Residential Damage Patterns Following the 2011 Tuscaloosa, AL and Joplin, MO Tornadoes

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ABSTRACT

Two of the most powerful tornadoes in 2011, occurred in Tuscaloosa, AL on April 27th, and in Joplin, MO on May 22nd. These tornadoes caused a significant amount of damage ($13 billion), and resulted in an estimated 175 fatalities. Despite decades of damage reports on violent tornadoes, little is known regarding the structural loading imposed on buildings by these events. However, non-engineered residential property suffered the worst damage as documented by two damage survey teams. The post-tornado damage surveys documented the structural performance of houses, and spatial distribution of residential damage within the tornado wind field. The data include damage observations from over 1600 homes that were assigned degrees of damage (DOD) ratings using the EF-Scale procedure. Publicly available information such as the age, construction materials and size of the homes were also collected.

An analysis of the failure patterns was performed on the combined dataset to quantify the magnitudes and distributions of tornado loads on buildings, relating the damage to distance from the centerline of the tornado, orientation of the structure and variation along each tornado path. The study presents correlations among major failure mechanisms; i.e. between roof removal and ensuing wall collapse, and between roof sheathing loss and resulting failure of gable-end walls. The paper presents common failure patterns related to specific construction practices that increase the vulnerability of houses to tornadoes. These field studies and analyses are being used to inform the development of full-scale structural testing wall components with the goal of developing structural retrofits and improved design practices for tornado-resilient houses.

INTRODUCTION

On average over 1200 tornadoes occur in the United States causing nearly $1 billion in insured losses each year (Changnon, 2009). The year 2011 was an exceptional year for tornadoes in the US with at least 1625 confirmed tornadoes, 794 tornado-related fatalities and an estimated $46 billion in economic losses from tornadoes and thunderstorms. The total of insured losses, $25 billion, more than doubled the previous record year. Two outbreaks in particular, the April 25-28th outbreak and the May 22nd outbreak, caused catastrophic damage to a large number of communities. Some of the greatest impact was seen in Tuscaloosa, AL and Joplin, MO, where EF-4 and EF-5 tornadoes respectively impacted urban regions with dense populations. In both of these communities, newer homes are nominally built to withstand design wind speeds of 90mph through the use of prescriptive code provisions. However, the majority of the homes were built prior adoption of these codes, and even these new homes could not be expected to survive the impact of an EF4 or EF5 tornado (with wind speeds as high as 200 mph). As a result, damage was catastrophic, with an estimated 13,000 buildings damaged or destroyed in the two communities combined. With growing urban populations in tornado-prone regions, it is likely that such events will become more frequent. It is important then to identify key failure patterns present in these two storm damage databases as well as others in order to better understand the unique loads imposed by tornadoes and to provide the necessary design improvements that can improve the performance of residential homes (the majority of which in the US are wood-frame (Rosowsky, 1999)) to tornadoes.

ASSESSMENT METHODOLOGY

In the immediate aftermath of each of the Tuscaloosa and Joplin tornadoes, engineering assessments of the damage were conducted by a team that included engineering faculty, local engineers, scientists and students. Complete details of the assessments are available in the published literature (Prevatt, Van De Lindt *et al.*, 2011; Prevatt, Lindt *et al.*, 2011). Over 14,000 photos were taken of the damage, the majority of which were linked to a geographic location using either GPS-capable cameras or standard cameras in combination with hand-held GPS units and geotagging software. This complete dataset includes nearly 3,000 unique residential structures that were rated to estimate a wind speed in accordance with the EF scale provisions. The location of each of these homes is shown in Figure 1.

