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Changing the Paradigm of Tornado Design Based on Evidence from the 22 May, 2011 Joplin, MO Tornado

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Tornadoes are by nature extremely low probability, high impact events for a given finite location, even in the heart of tornado alley. It is widely held that tornadoes produce forces that are so extreme it would make the cost of designing buildings to resist them too prohibitive. As a result, there has been little impetus to develop structural design criteria for tornado loads. Indeed the current minimum design load guide ASCE 7-10 states in Clause 26.5.4 Limitation that "Tornadoes have not been considered in the developing the basic wind-speed distributions." The design wind speed for Category II buildings in inland areas of the US is 51 m/s (115 mph), which was developed by ignoring potential of tornadoes occurring. However, violent tornadoes can generate winds estimated greater than 74 m/s (166 mph) that conservatively will produce building loads at least double those stipulated by code.

Most jurisdictions and code-writing bodies have not considered amending building codes to include tornado-resistant provisions. The one outlier has been Moore, OK which following the 2013 tornado that destroyed hundreds of homes and several schools, amended its building code in 2014 to increase design wind speed to 60 m/s (135 mph). This decision was motivated in part because the City of Moore has experienced three powerful tornadoes within a 12-year period that destroyed hundreds of residential buildings. In essence though, most communities have made the choice to accept that the current level of annual occurrences of tornado-related fatalities, levels of damage and injuries are inevitable. A closer look at the destruction in recent tornadoes however provides strong motivation for changing the status quo. In this article we use the May 22, 2011 Joplin, MO tornado as a case study to illustrate the problems with the current wind design paradigm and the way forward more tornado-resilient communities.

Building Performance in the 22 May, 2011 Joplin, MO Tornado

The 2011 Joplin tornado, rated an EF5 on the Enhanced Fujita (EF) Scale by the National Weather Service (NWS), was one of the most powerful and deadly tornadoes ever recorded in the US. It caused 158 fatalities, damaged or destroyed over 7,500 homes, and caused over \$2 billion in economic losses. Several engineering teams, meteorologists and agencies assessed the damage, including teams from NIST and ASCE (Kuligowski et al. 2014; Prevatt et al. 2012). One outcome of the NIST investigation was the development of a tornado wind field model calibrated to match tree fall patterns observed in the tornado path (Lombardo et al. 2015). The ASCE team, which included the authors, developed a database of 1,349 individual structures, rating the level of damage (expressed as Degree of Damage [DOD] from the EF Scale) and the location of each structure. When comparing the estimated peak wind speeds to the observed damage as shown in Figure 1, it can be observed that the structures located in areas that experienced below the design wind speed for Joplin area, (i.e. 62 m/s [115 mph] based on ASCE 7-10) generally performed well, with damage to homes limited primarily to loss of roof covering, building cladding and sheathing (DOD 4 or less). More quantitatively, fragility functions were developed from the wind speed estimates and damage observations. These functions provide the conditional probability of reaching or exceeding a specific damage state (i.e., DOD level) given a gust wind speed, or $P(DS \geq ds | V = v)$, where DS is damage state and V is 3-sec gust wind speed at 10 m. The fragility functions were assumed to follow a lognormal distribution, and logistic regression with a probit link was used to fit the fragility functions for each DOD level (for D12, 1- and 2-story homes) to the empirical data, as described more fully in Roueche et al (2015).

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Figure 2 provides the survival functions (i.e., $1 - P(DS \geq ds | V = v)$) for the empirical data, demonstrating that at the design wind speed of 51 m/s (115 mph), the probability of experiencing repairable damage (less than DOD5) was 62%. Even at wind speeds as high as 65 m/s (145 mph), there was still a 20% probability that the building was repairable. For a building code whose intention is to protect life safety, not necessarily minimize building damage, these results would indicate that the structures are performing as good as or better than expected. For engineered buildings one would expect to see a higher survival rate for structures experiencing the design event, but the majority of the damaged structures were non-engineered, wood-framed construction, most likely designed in accordance to prescriptive requirements that inevitably lack strengthened vertical and lateral load paths. Thus it should come as no surprise that the destruction is so extensive. The community-wide decision of selecting the specific design wind speed and construction requirements that ignores a particular tornado hazard leads to this result. The questions are, should we continue to make that same choice in future, and if so what should the role of the engineering community be in the debate?

