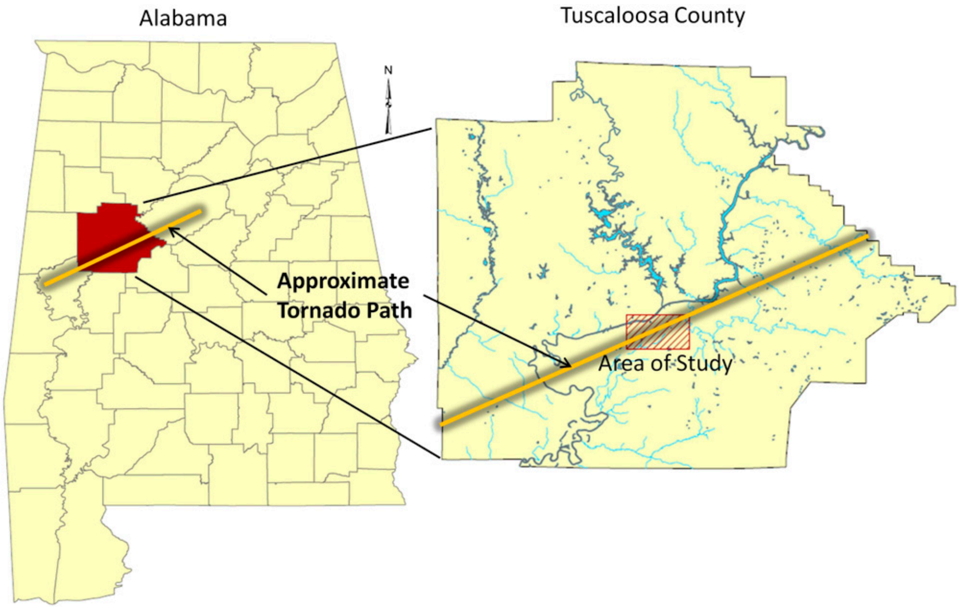

Fig. 1. Locator map of Tuscaloosa County and the study area showing the path of the April 27th Tuscaloosa tornado

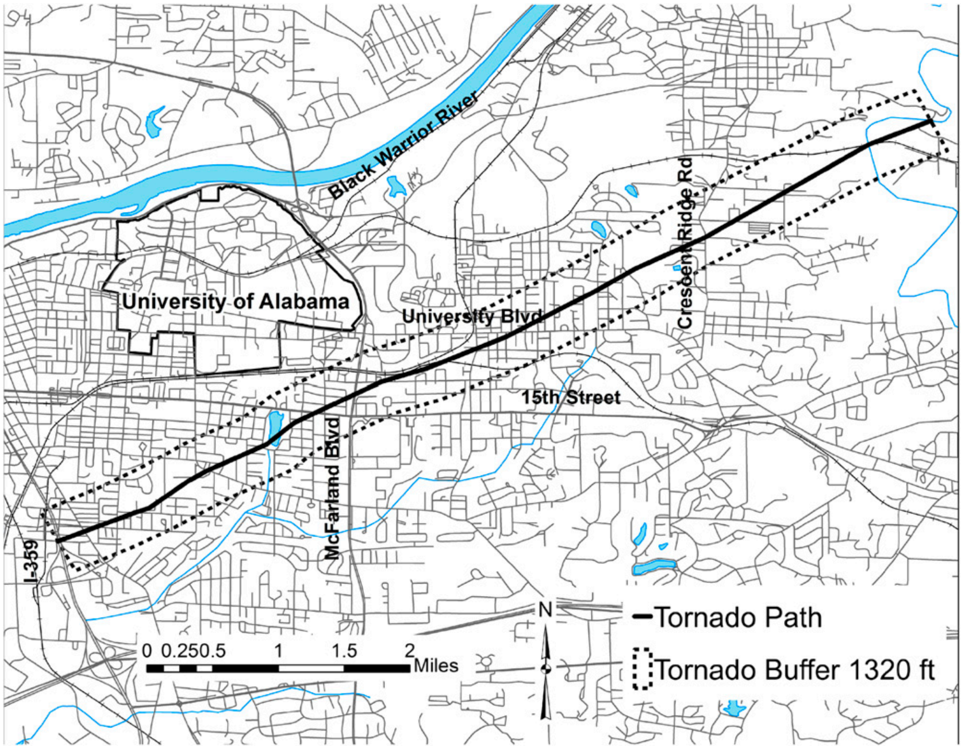

Fig. 2. Downtown Tuscaloosa showing the tornado path and study area in relation to major roads, water, and The University of Alabama