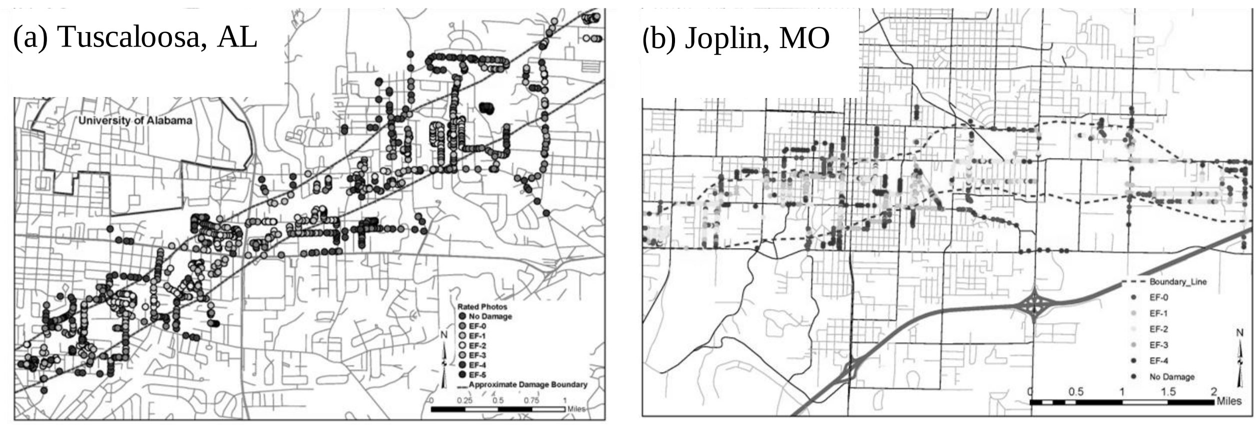


Figure 1: Locations of Rated Homes

TORNADO WIND FIELD

By relating the estimated wind speed from the damage at each home to the location of the home, a more precise estimate of the distribution of wind speeds throughout the tornado wind-fields was obtained. Contour plots of the estimated wind speeds for each tornado were developed and are shown in Figure 2.

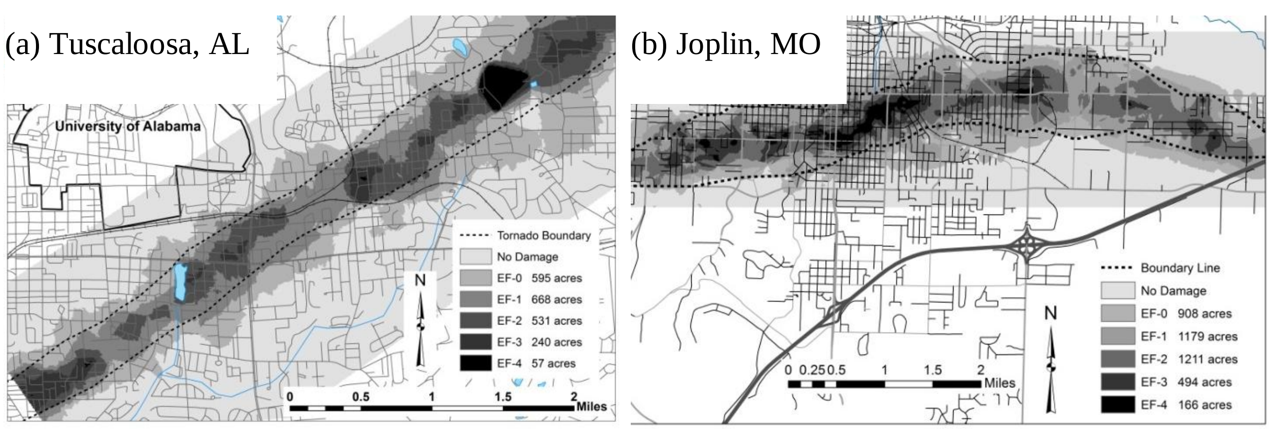


Figure 2: Wind Speed Distributions within the Tuscaloosa and Joplin Tornadoes

Further analysis of the distribution of wind speeds was performed by determining the distance from the estimated centerline of the tornado vortex to each rated building (and therefore estimated wind speed) in both Tuscaloosa and Joplin. The results of this analysis are plotted as normalized histograms in Figure 3, illustrating the distribution of wind speeds within the complete damage path. Box plots are also used In Figure 4 to depict the median, 25th and 75th percentiles of the distributions, with EF-1 representing homes with no observed damages. The "+" data marker represents data that falls outside of ±2.7 standard deviations from the mean. It is possible that such outliers represent the locations of secondary vortices, but other options such as undocumented tree damage should also be considered.