The Way Forward

Society relies upon the engineering profession to provide sound, scientific information upon which rational decisions can be made. Our research on tornadoes is attempting to illustrate the consequences of community-wide decisions on residential infrastructure, by pointing out that the level of structural damage observed in the Joplin tornado is commensurate to the building code guidelines adopted and current construction practices. Changes in the building code and mandating better construction can, we feel, result in considerable improvements and greater resilience of structures following future tornadoes. Through the research underway at the University of Florida and elsewhere, significant advancements have been made towards addressing tornado design. Tornado simulators, both numerical and physical, have given us a better understanding of tornado-induced loads on buildings, and will continue to do so with new, even more advanced facilities such as the WindEEE Research Institute at Western University. Researchers at Applied Research Associates (Phan et al. 2015), and at the University of Florida (Peng et al. 2014), have separately developed engineering-based tornado catastrophe models that estimate probabilistically the performance of structures in tornadoes. Post-tornado dam-

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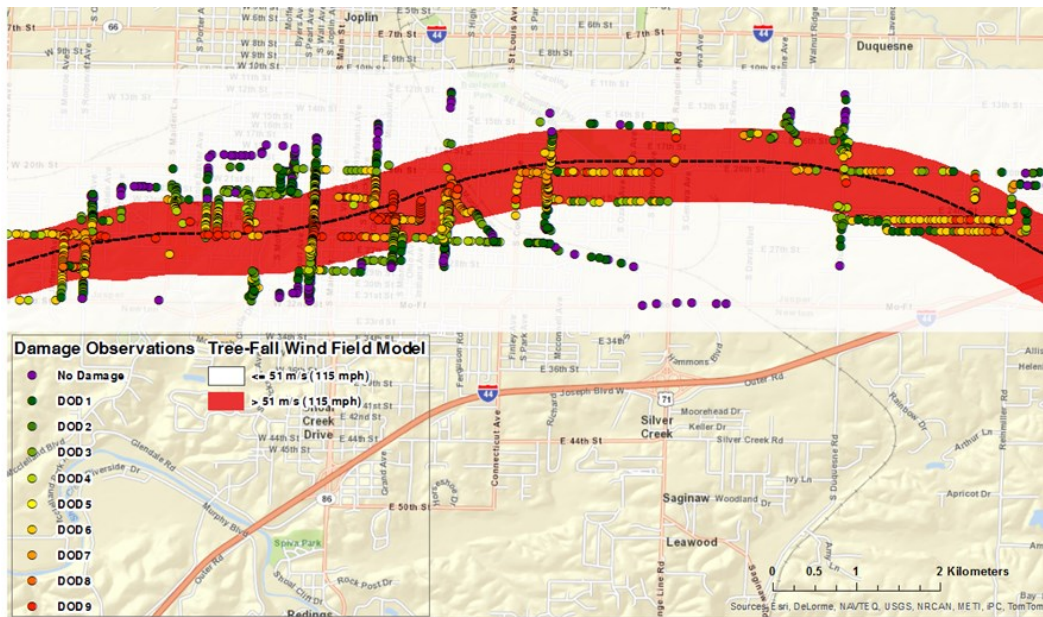
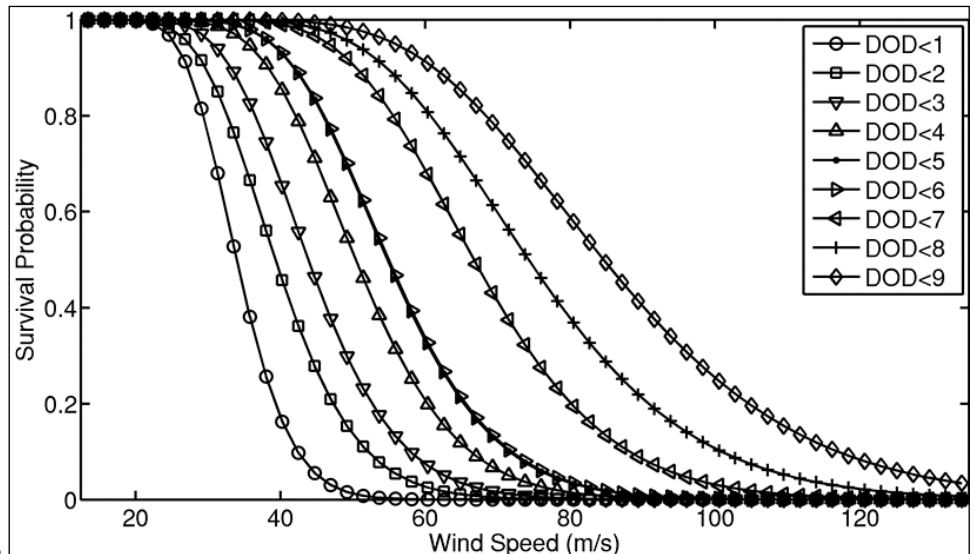


Figure 1. Observed damage levels from ground survey compared to wind speeds above or below the design wind speed. Wind speed estimates are from the tree-fall based wind field model described in Lombardo et al (2015).