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 to May 5, 2011. Approximately 0.8-km-long (1/2-mi-long) transects across the path of the tornado, spaced approximately 0.8-km (1/2-mi) apart were studied, and building damage ranging from no damage to total destruction was recorded in the form of georeferenced 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 photographs 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 the photography locations from the daily GPS tracks and photography times. The photography locations were then displayed as points and overlaid on a base map of Tuscaloosa and the photographs were hyperlinked to their locations. Individual building damage was rated on an EF scale based on the photographic evidence, and specific buildings were identified for detailed case study investigations.

A map showing the EF categories for buildings is shown in Fig. 3 and is available 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 Fig. 3 that higher EF wind speeds (2, 3, and 4) tend to be located along the center line of the tornado, while lower EF wind speeds (no damage, 0, and 1) tend to be along the edges of the tornado path. A contour map of the EF wind speeds developed from the observed building damage is shown in Fig. 4. As expected, the contours in Fig. 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 Fig. 4. It was observed that the vast majority (86%) of the affected area was at the EF2 category or lower [wind speeds below 219 k/hr (135 mi/h)].

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 caused by 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 from residential buildings that once stood there, corresponding to a degree of damage (DOD) of Level 10 (DOD10). Moving out perpendicular to the direction of travel of the tornado the DOD is reduced at some gradient to a DOD1, which is the threshold of visible damage (WSEC 2006). The DODs 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 (LS). This dual design approach can be achieved using three philosophies, as