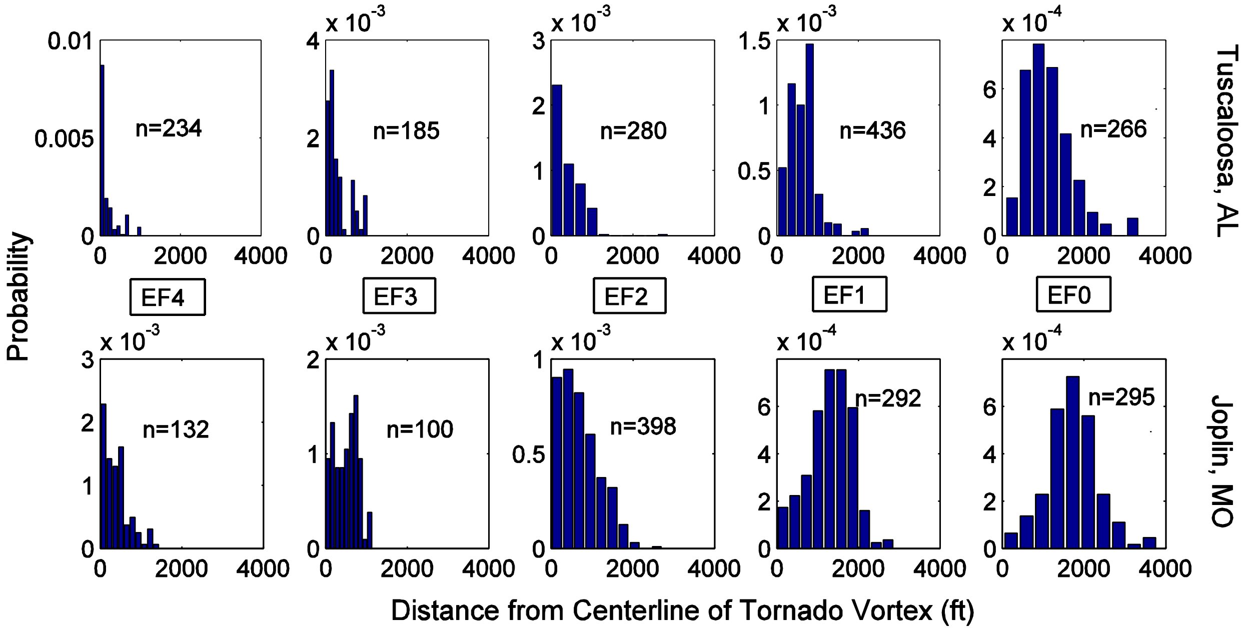
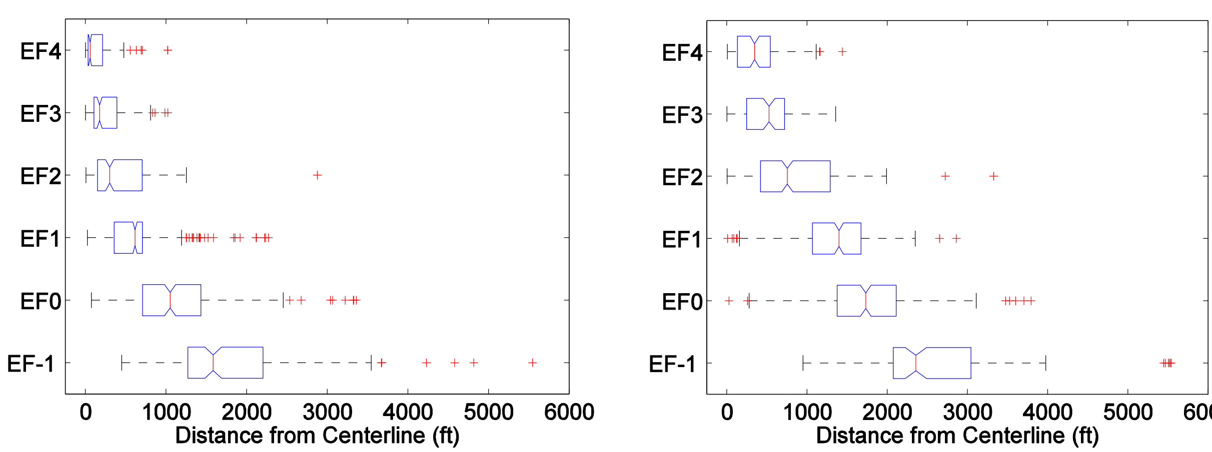


