9th Asia-Pacific Conference on Wind Engineering
Auckland, New Zealand
3-7 December 2017

9th Asia-Pacific Conference on Wind Engineering: Analysis of residential building performance in tornadoes as a function of building and hazard characteristics

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Abstract

Although it is known that some building and hazard characteristics are the determining factors for the level of devastation caused by a tornado, quantification of how much specific parameters contribute to damage is still unknown. This research will use empirical remote sensing damage data from the May 22, 2011 tornado in Joplin, MO to create fragility curves based on specific building and hazard characteristics.

Introduction

One of the most devastating aspects of a tornado is the destruction to the built environment. When homes and businesses are destroyed, it leads to disruptions that will require significant recovery time. Tornadoes cause not only economic losses, but also stress and anguish, injuries, and loss of life. Newer structures have performed better as building codes are improved and adopted by local jurisdictions, but structures that are not designed to withstand the extreme winds of a tornado are still vulnerable to damaging wind. Further research is needed in order to find technically feasible and cost effective ways to lessen the vulnerabilities of existing building stock and new construction. Analysing building performance in past tornado events could provide further understanding of the interaction between buildings and tornadic winds and help quantify the effect of certain building and hazard characteristics on their risk to high winds. Identification and quantification of these parameters contributing to building performance would be highly useful to mitigation efforts.

One of the recent major tornadoes available for analysis is the Joplin, Missouri tornado that occurred May 22, 2011. Several research teams from different organizations and universities were deployed to collect data and investigate the damage, including Texas Tech University (TTU), National Institute of Standards and Technology (NIST), Federal Emergency Management Agency (FEMA), University of Florida (UF), and University of Alabama (UA). Therefore, a significant amount of remote sensing data exists on this event. Wind field models based on tree fall data were developed at NIST and Iowa State University which could be used to estimate the distance of each building relative to the centreline of the tornado path and the wind speeds it was subjected to.

The Joplin tornado was rated by the National Weather Service (NWS) as an EF5 tornado [10]. The event resulted in 161 fatalities, the most fatalities from a single tornado on record, and over 1,000 injuries reported [5]. The tornado was on the ground for a total of 38 minutes resulting in a 22.1-mile long and 0.75-mile-wide path causing $1.78 billion of insured losses for commercial and residential property making it the costliest tornado on record [2, 5]. The tornado was inside the city limits of Joplin for 15 minutes and 6 miles of the total path, which struck areas consisting of both residential and commercial buildings providing a rich inventory of building types for analysis, although this research focuses primarily on residential structures.

Objective

Current building codes (e.g. International Building Code and International Residential Code) require that buildings are designed to withstand the wind loading and pressures induced up to a certain minimum design wind speed depending on their location. These design wind speeds are determined as 3 second gust speeds at 33 feet above the ground with an exposure category C for 500 year events (0.2% probability of exceedance). Extreme winds, such as those that occur during a tornado, have a much smaller probability of occurrence, but have the potential of inducing pressures way beyond what a structure would have been designed for using the minimum design wind speed. Because these pressures vary based on the geometry of the structure and the direction of wind flow, certain characteristics of the building and tornado would influence structure-fluid interaction. These building characteristics would include roof shape, roof slope, dormers, porches and decks, number of stories, an attached garage, building shape, etc. Other non-architectural building characteristics will be analysed as well including data obtained from the tax assessor such as year built and square footage. Tornado characteristics would include peak wind speed, direction of flow, and duration.

The main objective of this research is to gain a better understanding of the effect of building characteristics and location for their survivability in a tornado event. It will estimate the probability of the structures to exceed given damage states and create fragility curves for the features or combinations of features contributing to differing performance levels.

Building Damage and Wind Field Data

Empirical data are collected through remote sensing images from the aftermath of the tornado that caused damage to nearly 8,000 residential structures in its path [10]. The initial dataset used for this research is the data provided by TTU which includes tax assessor data and the Degrees of Damage (DODs) for 6,579 buildings as rated by TTU students [8]. The DODs are assigned using the Enhanced Fujita Scale (EF Scale) where 28 Damage Indicators (DIs) have predicted DODs for estimated wind speeds [9]. The tax assessor data contains basic information for each site such as address, GPS coordinates, year built, building type, exterior wall material, building style, number of stories, foundation type, and square feet. This dataset contains DODs for 21 different DIs as determined using drive-by photos. The DI with the most DODs in the dataset is FR12 (1- to 2-family residences) with 5,450. The NIST dataset used to create their wind field model based on tree fall data also contains tax assessor data and geolocated polygons of each of the structures which will be useful for analysis involving hazard characteristics that need location information [5]. The data from the University of Alabama includes an EF rating for 1,417 structures. The remote sensing sources available to assess the damage include: high resolution aerial imagery (available from Surdex and National Geodetic Survey NOAA), drive-by pictures (from Google Street View, Texas Tech, University of Alabama, and University of Florida), low resolution aerial imagery (Google Earth), oblique imagery (Bing Bird's Eye Imagery and Pictometry), and field survey pictures (University of Florida).