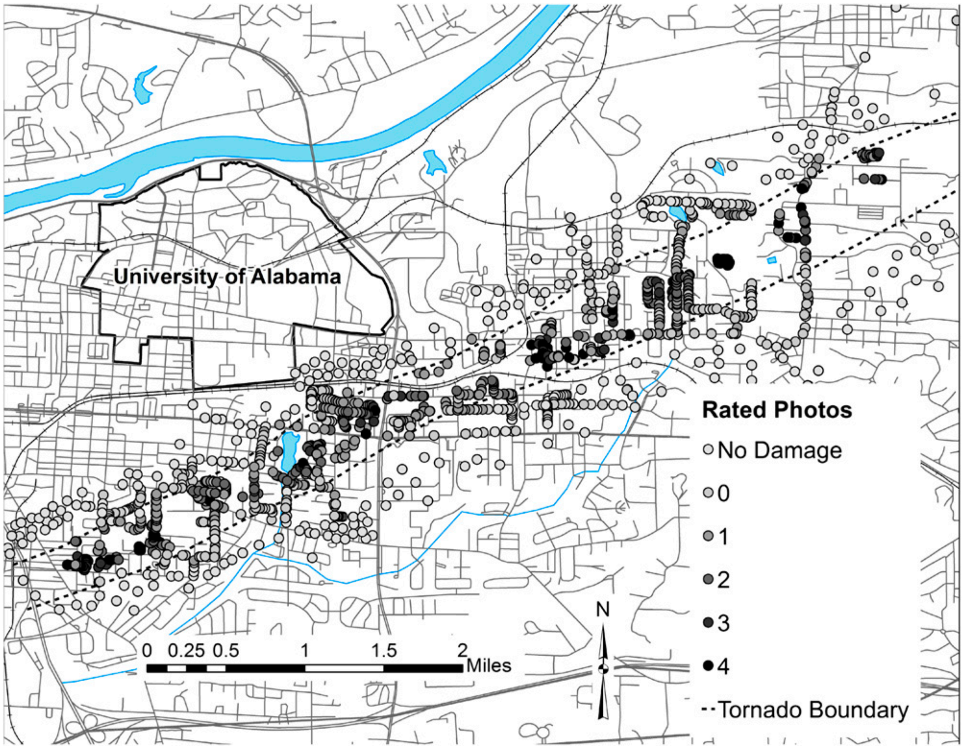

Fig. 3. Map showing EF-rated photographs along the tornado path in Tuscaloosa

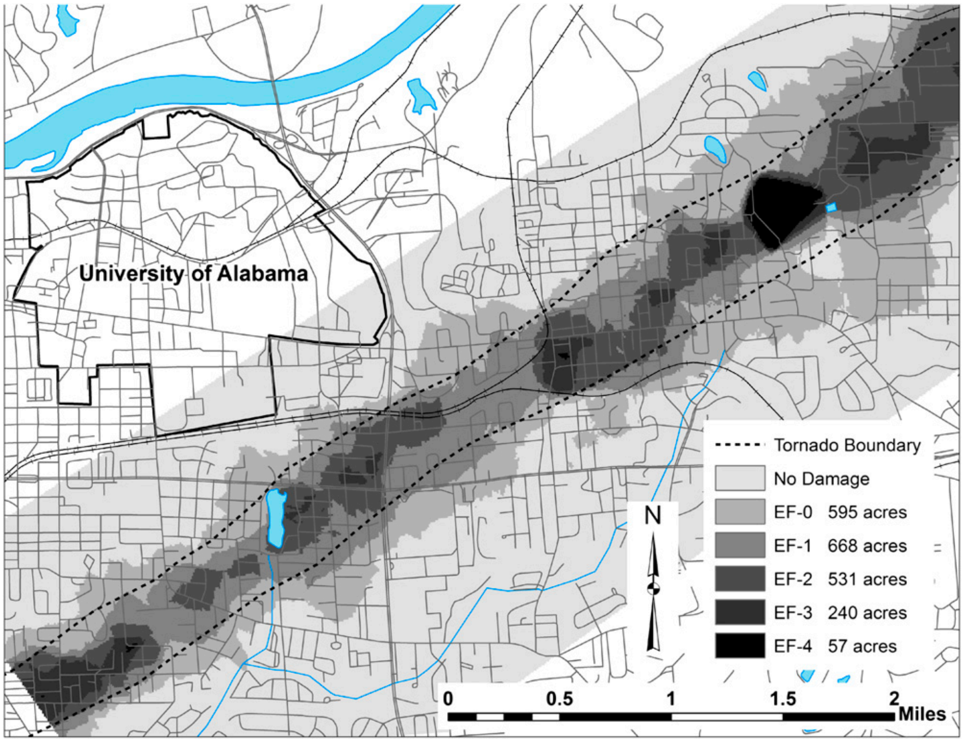

Fig. 4. Contour map of EF wind speeds based on observed building damage

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

	Enhanced Fujita scale winds (3-s gust)					
Methodology proposed	EF0 105–138 k/hr (65–85 mi/h)	EF1 139–178 kh/r (86–110 mi/h)	EF2 180–219 k/hr (111–135 mi/h)	EF3 220–267 k/hr (136–165 mi/h)	EF4 269–324 k/hr (166–200 mi/h)	EF5 269–324 k/hr (>200 mi/h)
Design objective	D	D	D/LS	D/LS	LS	LS
Philosophy considered	C	C	C/S	S	S/A	A

Note: D = damage; LS = life safety; C = component; S = system; and A = alternative.

shown in Table 1 and explained here. (1) Damage can be controlled at lower levels of the EF 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 and 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 among wall lines and distribution of the lateral load path as a whole throughout the building when 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 the system effects and other alternatives (A) to provide LS to the building occupants. These alternatives are safe rooms, underground shelters, and often basements, most of which assume 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 use the dual objectives simultaneously in building design; therefore, the three philosophies that drive the design toward the objectives should also be used simultaneously. This will ensure minimization of financial losses when possible and protection of LS 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 previously; 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 (C) level design philosophy, (2) a system (S) level design philosophy, or (3) an alternative (A) philosophy. Specifically, an engineering solution typically focuses on either the component level such as a connection or single wall, or on the system such as the lateral force resistance for a building. Additionally, as can be seen from inspection of Table 2, an alternative approach for LS must be considered at the high EF3–EF5 wind speeds. Because 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