Figure 3: Distributions of Wind Speed within the Tornado Wind-field



Tuscaloosa, AL Joplin, MO

Figure 4: Distribution of Damages around Centerline

Differences in the characteristics of the two tornadoes are apparent from these plots of the observed damages. While the maximum size of both tornadoes is similar (nearly 4,000ft radius, assuming equal distances each side of the centerline), the median values for each EF-scale rating are much more compact in the Tuscaloosa tornado than in the Joplin tornado. These distributions of damages around the centerline were analyzed to empirically develop a model of the changes in wind speed with increasing distance from the vortex. The midpoint value within the range of wind speeds attributed to each EF Scale intensity was paired with the median distances from the vortex that are presented in Figure 4. Wind speed as a function of this distance from the edge of the vortex is typically modeled as a Rankine vortex, with $V(r) = (V_{max})*(R/r)^a$, where V_{max} represents the maximum tangential velocity, R the radius to maximum wind velocity, r the radial distance from the center of the vortex, and a the decay coefficient, estimated to vary from 0.5 to 1.0. Wurman et al estimated a decay coefficient of 0.67 for the F4 tornado in Spencer, South Dakota (Wurman e Curtis, 2005), and this estimate is compared in Figure 5 to the empirically developed model, assuming the same maximum wind speed for all three models. The comparison demonstrates good agreement between the model observed by Wurman et al using Doppler radar and the empirically developed models from the damage assessments, particularly for the Tuscaloosa tornado. While it is possible that the exceptional agreement between the Tuscaloosa model and the observations by Wurman et al in the Spencer tornado is entirely coincidental, it suggests that the behavior of the boundary layer wind speeds in a large tornado is similar to that observed by Doppler in the upper atmosphere.

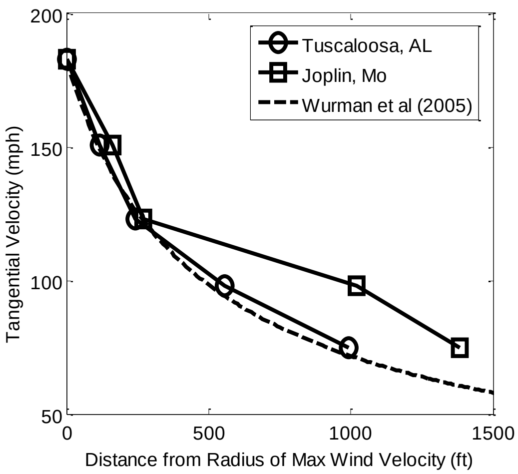


Figure 5: Comparison of Wind Speeds with Distance from Vortex

FAILURE MECHANISMS IN WOODFRAME HOMES

Of particular concern in these assessments was the performance of residential housing, the majority of which was wood-frame construction. A number of previous reports have well documented the typically poor performance of residential housing during tornadoes, particularly wood-frame homes (Minor, Mcdonald *et al.*, 1978; Fema, 1999; Urs, 2007; Bienkiewicz, 2008). The poor performance stems from the fact that the majority of the homes in these two regions were built using traditional methods or conforming to prescriptive building codes, and as a result these structures typically lack the strong connections necessary to provide an adequate vertical or lateral load path to resist tornado loads. Furthermore, as shown in Figure 6 the majority of the

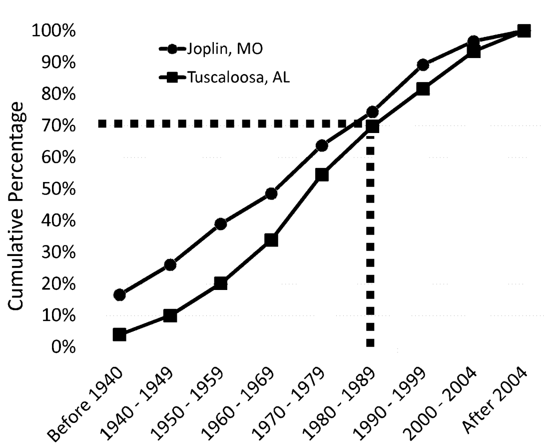


Figure 6: Age Distribution of Housing (Bureau, 2011)

homes were built over 30 years ago and the effects of aging reduce the expected performance as well. The result is a large number of homes that are particularly vulnerable to extreme wind events such as tornadoes.

