J. Wind Eng. Ind. Aerodyn. 138 (2015) 27–35

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

An estimate of tornado loads on a wood-frame building using database-assisted design methodology

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ARTICLE INFO

Article history:
Received 5 December 2013
Received in revised form
16 November 2014
Accepted 16 November 2014
Available online 9 January 2015

Keywords:
Tornado
Database-assisted design
Finite element modeling
Wind loads

ABSTRACT

Thunderstorms and related tornadoes caused over $25 billion in damages in 2011, the majority of which occurred to residential structures. Over 13,000 homes were damaged or destroyed by two tornadoes in Tuscaloosa and Joplin alone. Such substantial losses should not be surprising because as yet, no design guidelines exist for tornadoes, and with the current wind provisions in accepted building codes there is limited capacity in any wood-framed structure to withstand tornado loads. The objective of this current study is to develop appropriate design structural reactions for light-framed wood structures that is subjected to tornado loads. The study uses tornado simulator-generated surface pressure data from a fully sealed 1:100 scale gable roof model, experimentally-determined structural influence functions, and a modified database-assisted design (DAD) methodology to predict the reactions. Forces are established at structural connections for a tornado with peak wind speeds of 60.3 m/s (135 mph). Results are compared against structural reactions due to straightline winds with an identical peak wind speed, as determined using ASCE 7–10 wind pressure distributions. It is shown that for a sealed building (i.e., no pressure equalization between the building interior and exterior), the peak shear forces under tornado loads are 1.8 times as strong for roof-to-wall connections and twice as strong for wall-to-foundation connections, as compared to those from ASCE 7–10 wind loads. The peak vertical loads on connections are even higher, nearly four times as high for the roof-to-wall and wall-to-foundation connections. Nearly 60% of the peak loads can be attributed to the assumption of a fully sealed building mode, which results in the full effect of the pressure drop within the vortex being experienced on all surfaces of the building.

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1. Introduction

From 1950 through 2012, 94% of US tornadoes were rated EF2 or less (SPC) using the Enhanced Fujita Scale (McDonald et al., 2006). Further, nearly 90% of the area within the damage path of an EF4 or EF5 tornado can sustain EF2-rated wind speed damage or less (Prevatt et al., 2012). However, tornadoes continue to cause significant economic losses each year. In 2011 alone, tornadoes and related thunderstorms caused over $25 billion in property damage (MunichRE, 2012), the majority of which was to residential structures. Nearly 13,000 homes were damaged or destroyed in Tuscaloosa and Joplin alone by two tornadoes (Prevatt et al., 2012).

The extensive damage highlights the vulnerability of homes in the United States, particularly when a violent tornado impacts a densely populated area of single-family residential structures. Due to the low ductility inherent in the connections between structural components, residential structures typically experience brittle failures in high winds, because they have little capacity to absorb loads that exceed their design levels. It is generally assumed that methodologies to mitigate tornado damage are uneconomical, but this assumption has been made primarily from observations of catastrophic damage occurring to buildings that had minimal engineering attention and low structural capacities. Unfortunately this catastrophic damage could be predicted, because most residential construction is governed by codes calibrated for performance at very low wind loads. For instance the ASCE 7–10 design wind speed for structures in Okalahoma is 51 m/s (115 mph), as compared to estimated wind speed in an EF-2 tornado of 60 m/s (135 mph). As a simple comparison, this difference results in a design load that is 70% of the expected tornado-induced load.

Typically, the level of structural design is governed by the potential for catastrophic loss of life. This life-safety design philosophy accepts total loss in residential structures under tornado loads, despite the substantial collective economic value of housing

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http://dx.doi.org/10.1016/j.jweia.2014.11.011
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that is lost and the high likelihood that people may be in their homes rather than other commercial structures during the most common times of the day for tornado strikes.

The motivation for this research is the currently accepted paradigm which accepts the catastrophic collapse of residential structures within the direct tornado path. The new paradigm should be based on the dual-objective design philosophy for tornado engineering proposed by van de Lindt et al. (2012), which stipulates structural designs that simultaneously ensure life safety while reducing structural damage and economic losses. The current study quantifies a specific level of tornado load (from experimental studies), and estimates the effects of the simultaneous interaction of these loads on multiple building surfaces. The structural analysis approach enables determination of the magnitude of tornado load effects at the critical structural connections (roof-to-wall, and wall-to-foundation locations) of a typical light-framed wood structure, gabled-roof house. Ultimately the research envisages cost-effective structural designs for tornado-prone regions, as is common now in hurricane-prone regions, and which have been shown to reduce the level of structural damage in residential structures.

2. Previous research

Cost-effective structural designs to mitigate catastrophic tornado failures require knowledge of tornado pressures, structural load paths, and structural resistance of components and their connections. For this current study the estimate of tornado pressures was obtained from previous work by Haan et al. (2010) using a physical tornado simulator at Iowa State University. Load paths are defined by building upon previous work defining load paths in a light-frame wood structure (Mensah et al., 2011).