Table 2. Dual Design Objectives, Philosophy, and Examples of Engineering/Construction Improvements

Proposed design objective	Philosophy	DOD[a]	Damage description	Example engineering and/or construction improvements
Damage mitigation	Component	1	Threshold of visible damage	Not applicable
Damage mitigation	Component	2	Loss of roof covering	Use manufacturer recommended number and placement of fasteners for high-wind shingles.
Damage mitigation	Component	2	Loss of vinyl/metal siding	Use high wind–rated siding and ensure fastener penetration into studs (not board of any kind).
Damage mitigation	Component	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.
Damage mitigation	Component	4	Uplift of roof deck and loss of significant roof covering material	Use hurricane clips on both sides of truss, 2 × 6 trusses, heavier nail schedule on roof sheathing, add blocking for short edge nailing of roof sheathing.
Damage mitigation	Component	4	Collapse of chimney	Better connection to the structure.
Damage mitigation	Component	4	Garage door blown inward	High wind–rated garage door and track system.
Damage mitigation	Component/system	4	Failure of porch or carport	Ensure continuous vertical load path through engineered metal connectors from roof into foundation.
Damage mitigation	Component/system	5	House shifts off foundation	Ensure adequate number and placement of anchor bolts, use steel hold downs, 2 × 6 sill plates with washers.
Damage mitigation	System	6	Large sections of roof structure removed	Ensure connection between trusses/rafters to wall top plates. Space trusses at 16 in. o.c. and line them up with vertical wall studs.
Life safety	System	7	Exterior walls collapsed	Closer nail schedule for shear capacity, provide full anchorage for all walls; safe room or shelter.
Life safety	Alternative	8	Most walls collapsed	Safe room or shelter.
Life safety	Alternative	9	All walls collapsed	Safe room or shelter.
Life safety	Alternative	10	Slab swept clean	Safe room or shelter.

[a] Recommendation for an EF scale (2006), Wind Science and Engineering Center, Texas Tech University, Lubbock, Texas.

design philosophy, a portion of the damage that occurred as a result of EF0, EF1, and EF2 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 LS at wind speeds exceeding that threshold. Fig. 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 as a result of the implementation of the dual-objective design achieved by applying all three philosophies; namely, component, system, and alternative.

In the subsequent list, selected photographs from the Tuscaloosa tornado damage assessment are presented to illustrate several critical

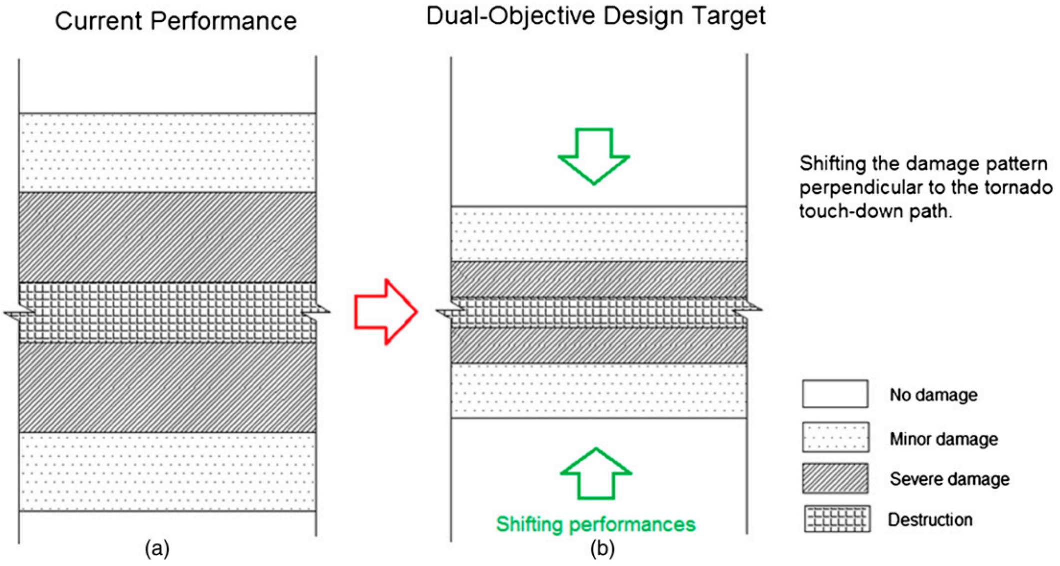

Fig. 5. (a) Conceptual tornado damage swath based on current performance and (b) after the implementation of the dual-objective design that reduces lower wind-speed damage

damage states outlined in Table 2. As illustrative examples, the 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 previously, 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 performance improvement.