Wind speed estimates are from wind field models based on the tree fall patterns [4, 5]. Multiple wind field models have been created based on the damage caused by the Joplin tornado. The wind field model created by NIST used the wind speeds estimated using a Rankine vortex model fitted to the observed tree fall data [5]. Karstens et al. also created a wind field model from the tree fall data using a Gumbel distribution and assuming a Rankine velocity distribution [4]. Both models assume that the damage to structures or trees was caused by the peak wind speed experienced at its location. The tree fall models will be used to estimate the peak wind speed, direction, and time history data for the residential structures being evaluated.

Preliminary Analysis

Data analysis leads to the development of fragility curves for specific building characteristics to quantify how the feature effects building performance as tornado wind speeds increase. Only a subset of data is presented as data collection process is still underway. The latitude and longitude of the center point of each home was determined using the NIST ArcGIS file with polygons representing each structure. These latitudes and longitudes were run through NIST's tree fall model which produced estimated wind speeds at each of the points for a more precise wind estimate as opposed to using the nearest grid point wind speed estimate. The estimated wind speeds experienced by the homes in this dataset range from approximately 70 mph to 175 mph. Figure 1 shows the number of homes in each 10s of wind speed for this range.

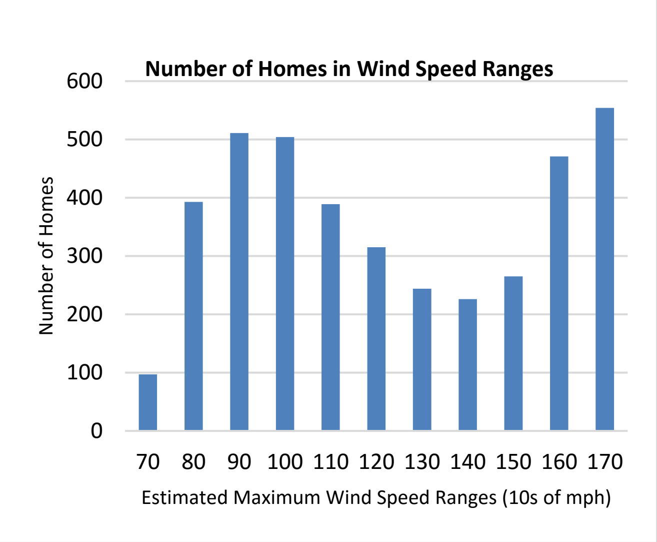

Figure 1. Number of homes in each 10s of wind speed for the range between 70 mph to 175 mph.

Initial review of the data led to some expected findings. The linear regression of the DOD vs estimated wind speeds increases as wind speed increases (Figure 2). DOD 0s found in the dataset are from houses that were unrated for reasons such as no drive-by photos or inadequate remote sensing data available to determine a DOD. Addresses with DOD ratings of 0 were removed from the dataset for the linear regression and R^2 determination in Figure 2 so they would not skew the results.

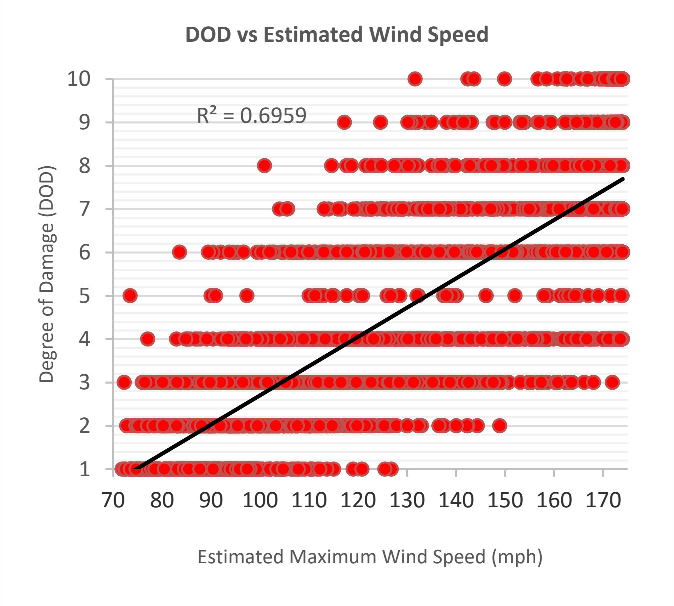

Figure 2. Degree of Damage (DOD) vs Estimated Wind Speed for homes in the 2011 Joplin tornado.

