

Failure of wood-framed low-rise buildings under tornado wind loads

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ABSTRACT

Buildings in the “tornado alley” of the United States, are built to withstand 3-s wind speeds of 90 mph (40.2 m/s), whereas 90% of the tornados are of F2 or lesser intensity that generate anywhere from 40 to 157 mph (17.9–70.2 m/s). At the same time, these codes are based mostly on studying the effects of straight line winds and not on tornado type winds, especially on low-rise, wood framed buildings which make up majority of structures in the United States. Previous research at Iowa State University (ISU) includes extensive testing on a scaled down low-rise gable roof building model (1:100) to understand tornado induced loads as the tornado sweeps past the building. In the present work, Finite Element (FE) models were developed using ANSYS for full-scale numerical simulation of the gable roof buildings with three different roof angles (13.4°, 25.5° and 35.1°). The nail is modeled as a non-linear element but the wood is assumed to be linear. The tornado-induced wind loads recorded in the laboratory were scaled up and applied to the models to determine the detailed stress distribution in the structure. This numerical study was performed using the same parameter as in the laboratory experiments such as those listed earlier. The deterministic FE model incorporated the damage criteria to assess the damage potential due to tornadic forces. The stress distribution, pattern of failure, the order of failure and the type of failure have been studied as the tornado sweeps past the building at different angles to the building centreline.

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1. Introduction

Tornados are violently rotating columns of air, extending from a thunderstorm to the ground. Though they occur in many parts of the world, they are found to occur most frequently in the United States. There are around a thousand tornados reported annually in the US, causing around 60 fatalities, thousands of injuries, Grazulis [1], and resulting in damage of over a billion dollars. Though tornados have occurred in all fifty states, they are concentrated in what is known as the “tornado alley”, located in the central region of the country. According to the current design codes, low-rise buildings are built to withstand only up to 3-s gust of 90 mph (40.2 m/s) of straight-line winds, while 90% of the tornados are of F2 or lesser intensity that generate anywhere from 40 to 157 mph (17.9–70.2 m/s) fastest $\frac{1}{4}$ -mile wind speed. At the same time, these codes are based on studies involving the effects of straight line winds and not the tornado type winds. Also, the property damages that occur due to tornados are significant due to wind-borne debris similar to the direct effect of high speed wind on them. It is therefore necessary to assess the wind damage potential of buildings as a function of distribution of local wind speed and map the generation of wind-borne debris from the

buildings. Extensive wind tunnel tests have been performed on these types of structures under tornado type winds to obtain the forces acting on the structure. These tests were performed on low-rise building models with a variety of commonly used roof angles and shapes.

It is needless to say that even though the buildings are designed for 90 mph wind speeds, the probability of it being subjected to tornado loads is small. Nevertheless, one fatality is too many and hence the building codes are developed to minimize such losses.

The main objective of this research work was to apply these tornado-induced wind loads, obtained in the laboratory using a scaled model of a low-rise building, to a numerical Finite Element model (FEM) of the building to assess its damage potential. Loads are applied in the quasi-static manner, i.e. the experimental loads are applied to the building at discrete intervals and analysis performed to calculate the internal stresses and failure criteria is applied to determine the integrity of the elements. The model is assumed to be deterministic and the probabilistic nature of loading, material properties, nail pull-out have not been included.

1.1. Previous work

A lot of work has been done to deal with 3-D performances of timber framed buildings. One of the first analytical models was developed by Tuomi and McCutcheon [2] which assumes linear elastic behavior of nails. The nail deformation here is defined by

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the relative deformation of sheathing and frame at each point. Gupta and Kuo [3] presented a linear building model with shear wall elements using 9 degrees of freedom and seven superelements. This model used a strain energy formulation and analyzed the building tested by Tuomi and McCutcheon [2]. Foschi [4] developed a Finite Element model which included nonlinear load-deflection properties for fasteners. Frame elements were modeled linearly and sheathing elements were modeled elastic and orthotropic. Kasal [5] used the Finite Element software ANSYS to develop a three-dimensional model. It consists of linear orthotropic 2-D shell elements and fasteners represented by three 1-D spring elements at each node. The properties of nails, when pulled out and pulled through plywood and OSB boards were studied by Herzog and Yeh [6]. He et al. [7] developed a 3D model using the FE technique with plate, beam, and nonlinear nail connections. Kasal et al. [8] have developed a non-linear model of a complete light-frame wood structure and performed analysis under static loads. They were able to get a good correlation between the theory and experiments which were limited to static loads only. Collins et al. [9,10] published two papers where in the first one they have described the details of the model of a three-dimensional light framed wood building and in the second they have reported experimental investigation and analytical studies. They applied static-cyclic lateral loading and were able to get a reasonable correlation between energy dissipation, hysteretic response, the load sharing between the walls and the torsional response. They modeled the spring as non-linear springs under hysteretic loads and hence their model and analysis is restricted to cyclic loads only. Foliente [11] also has modeled the wood joint and structural systems under hysteretic behavior. The objective of the research has been to model the behavior of wood under seismic loads. Paevere et al. [12] has studied the load-sharing and redistribution in a one-story wood framed building which was subjected to lateral loading in static and static-cyclic modes.