- DOD2: Loss of roof covering. Loss of roof covering may a result of aging of roofing material or improper fastener schedule. With high-wind-rated roof shingles and correct installation details, the damage shown in Fig. 6(a) 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 because of the geometry and improper installation details. An example of observed siding damage is shown in Fig. 6(b). 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.
- DOD3: Broken glass in doors and windows. The damage to door glass and windows (examples of which are shown in Fig. 7) is difficult to design against because of 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 wind-borne debris penetration for lower wind speeds but likely not for wind speeds in excess of 227 k/hr (140 mi/h). The potential difficulty of implementing this component-level change is high.
- DOD4: Uplift of roof deck and loss of significant roof covering material. Roof coverings are typically not designed for significant internal pressure. High internal building pressure is common in high wind because of 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

Fig. 6. Examples of observed DOD2: (a) loss of shingles; (b) loss of siding

Fig. 7. Example of observed DOD3: broken windows

occur as shown in Fig. 8(a). 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.

- DOD4: Garage door blown inward. Garage doors are a very commonly observed weak link in residential building envelopes, as shown in Fig. 8(b). Once a garage door fails, further breaching of the main portion of the house can occur because attached garages 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 Fig. 8(c). Once these weak interfaces are designed properly, extended roofs for porches and carports will withstand wind speeds beyond 90 mi/h, perhaps even as high as 140–150 mi/h. 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 Fig. 8(d). 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 a 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 Fig. 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 Fig. 10, may be mitigated through the use of connection hardware and nonconventional 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 259 k/hr (160 mi/h) (e.g., DOD7–DOD10). The majority of exterior walls of a wood-framed structure will collapse in wind with speeds in excess of 259 k/hr (160 mi/h). An observed example of a building where the exterior walls collapsed is shown in Fig. 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 Fig. 12.
- DOD10: Slab swept clean. An example of an entire building blown away, leaving only the slab, is shown in Fig. 13. The building in Fig. 13 was a newly constructed apartment complex built in 2010; even the linoleum on the floor was pealed up from the tornado.

From the discussion on the DOD levels observed during the Tuscaloosa investigation, it is clear that there are design measures that can be taken 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 in regions under a certain threshold level (e.g., 135 mi/h), which is the vast majority of the tornado-affected region according to the survey results from the Tuscaloosa tornado.

Illustrative Fragilities

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

To compare the probability of failure for roof-sheathing panels or roof-to-wall connections (hurricane clip) between a hurricane and

Fig. 8. Examples of observed DOD4: (a) significant roof damage; (b) garage door blown in; (c) porch damage; (d) chimney collapse

a tornado, a fragility analysis was conducted in this example. In general, the failure probability can be defined through the expression of the following limit-state function:

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

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

The limit state describing the 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 = resistance of the roof panel or hurricane clip to uplift (Table 3), W = uplift wind load, and D = 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 = velocity pressure evaluated at the mean roof height, G = gust factor, C_p = external pressure coefficient, and C_{pi} = internal pressure coefficient. Eq. (3) is used to calculate the wind load induced by hurricane wind. To approximate tornado wind, the total pressure coefficient is scaled by a factor H to account for the increase in vertical wind velocity pressure

$$W = q_h H\left[GC_p - GC_{pi}\right] \tag{4}$$

In this example, 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 of Haan et al. (2010). Here, the pressure coefficient on the components and cladding is still larger than the main wind force–resisting system even when factor H is applied. The velocity pressure is calculated following ASCE-7 (ASCE 2010) as