Figure 2. Probability of survival, i.e., $P(DS < ds | V = v)$ for a given wind speed.



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age surveys continue to provide critical data that is used to validate the ongoing research and answer questions about interaction of tornado-induced forces and existing building performance.

As more and better tools are deployed for field data collection, potentially under the ambit of a future NSF-sponsored NHERI RAPID, the wind engineering community can improve estimates of wind speeds causing damage throughout populated areas. Experimental research continues towards developing effective, economical retrofit solutions for our existing homes, focusing on prevent immediate collapse of exterior walls when the diaphragm support at roof level is compromised (Roueche and Prevatt 2013). The intention is to provide better overall structural rigidity to the structure and thereby reduce risk of death or injury from flying debris and structural collapse. Another positive development has been the formation of the EF-Scale Standards Committee, formed by collaboration of the American Society of Civil Engineers (ASCE) with the Storm Prediction Center. This body comprising mainly volunteer engineers is working to improve our classification methods for tornadoes. To disseminate the latest research to practitioners, the ASCE Wind Load Subcommittee has developed an Appendix for estimating tornado design loads to be included in the Commentary of the forthcoming ASCE 7-16 minimum load standard. There is a synergy to these efforts that must be recognized and continued. New tornado design criteria, with dual performance objectives of life safety and minimizing structural damage, should be the new paradigm for the communities (van de Lindt et al. 2012), and AAWE and others are going to be instrumental in disseminating the knowledge through education and engagement of our communities.

Challenges remain of course and there are still many questions to answer, but there is reason to believe a future of continued catastrophic tornado losses is not inevitable. The improved post-hurricane performance of buildings in Florida points us towards solutions now required. Many of us have stood on street corners in the aftermath of catastrophic tornadoes like Joplin's, where the individual piles of debris used to be what someone called their homes, where families once felt safe. It is an overwhelming feeling, to know that that pattern need not be always inevitable, and as engineers we can bring hope for a better future.

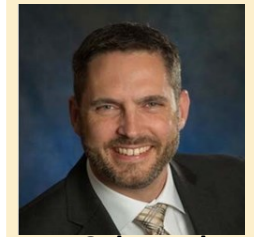
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Results of the AAWE Election

Congratulations to **Jon Galsworthy** on his election as President-elect of AAWE (President in 2017-2018). And to newly elected Board Members: **Girma Bitsuamlak**, **Murray Morrison** and **Steve Camposano** (2015-2018).



Jon Galsworthy

The balloting was conducted on Survey Monkey and the results were confirmed by former AAWE Presidents, Partha Sarkar and Greg Kopp. A special thanks to the other candidates who stood for election and the 7 write-in candidates which prove our organization is robust!

I look forward to working with the new Board and its President-elect.

Chris Letchford
President, AAWE

ASCE Awards

Ahsan Kareem, the Robert M. Moran Professor of Engineering and Director, NatHaz Modeling Laboratory, University of Notre Dame received the 2015 Theodore von Karman Medal for fundamental contributions to the quantification, modeling, simulation and analysis of dynamic load effects, and its application in aerodynamics in civil engineering, in the best forward looking tradition of Theodore von Karman. The Theodore von Karman Medal was established and endowed in 1960 by the Engineering Mechanics Division (now Engineering Mechanics Institute) of the Society to honor the seminal contributions of Theodore von Karman in mechanics. It is awarded to an individual to recognize distinguished achievement in engineering mechanics, applicable to any branch of civil engineering. Prof. Ahsan Kareem is a former president of AAWE and serves as elected president of IAWE.

Lord Julian C. R. Hunt, University College London and University of Cambridge (formerly Head of the UK Met Office) received The 2015 Jack E. Cermak Medal for his many contributions to turbulence modeling leading to better understanding and quantification of wind structure interactions, and his vision in propelling the quantitative world of engineering into the problem domain of climate change which will dominate the 21st century. This medal was established by the Engineering Mechanics Institute and the Structural Engineering Institute to recognize Dr. Jack E. Cermak's lifetime achievements in the field of wind engineering and industrial aerodynamics. It is awarded to an individual to recognize outstanding contributions to research and/or practice in wind engineering.

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