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Effect of low-rise building geometry on tornado-induced loads

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ABSTRACT

Despite the destructive effects of tornadoes, limited attempts have been made to quantify tornado-induced loading. The purpose of the study presented here was to investigate the effect of different building geometry on the forces and pressures that low-rise buildings would experience in a simulated tornado with a swirl ratio comparable to what has been measured and recorded for full-scale tornadoes. Measured force and pressure data were then used to judge whether tornado-resistant design for residential structures is feasible. The tornado-induced wind loads were measured on scaled models of buildings in a laboratory-simulated tornado with a core diameter (56 m) and relatively high swirl ratio (2.6) representing an EF3 tornado. The study found that the peak loads vary as a function of eave height, roof pitch, aspect ratio, plan area, and other differences in geometry such as the addition of a garage, roof overhang and soffit. The required strengths of the roof-to-wall and roof sheathing-to-rafter connections were calculated based on the measured loads and compared with their capacities to assess the possibility of failure. It appears that the design of the two critical roof connections in residential construction for tornado-resistant design up to and including EF3 tornadoes can ensure adequate safety cost-effectively by using currently available technology.

1. Introduction

Various opinions as to whether tornado-resistant design of residential buildings is possible, let alone feasible, have been offered. These opinions have been largely motivated by experience obtained from evaluating structural failure due to strong winds and prejudiced by the awe-inspiring destructive capacity of tornadoes, but they have not been based on the comparison of pressure data obtained from either full-scale or laboratory simulated tornadoes with the capacities of the structural connections and members of typical residential construction. Modern engineering is based on the application of rational and empirical principles, but for tornado-resistant design, there has been little or no data that could be used to form engineering principles. In the past, quantification of pressures on a building envelope and forces on a building structure due to the occurrence of a tornado in its proximity has been limited to forensic investigation and engineering judgments. The reason for this limitation is threefold: the lack of research facilities capable of determining the pressures and forces on structures due to tornadoes; the absence of full-scale data to corroborate the results from laboratory experiments or field structures; and a lack of interest in pursuing tornado-resistant design on the part of many as it was assumed to be cost prohibitive.

A tornado simulator has been constructed at Iowa State University (ISU) to overcome the first challenge (Haan et al., 2008). The ISU tornado simulator is capable of creating a model scale tornado that allows building models to be placed in its path as well as having the ability to travel relative to a building model to be investigated. The ISU tornado simulator also has mechanisms to adjust several different variables resulting in different types of tornadoes. The second challenge has also been overcome recently with full-scale data obtained from several recent tornadoes (Karstens et al., 2010; Lee and Wurman, 2005; Wurman, 2002). Subsequent effort has enabled the characteristics of the laboratory simulated tornadoes generated by the Iowa State University (ISU) simulator to be compared with both full-scale data and with computational fluid dynamic models (Sarkar et al., 2005). Work by Thampi et al. (2011) has verified that when the pressures on low-rise building models obtained from a tornado simulated by the ISU simulator are input into a finite element model of a structure, the damage experienced by the corresponding full-scale building in a tornado can be replicated. These advancements

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enable determination of forces and pressures on a structure and the exploration of cost-effective solutions for tornado-resistant design.

This paper presents the results of a study that determined the variation of tornado-induced pressures and forces as a function of the geometry and orientation of the low-rise building. In addition, the uplift load capacities of two of the most vulnerable roof connections in light-framed wood construction, as obtained from the literature, in the context of tornado-induced loads based on tornado-induced pressures measured in the laboratory were studied to investigate the viability of tornado-resistant design.

2. Description of simulated tornado

Pressures on low-rise building models obtained from a tornado simulated in a laboratory are useful for investigating the viability of tornado-resistant design only to the extent that the simulated tornado possesses the characteristics of possible full-scale tornadoes. For the purpose of obtaining pressures and forces for the structural design of low-rise buildings, the most important characteristics to reproduce are those that influence the loading on the structure. According to Haan et al. (2010), these characteristics include maximum horizontal wind speed, radius of the core of the tornado and its path, swirl ratio, and translation speed.

2.1. Maximum horizontal wind speed

Based on forensic evidence, around 90% of all tornadoes are rated F2 or less (Bluestein and Golden, 1993). In the EF (Enhanced Fujita) scale (TTU, 2004) this corresponds to an upper bound EF3 tornado, which is estimated to have a maximum velocity of 74 m/s (3-s gust). The design wind speed for the south-eastern and gulf coasts of the United States for occupancy category II buildings per ASCE 7-10 (2010) ranges from 63 m/s to 80 m/s and the basic design wind speed for the same region per the International Residential Code ranges from 54 m/s to 63 m/s (ICC, 2012). The design requirement for straight-line wind speeds of this magnitude implies that design for these wind speeds is possible. Based on the fact that building codes require the design of low-rise building structures for wind speeds of similar magnitudes and that most tornadoes are considered to have maximum wind speeds of 74 m/s or less, the target full-scale horizontal wind speed for this study of tornado-induced loads was chosen to be 74 m/s.