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

where K_h = exposure factor, K_{zt} = topographic factor (taken as equal to unity in order not to make the results dependent on the local topography surrounding the building), K_d = directional factor (it is assumed that the wind direction is known and K_d is set to unity), and V = basic wind speed. Here, R, D, GC_p, GC_{pi}, and K_h are taken as random variables in the reliability analysis. The mean value of GC_p

Fig. 9. Example of observed DOD5: building shifted off of the foundation

Fig. 10. Example of observed DOD6: large sections of roof removed

Fig. 11. Example of observed DOD7: exterior walls collapsed

Fig. 12. Example of observed DOD8: most walls collapsed

Fig. 13. Example of observed DOD10: newly constructed (2010) apartment complex with slab swept clean

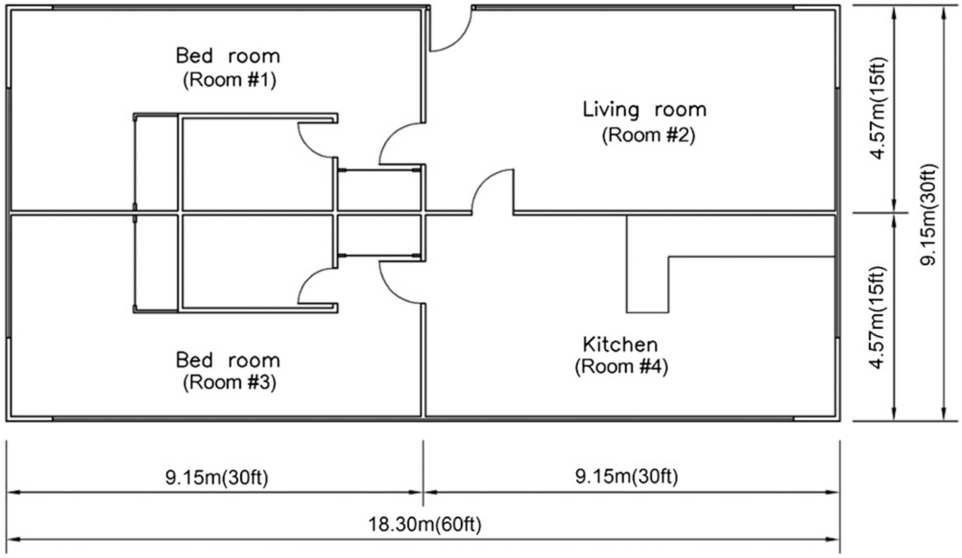

Fig. 14. Plan of the house used in the example

was evaluated by wind tunnel tests (Datin and Prevatt 2009). The statistics of random variables for wind load and dead load are presented in Table 4. It was observed from the wind tunnel test data that the largest wind pressure coefficient occurred on the roof at Panel B (Fig. 15) with wind direction $a_{\text{wind}} = 45°$ ($C_p = 2.3$). For wind direction $a_{\text{wind}} = 0°$, the largest wind pressure coefficient was at Panel A ($C_p = 1.47$).

Fig. 15 shows the fragility curves of the two panels with various nail patterns under the wind load induced by hurricane wind and the approximate tornado wind loading. It can be seen from Fig. 15 that the lowest risk of failure is for Panel A with the nail pattern of 15 cm/30 cm (6 in./12 in.) 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 in Fig. 15 by the large bold curve. Comparing these two curves, it can be seen that Panel A with the nail pattern of 15 cm/30 cm (6 in./12 in.) almost has zero probability of failure at hurricane wind $V = 224$ km/h (140 mi/h). However, 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 15 cm/61 cm (6 in./24 in.) under tornado wind, whose fragility curve is represented by the curve on the far-left end. It can be seen that this panel has less than 10% failure probability under hurricane wind velocity of 150 km/h (93 mi/h) 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 Figs. 16(a and b). The wind direction used in the calculation was 45°, which was the same as the wind direction that induced 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 Fig. 16(a). The toe nails had a 67% probability of failing at 160 km/h (100 mi/h). However, simply replacing them with a single H2.5 hurricane clip virtually eliminated the likelihood of failure. In a tornado, recall from the previous 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 49–89% if loaded by an EF2 tornado [expected wind speed range of 180–219 k/hr (111–135 mi/h)]. 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 2–18% failure probability in an EF2 tornado. This illustrates the damage reduction possibility for a single damage mechanism through the use of hardware. Finally, 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.