A few examples of the relative frequency of the DODs occurring from experiencing the range of estimated wind speeds are shown in Figures 3 through 6. As the DOD increases, the frequency of occurrence is higher at higher wind speeds. Residential structures rated DOD 3 appear to match up with the estimated wind speeds for this level of DOD per the EF Scale which has a lower bound of 79 mph and upper bound of 114 mph (Figure 3). However, some of the DODs have higher frequency at higher wind speeds than expected per the EF Scale. For example, in Figure 4 structures assigned DOD 7 have a higher frequency in the 160s even though the expected wind speed is 132 mph with a lower bound of 113 mph and upper bound of 153 mph. Structures assigned DOD 8 have higher frequency in the 160s and 170s, higher than the expected wind speed of 152 mph, although the range from lower bound to upper bound is 127 mph to 178 mph so they are captured by the upper bound (Figure 5).

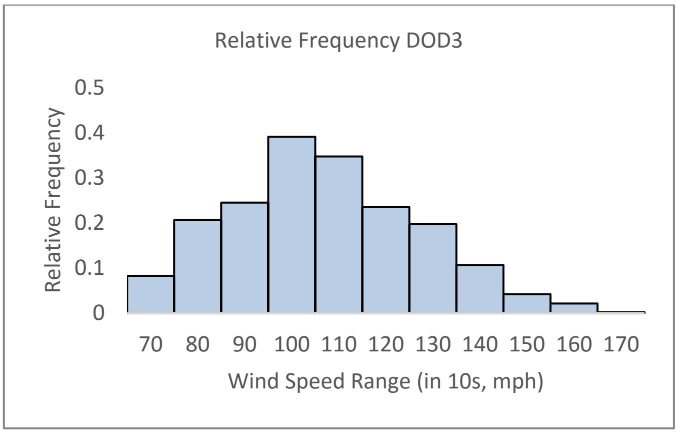

Figure 3. Relative frequency of homes with DOD3 in each wind speed range.

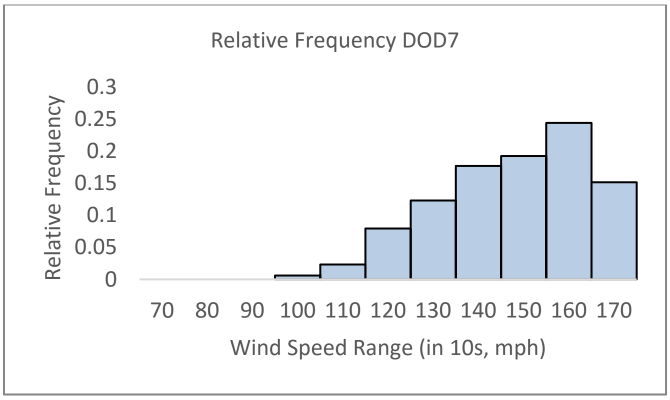

Figure 4. Relative frequency of homes with DOD7 in each wind speed range.

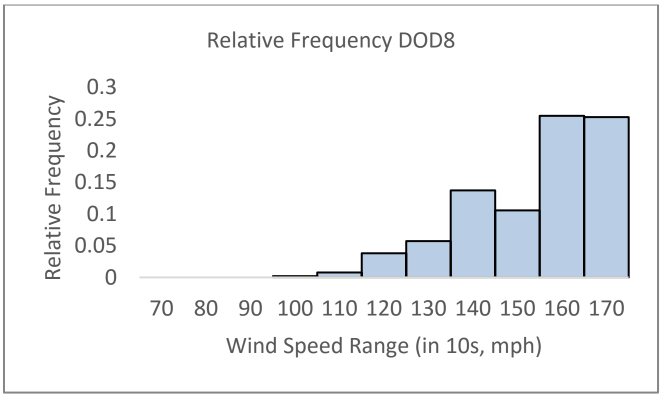

Figure 5. Relative frequency of homes with DOD8 in each wind speed range.