Wood-frame homes are unique in that typically the components and cladding elements of the home also dictate the system response. Roof sheathing serves to tie the individual trusses together to act as a single diaphragm and similarly the wall sheathing to the stud walls as shown in Figure 7. These two diaphragms act together, with the roof diaphragm acting to support the interior portions of the transverse walls and transferring those lateral loads to the shear walls. As a result, the components of the structure are necessary to the capacity of the system, and loss of the components significantly weakens the system. The importance of the components however does not minimize the importance of the system, and particularly the various connections in the vertical and lateral load paths. Every element is needed to create a tornado-resistant home.

With this understanding, a sample set of 244 homes was selected from the dataset to perform a pilot study to examine correlations between the observed damage patterns. Seven damage patterns in all were identified in the sample set used for this pilot analysis and they are defined as given in Table 1.

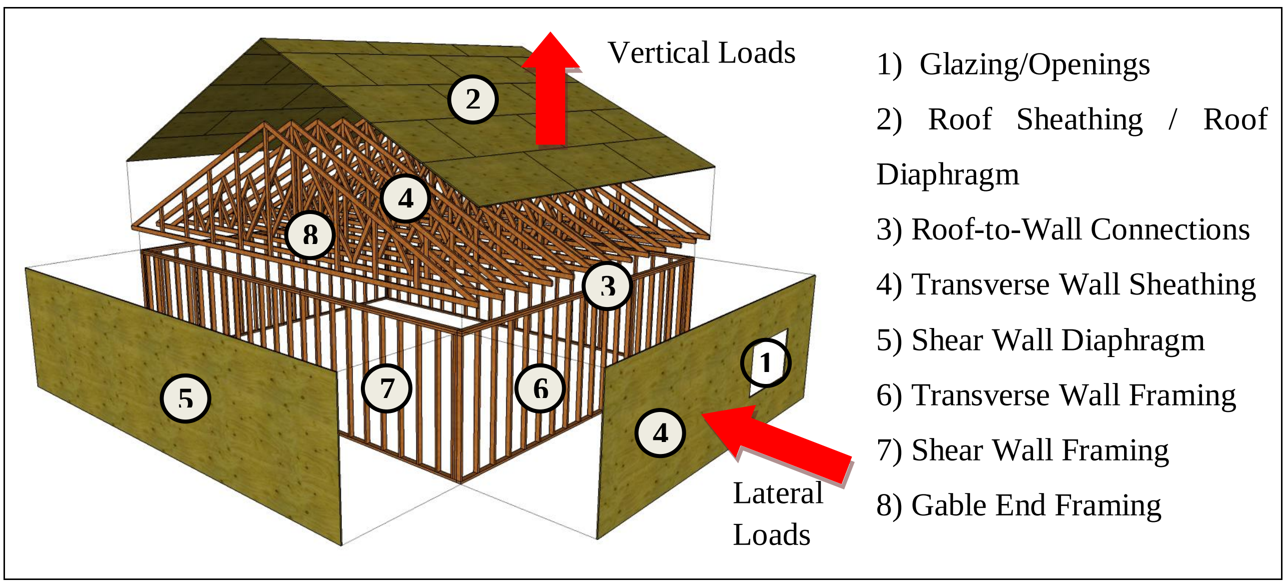


Figure 7: Major Components and Systems in a Typical Wood-frame Home

Table 1: Defined Damage Mechanisms for Wood-frame Homes

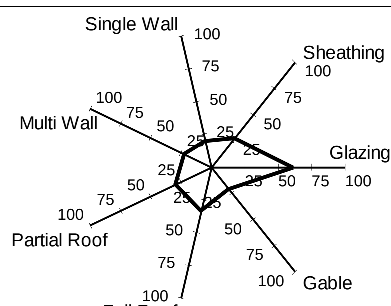
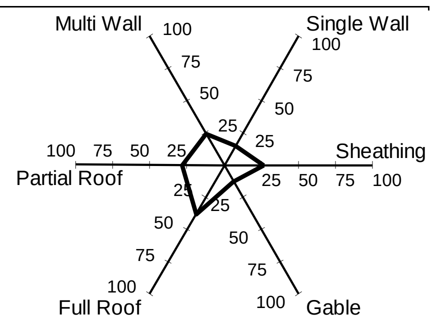
Glazing/Envelope Breach Broken glass in doors or windows or failure of a door or other opening. Broken glass is typically the result of wind-borne debris, the effects of which can be accelerated in dense residential regions or in the presence of trees, gravel or other potential projectiles. Door failures, particularly garage doors, are indicative of wind speeds near 100mph according to the EF scale provisions.	
Sheathing Failure Uplift of one or more sections of roof deck. This failure mechanism corresponds to a Degree of Damage of 4 and is indicative of significant uplift forces on the roof. Although typically not a major structural failure, it can lead to progressive failures, due to the resulting weakening of the roof diaphragm, and significant economic losses from the resulting water ingress.	
Partial Roof Removal Failure of one or more roof trusses at the roof-to-wall connection. The loss of multiple such connections weakens or eliminates the transfer of lateral load from the walls into the roof diaphragm and can lead to collapse of walls.	
Full Roof Removal Failure of all roof-to-wall connections, such that no part of the roof remains. The complete removal of the roof leaves the walls particularly vulnerable to collapse due to the loss of the roof diaphragm.	
Single or Partial Wall Collapse Collapse of an entire single wall or any significant portion of a wall	