Table 3. Capacity Statistics

Variable	Mean	COV	Distribution
Roof sheathing panel [15 cm/30 cm (6 in./12 in.)]	69 lb/ft^2	0.22	Lognormal
Roof sheathing panel [15 cm/61 cm (6 in./24 in.)]	34 lb/ft^2	0.29	Lognormal
Hurricane Clip H2.5	1,312 lb	0.12	Normal
2–16d toe nails	350 lb	0.16	Normal

Table 4. Wind Load and Dead Load Statistics

Variable	Mean	COV	Distribution
Dead load D	0.077 kPa (1.6 psf)	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

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

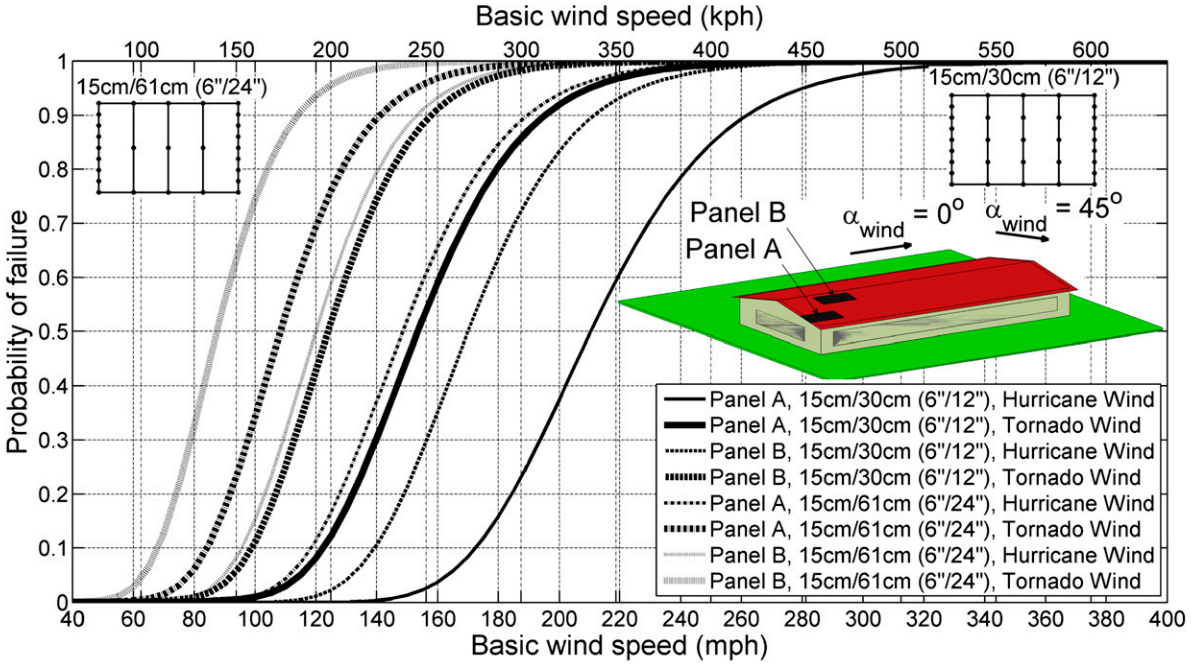

Fig. 15. Fragilities for loss of roof sheathing panels

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 previously. 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 the following:

- Issue 1: 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 194–243 k/hr (120–150-mi/h) range.
- Issue 2: 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 a result of 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 various 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.
- Issue 3: Acceptable and implementable approaches in the design and construction of residential buildings to reduce tornado damage are needed. 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 an 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.
- Issue 4: Implementation of 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 LS to building occupants. The shelter must be designed to handle both wind pressure and debris impact as in the current guidelines (FEMA 2008a, b) to build safe rooms and shelters. These can be built per FEMA recommendation and their increased use should be further enabled in more tornado prone regions. Shelters should be included at the same time as the component and system philosophies are implemented as discussed previously.