The maximum tangential velocity of the tornado generated by the ISU Tornado Simulator in this study was measured to be 11.6 m/s at a height of 19 mm and a maximum horizontal velocity of 11.7 m/s at the same height. Using a full-scale tornado with a maximum horizontal velocity of 74 m/s (EF3) gives a vortex velocity scale of $\lambda_V = 11.7/74 = 1/6.3$ for a full-scale averaging time equivalent to the model-scale averaging time. A contour plot of the tangential velocity normalized with the maximum tangential velocity is shown in Fig. 1.

2.2. Tornado vortex diameter

Brooks (2004) conducted a study using reported tornado damage path lengths and widths to model Weibull distributions of Fujita scale levels. The distributions produced by the study showed the probability of a tornado path width, given the occurrence of a tornado at a specific Fujita scale intensity. This study showed that a tornado's mean path width increased with its Fujita scale rating. According to Brooks for a F1 or a F2 tornado (corresponding approximately to an EF2 or EF3 tornado), the path would be most likely between 100 and 500 m.

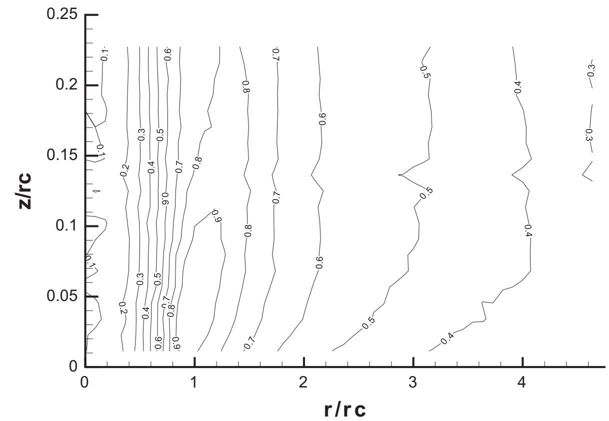

Fig. 1. Contour plot of tangential velocity magnitudes normalized with respect to the maximum tangential velocity.

Assuming that damage occurs at the design wind speed specified in the building codes, which for the Midwestern United States is 40 m/s, and the full-scale horizontal velocity is 74 m/s (EF3), the damage to buildings and other structures may be expected to occur within a diameter where the horizontal wind speed exceeds approximately half of the maximum tangential wind speed. The “0.5” contour in Fig. 1 is located at 2.2 times the radius of the maximum wind (radius of the core) near the ground. According to the results of the study conducted by Brooks (2004), the radius of the core of an EF3 tornado would have a high probability of being between 45 and 225 m. The radius of the core for the simulated tornado used in the study presented here was 0.56 m, which matches with the study done by Brooks (2004) when scaled using a length scale of 1:100.

2.3. Swirl ratio

One of the most commonly used parameters for laboratory and numerically simulated tornadoes is the swirl ratio (Haan et al., 2008; Hangan and Kim, 2008). The swirl ratio (S) is the ratio of the tangential momentum to the inflow rate (Q) of the vortex measured at a particular radius ($S = \pi V_{\theta max} r_c^2 / Q$, r_c is core radius where maximum tangential wind speed $V_{\theta max}$ occurs). Several studies have shown that the swirl ratio is the parameter that governs the flow characteristics of a tornado (Hangan and Kim, 2008; Church et al., 1979). Davies-Jones (1973) demonstrated that the radius of the vortex core is a function of the swirl ratio. Both Davies-Jones (1973) and Church et al. (1979) showed that the vortex structure is related to the swirl ratio; as the swirl ratio increases the vortex breaks down into multiple vortices (Davies-Jones, 1973).

The data from full-scale tornadoes indicate swirl ratio values of 2.0 or greater. For example, when comparing the full-scale data from the Spencer, South Dakota, tornado with 3D numerical simulations Hangan and Kim (2008) found that the best fit was for a swirl ratio of $S = 2$. Using data obtained with a Doppler on wheels (DOW), the swirl ratios of the Mulhall tornado were calculated by Lee and Wurman (2005) to be between 2 and 6 for the F4 level tornado. These swirl ratios were measured at the radius of the vortex core (r_c). Based on the latest data obtained by DOW and the best fit of that data with numerical results, it was decided that an attempt should be made to increase the swirl ratio of the tornado used in this study to a value of 2 or greater. In the ISU tornado simulator, a 1.83 m (6 ft)-diameter fan creates an updraft. The flow is then directed downward through concentric ducts. Rotational flow is created by several vanes fixed at a given angle with respect to the radial direction that is normal to the tangent of the duct. The swirl ratio of the vortex generated in the Iowa State University's tornado simulator can be increased by