2.1. Tornado pressures

Haan et al. (2008) developed a large physical tornado simulator that translated a tornado-like vortex over instrumented scale building models. Flow structure of the simulated tornadoes was validated by comparing the results with mobile Doppler radar observations of two major tornadoes and good agreement was found. The tornado pressures used for this study represent Case 1 from the 140 Cases studied by Haan et al. (2010) and was chosen because it resulted in the highest uplift force coefficient of all cases considered. The simulated tornado for Case 1 had a swirl ratio of 0.08, a radius to maximum winds of 0.23 m (9.1 in.), a mean horizontal velocity of 8.3 m/s (18.6 mph) and a translation speed of 0.15 m/s (0.34 mph). A 1:100 scale gable building model was used (Fig. 1), having plan dimensions of 91 mm by 91 mm (3.6 in. by 3.6 in.), an eave height of 36 mm (1.4 in.) and a roof angle of 35°. Vortex-produced pressures on the walls and roof were captured as the vortex translated directly over the building model using 89 total pressure taps and a sampling frequency of 430 Hz. The passage of the vortex over the building model was repeated ten times and the ensemble median is used in this study to establish the pressure distributions through time on a gable building.

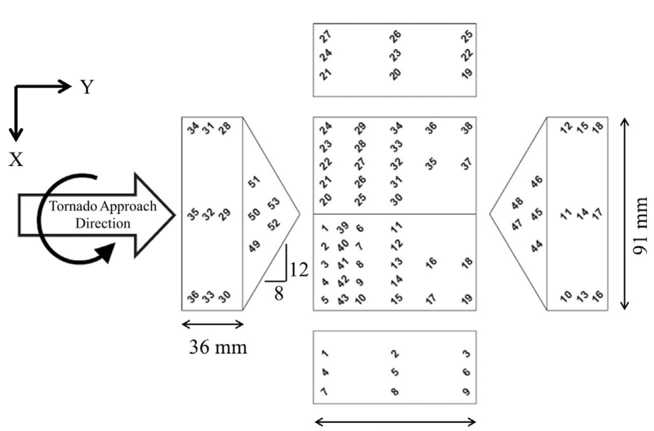

Fig. 1. Layout and dimensions of building model used in vortex simulator (Haan et al., 2010). Pressures captured as the vortex translated over the model were used for this study.

The implications of scaling the tornado in relation to the structure in laboratory experiments is not yet known and deserves further study. The researcher must strike a balance between the physical size of the facility that creates as large a vortex as possible and the need to use a minimum size for small-scale model of the structure for proper installation of pressure taps and tube connections to pressure measurement systems. For the case considered in this study, the ratio of the simulated vortex diameter (0.46 m) to the characteristic building length (0.091 m) is 5. Other recent studies using vortex simulators have reported factors of 0.43 (Mishra et al., 2008) and 3 (Sabareesh, 2012). The average width of an F/EF2 tornado damage path according to records maintained by the US Storm Prediction Center (SPC) is 158 m (518 ft), which compared to a full-scale structure with characteristic length of 9.1 m (30 ft) would give a ratio of 17. The actual vortex core diameter however is difficult to measure and is not part of the tornado records. It is smaller than the width of the entire damage path though, and thus the actual ratio of an average F/EF2 vortex core diameter to a structure is likely also less than 17. Therefore the ratio used in this study could be considered a reasonable representation of perhaps a slightly narrower than average full-scale EF2 vortex. The implications of this ratio for the scaling of pressure data obtained from small-scale models is not well understood, but it is an area that deserves further research and may be resolved with the development of larger facilities such as the WindEEE dome at the University of Western Ontario.

2.2. Comparison of tornado to straightline wind pressures

A generalized comparison of the wind flow structure during a tornado with that during straightline winds reveals differences that have significant implications with regards to the resulting wind loads on a typical enclosed structure. While straightline winds nominally consist of a single flow vector oriented along a dominant wind direction, tornado wind flow consists of significant tangential, radial and vertical components that create very different loading patterns on an enclosed structure in the path of the flow (Hu et al., 2011). Moreover, the static pressure drop associated with the tornado vortex itself further contributes to the overall loading patterns on a structure, a mechanism not present with straightline winds. How much of an effect this static pressure drop has depends upon the ability of the structure to equilibrate the internal pressure to the pressure drop associated with the tornado vortex. A fully sealed building will feel the full effect, while leakage will decrease the effect (Kikitsu et al., 2011). This study uses a fully sealed building, which has been assumed in other studies with wind engineering applications (Haan et al., 2010; Amini and van de Lindt, 2013).

2.3. Structural load paths in a light-frame wood structure

Database-assisted design (DAD) has previously been proposed as an accurate means of estimating structural reactions in a building at a specific location (Rigato et al., 2001; Whalen et al., 2002). The DAD methodology utilizes three main components: (1) an aerodynamic database of wind pressure time histories; (2) climatological databases of historical wind velocities for a given location, and (3) a database of structural influence coefficients for the structure. For this study, a single wind speed and direction is used, which is not typical for a complete

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