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

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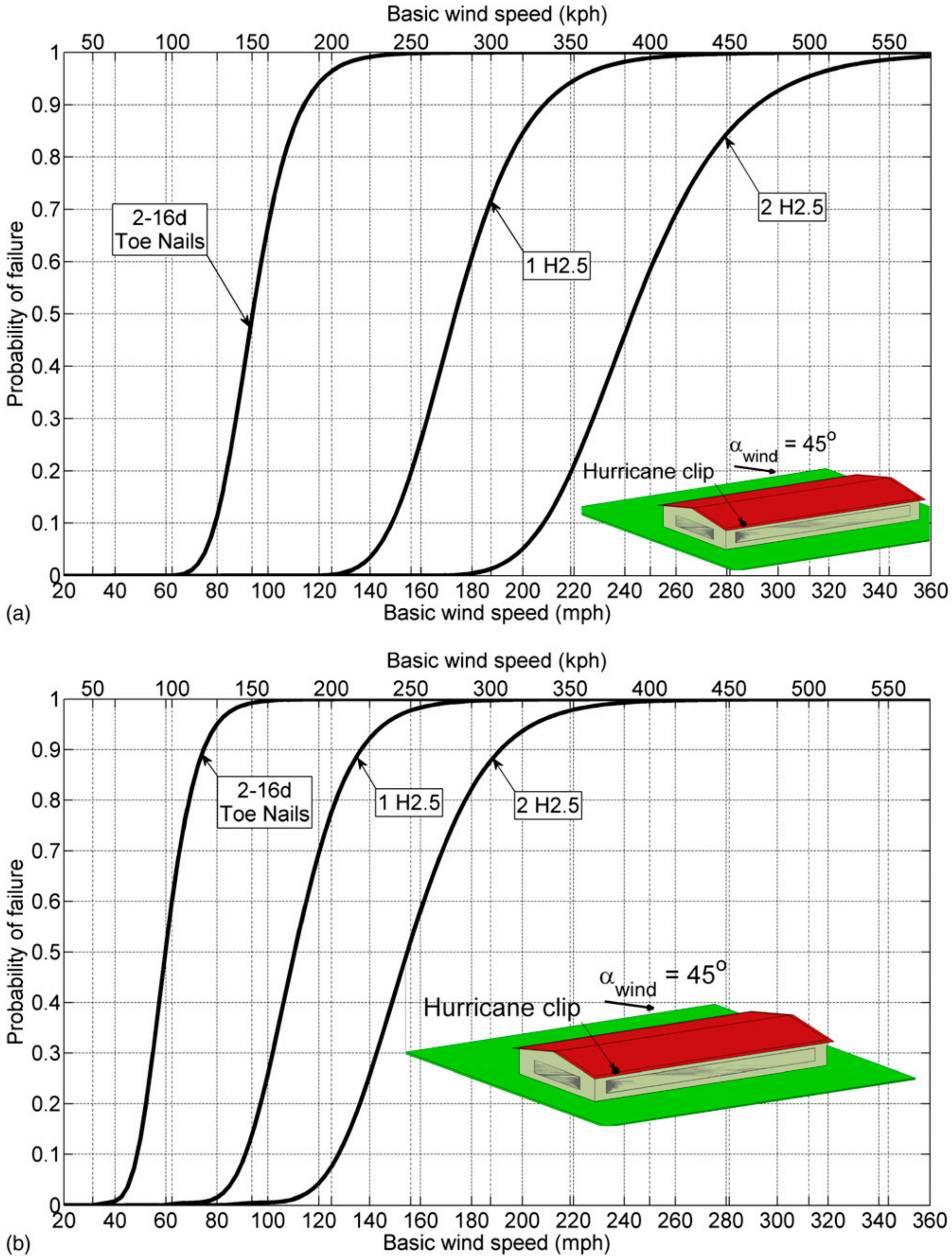

Fig. 16. Fragilities for roof to wall connection failure in a (a) hurricane and (b) tornado

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 speed LS 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.

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