Thus, we observe that starting from very simple linear models, the development has taken place in the analysis and more and more complex elements, such as orthotropic, and from linear to non-linear nail models have been incorporated. Researchers have studied the actual nail pull out and attempted to incorporate these into the Finite Element codes. This makes computation difficult and time consuming but with the development of faster and faster computers, these developments have been possible. One noticeable limitation of all these models has been the application of loads. Only the plane fronted wind has been considered. Work has also been done where the buildings were subjected to hysteretic loads and lateral loads. The work presented here is concerned with the tornadic loads on a wooden building.

The nail pullout of wood has been studied by Aune et al. [13] and Chow et al. [14] and they have developed theoretical models too. But we decided that it would be more realistic to use experiment

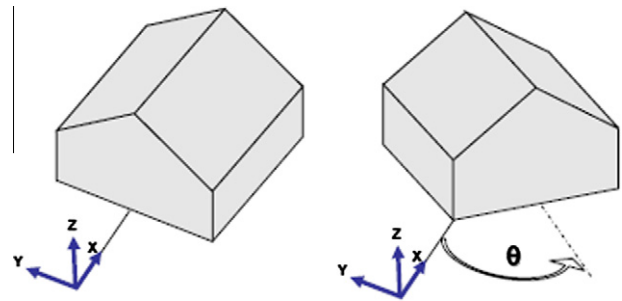


Fig. 1. Building orientation with respect to the vortex translation direction (x-axis).

based load–displacement relations and the details will be described later.

In this work, we have taken the pressure distribution measurements of Haan et al. [15]. The building was subjected to a moving tornado with a wind speed of 112 mph or 50 m/s (lower range of an F2 tornado) and five different swirl ratios (S) as reported in Table 1. This table mentions a ‘vane angle’ which is the angle set in the tornado simulator to generate different swirl ratios (S) and hence the vane angle may be taken as a case number only. We define the swirl ratio, S , as the ratio of the vortex circulation at the radius of maximum tangential wind (RMW), r_c , based on the maximum tangential wind speed ($V_{\theta\max}$), to the accompanying rate of inflow (Q) into the vortex ($S = \pi V_{\theta\max} r_c^2 / Q$). The pressure distributions for each model case were converted to full-scale values by adjusting the model pressure coefficients to full-scale equivalents first and then multiplying them with the wind speed of 112 mph (50 m/s) of an F2 tornado (=8-s gust). This adjustment was accomplished by adjusting the maximum tangential wind speeds ($V_{\theta\max}$) that were used to normalize the model pressure coefficients to account for the difference in time averaging between model scale and full scale. The averaging time for the velocity measurements of 26 s was converted to the full-scale equivalent ranging from 359 to 510 s using the time scale (λ_T) mentioned in Table 1 corresponding to Vane1 to Vane 5 cases. The $V_{\theta\max}$ corresponding to the full-scale equivalent averaged speed was then adjusted to 8-s gust wind speed using the Durst gust factor curve. The reasoning for using the Durst curve that is strictly valid for straight-line wind is that an equivalent gust factor curve is not available at this point for tornadoes.

Fig. 1 shows the building orientation with respect to the tornado translation axis. In each case tested, the tornado translation axis passed through the center of the building model. For all discussions in this paper the tornado approach angle θ , will be referred to as shown in Fig. 1. For all building orientations, four different cases of tornado translation speeds 0.15, 0.30, 0.46 and 0.61 m/s were used. Three one-story models with gable roof of

Table 1

Experimental simulator settings and the accompanying tornado vortex parameters.

Case name	Vane angle (°)	S at RMW	RMW (m)	$V_{\theta\max}$ (m/s)	V_H (m/s)	Q (m ³ s)	λ_T	$Re \times 10^4$
Vane1	15	0.08	0.23	6.9	8.3	14.4	13.8	3.6
Vane2	25	0.18	0.30	8.3	9.5	13.1	16.6	4.2
Vane3	35	0.24	0.30	9.7	11.3	11.5	19.4	5.0
Vane4	45	0.82	0.51	9.8	12.0	9.7	19.6	5.3
Vane5	55	1.14	0.53	9.7	11.9	7.6	19.4	5.2

S : swirl ratio at RMW.

RMW: radius of maximum wind.

$V_{\theta\max}$: mean tangential wind velocity measured at the building height at RMW.

V_H : mean horizontal wind velocity measured at the building height at RMW.

λ_T : time scale based on a velocity scale of $V_{\theta\max}/50$ and length scale of 1/100.

Re: Reynolds number based on V_H and building height.

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