DOD 5 per the EF Scale indicates, “Entire house shifts off foundation,” and estimated wind speeds of 104 mph for lower bound, 141 mph for upper bound, and 121 mph expected. This will be problematic for remote sensing data collection where this shift may not be apparent from the images, therefore there are not many residential structures with this rating. The estimated wind speeds are very similar to DOD 6 with a lower bound of 104 mph, upper bound of 142 mph, and expected wind speed of 122 mph so the fragility curves for these two DOD levels may overlap.

Figure 6 shows the probability of an address reaching each DOD level for each wind speed range. The result is mostly as expected with the higher the estimated wind speed, the higher the probability of each of the DODs occurring. The reason DOD 10 was at 0 probability for all wind speed ranges is because there were not enough instances of DOD 10 collected.

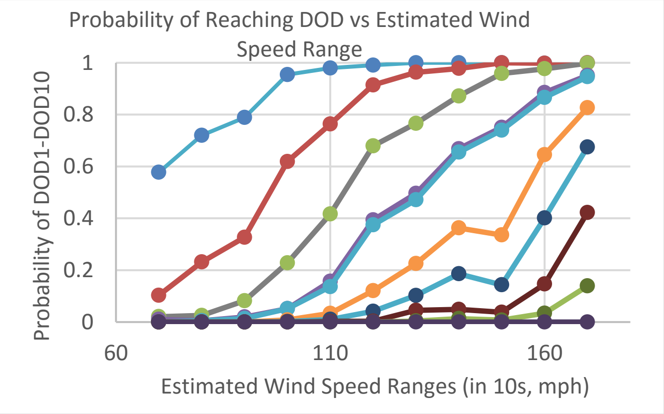

Figure 6. The probability of reaching DOD levels 1 through 10 (from left to right) for each wind speed range (in 10s) from the 70s mph to 170s mph.

Another example of the preliminary analysis conducted is a look at the difference between homes built using more modern building codes versus older building codes or no building code. The probability of exceeding each of the 10 DODs for one- and two-family residential structures built between 1859 and 1992 (Figure 7) and those built between 1993 and 2010 (Figure 8) were plotted. There is a slight shift in the lower DOD levels that show a slight increase in wind speed to achieve the same level of damage in newer homes compared to older homes, although there were only a couple hundred structures available to analyse of the newer housing stock. It may be possible to equalize the numbers of structures for a more in-depth analysis. Similar analysis will be conducted on the multiple parameters and variables which will inform which fragility curves will be created. Not all parameters are expected to effect structure performance during a tornado, although it is worth a look to determine which ones do.

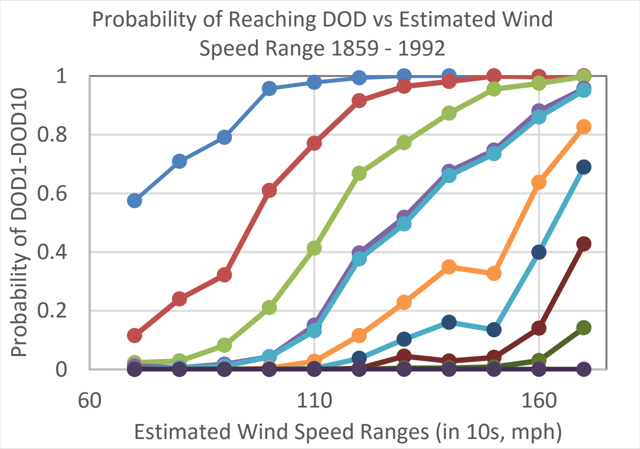

Figure 7. The probability of reaching DOD levels 1 through 10 (from left to right) for each wind speed rang (in 10s) from the 70s mph to 170s mph for homes built between 1859 and 1992.

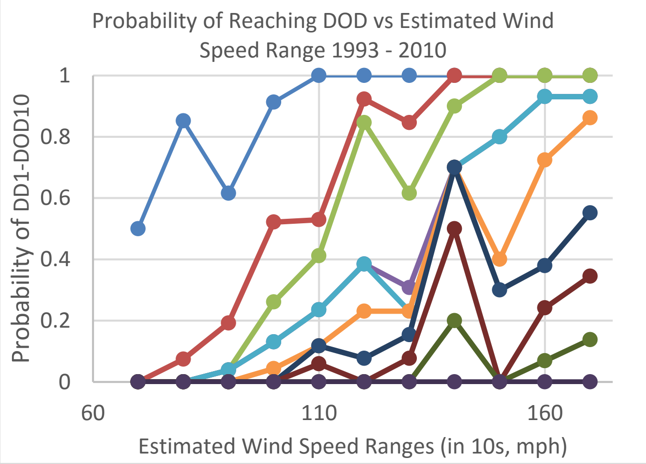

Figure 8. The probability of reaching DOD levels 1 through 10 (from left to right) for each wind speed rang (in 10s) from the 70s mph to 170s mph for homes built between 1993 and 2010.