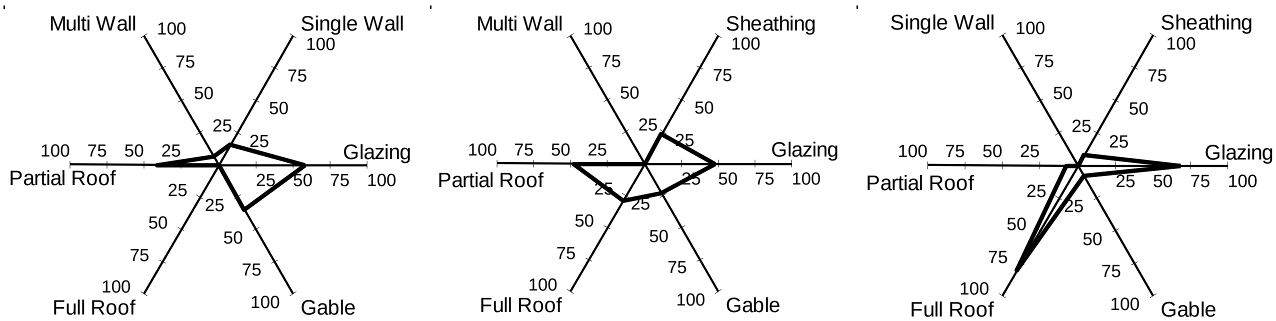
Multiple Wall Collapse Collapse of more than one wall, including complete collapse of all walls.	
Gable Failure Collapse of the gable truss or separation of the gable truss from the gable wall below. This damage mechanism was documented due to previous studies which have shown that a significant portion of the vertical load throughout the roof system is transferred to the walls through the gable end. (Datin, Mensah *et al.*, 2010)	

OBSERVED FAILURE PATTERNS

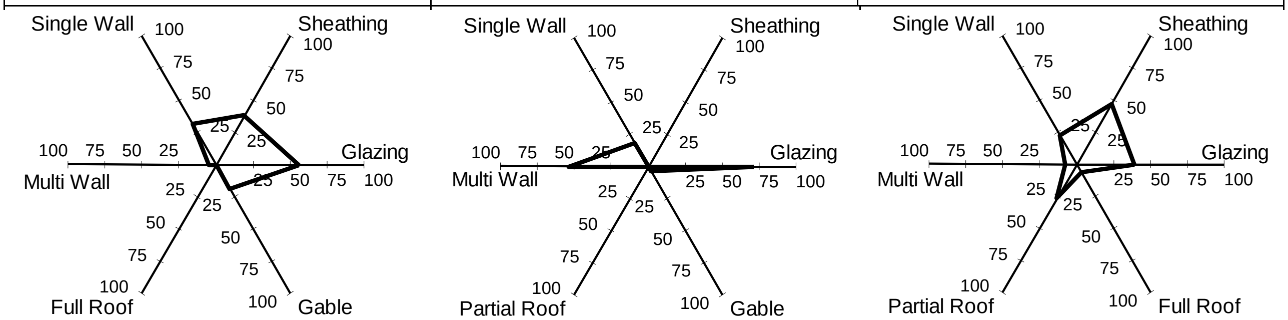
The subset of 244 wood-frame residential structures was analyzed to identify which failure mechanisms were present and the results are illustrated in Table 2 below. In the majority of the structures multiple failure mechanisms were identified. The overall distribution of failure mechanisms within this subset is illustrated by percentage in (a). Further, in each spider-web diagram (a) through (g) the association of each failure mechanism is analyzed showing their percentage frequency of occurrence, with which it was associated with the other defined failures.