Fragility Curve Development

Fragility curves are functions that express the probabilities of exceeding given damage states, specific parameters, and input variables. A common form of a fragility function is the lognormal cumulative distribution function (CDF) [11]. This is represented by

$$F_d(x) = P[D \geq d | X = x] \qquad d \in \{1,2, \ldots N_D\} \qquad (1)$$

$$= \Phi\left(\frac{\ln(x/\theta_d)}{\beta_d}\right)$$

where for tornado damage D is the degree of damage, d is a particular degree of damage, N_d is a number of possible degrees of damage, X is the demand on the system (an uncertain wind speed), x is a particular wind speed, Fd(x) is the fragility function for degree of damage d evaluated at x, Φ [] is the standard normal cumulative distribution function, θ_d is the median capacity to resist degree of damage d, and β_d is the standard deviation.

This has been widely used in earthquake damage, but can also be applicable to wind damage [6, 7]. Tornado damage is typically greater at the center of the tornado track which provides incremental data for several different wind speed ranges and the response of the structures in each range. While wind is not the only parameter which influences the level of damage, it is the parameter which will be used as the demand on the system as show above in the description of the parameters of Equation 1. The differences in damage states can indicate the level of expected performance such as intact, functional, collapse prevention (life safety), occupant comfort, continued occupancy, etc. [3, 7]. The damage states that will be used for this research are the DOD's for the DI FR12 (one- and two-family residential structures) from the EF Scale which range from DOD 1 to DOD 10.

The process of creating a fragility curve includes several iterations to determine θ and β which yield the fragility curve function that best fits the probability of damage that has been seen from the damage observations. Estimates of θ and β are denoted as $\hat{\theta}$ and $\hat{\beta}$ and will be determined using the maximum likelihood method (Equation 2) which estimates the parameters to provide the maximum likelihood of resulting in the observed data [1].

$$\{\hat{\theta}, \hat{\beta}\} = arg \max_{\theta,\beta} \sum_{j=1}^{m} \left\{ \ln \varnothing \left(\frac{\ln(X_i/\theta)}{\beta} \right) \right\}$$

$$+(n-m)\ln\left(1-\Phi\left(\frac{\ln(X_{max}/\theta)}{\beta}\right)\right) \qquad (2)$$

where $\hat{\theta}$ is the median, $\hat{\beta}$ is the standard deviation, m is the number of observed, n is the number of instances of equalling or exceeding the given damage state, and Φ is the standard normal CDF. Optimization of this formula to determine θ and β will be completed using Matlab.

The results of the fragility curve development are yet to come after the completion of the empirical data collection from the Joplin tornado. These fragility curves will be based on the parameters collected such as things like roof shape, roof slope, building shape, 1 story vs. multiple story, whether there is an attached garage, etc. in order to show the significance of specific building and hazard characteristics on the performance of a residential structure. Once these fragility curves are created, they will be compared to other existing fragility curves based on both empirical and analytical data for validation and comparison.

Conclusions

This research is ongoing, but significant progress has been made in the data collection process and preliminary analysis. The potential benefits of this research would be the ability to reduce damages to the built environment caused by tornadoes through providing a better understanding of what design features make structures more vulnerable and using that knowledge to inform mitigation efforts. Mitigating the destruction caused by a tornado could prevent hazards from becoming disasters, or at least lessen the extent of the disaster. This type of research is relevant to the wind engineering industry and has the potential to assist in research and development endeavors including the development of a wind speed estimate standard which is currently in progress and informing performance-based design efforts. The database created for this research could be used for future studies or even a model for future remote sensing data collection. Lessons learned from creating the database and the data collection process could be used to ensure the most efficient process for future databases of hazard damage that could further provide analysis opportunities as every tornado is unique.

Acknowledgments

The author would like to thank the National Institute of Standards and Technology for allowing use of their data and research facilities. Especially Dr. Marc Levitan who has provided invaluable insight and advice throughout the entire process.

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