Table 2: Observed Failure Patterns in Wood-frame Homes

	
(a) <u>Distribution of Damage Mechanisms</u>	(b) <u>Glazing</u>



(c) Sheathing	(d) Single Wall	(e) Multiple Walls



(f) Partial Roof	(g) Full Roof	(h) Gable

The analysis demonstrates several trends with respect to damage patterns in tornadoes that are worthy of discussion.

1) The most prevalent failure mechanism is the failure of glazing (50%) Table 2(a), which is to be expected given the large, circulating debris cloud associated with tornadoes.
2) The collapse of multiple walls was the most highly correlated (at 81%) with full removal of the roof, Table 2(d), illustrating the importance of the roof diaphragm in overall stability of the house. Of the homes that were observed to have multiple wall collapse, 81% were associated with full removal of the roof as well. This again illustrates the importance of the roof diaphragm in the support of the walls. Without the support of the roof diaphragm, the exterior walls function as inadequately fixed cantilevers and are prone to collapse. Interior walls could serve to provide additional interior support but in typical construction minimal attachment if any is used to connect the interior and exterior walls.
3) With nearly 60% of the homes experiencing envelope breaches of some kind, it is probable that internal pressures played a significant role in the final damages. Of the homes that experienced full roof removal, nearly 75% of them also had breaches in the envelope whether due to glazing fracture or door failure. Perhaps this should be expected given the large, fast-circulating debris clouds associated with tornadoes. But such breaches in buildings suffering full roof removal and multiple wall collapse occur 20% more often than in the other defined damage mechanisms. This suggests a failure pattern of glazing breach → buildup of internal pressures → full roof removal → multiple wall collapse.
4) Gable failures were associated with roof sheathing removal in nearly 50% of the observed homes. While not as strong a correlation as the others, it suggests an intuitive

failure pattern in which the loss of sheathing, typically along the gable wall in the ASCE 7 edge zones, can weaken the support of the gable truss and allow it to collapse.

DISCUSSION

The results of this analysis provide insight into what should be the primary areas of focus for tornado-resistant design. As discussed previously, the protection of the roof diaphragm is vital to maintaining the structural integrity of the home during a tornado, and this is validated by the results. In homes in which multiple walls collapsed, full roof removal occurred in 81% of the cases. The use of stronger roof-to-wall connections such as the metal ties used in hurricane-prone regions could significantly reduce the number of buildings that experience total collapse by strengthening the roof-to-wall connections and maintaining the structural integrity of the roof diaphragm.

With nearly 60% of the homes being identified with breaches in the envelope, it is obvious that unless debris-impact glazing and strengthened doors are used, the impact of internal pressures cannot be overlooked in design. Moreover with the significant debris-cloud and high winds associated with tornadoes, it may be necessary from a tornado design standpoint to design for internal pressures in addition to providing a certain level of debris-impact glazing.

To improve performance of residential structures van de Lindt et al (Van De Lindt, Pei *et al.*, 2012) proposed a dual-objective design philosophy approach seeking to mitigate damage from EF0 to EF2 tornadoes while maintaining life safety. Using this approach, buildings can be designed to minimize damage for tornadoes in the EF0 to EF2 range but also provide life safety during tornadoes of higher intensity. Our analysis suggests that were such a design approach in place in Tuscaloosa and Joplin prior to these tornadoes, it would be possible to reduce tornado damage in as much as 85% of the impacted regions, and the reduction in debris cloud would mitigate losses even further.

FUTURE RESEARCH

Several avenues are proposed for future research. A failure patterns analysis is underway using the complete dataset of nearly 3,000 houses surveyed in the two tornadoes. Further an in-depth correlation study of failure mechanisms versus building location within the tornado's wind field will be conducted. The field data provides the basis for developing empirical models of structural load distributions within the tornadoes which will be used in validation studies against small-scale experimental models of tornado loads variation with distance from the vortex (i.e. Haan et al (F. L. Haan Jr., Balarmudu *et al.*, 2010)) using tornado simulators.

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