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Characterization of translating tornado-induced pressures and responses of a low-rise building frame based on measurement data

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ABSTRACT

This study presents an analysis and characterization of dynamic wind pressures and internal forces of a low-rise building frame using measurement data obtained from a tornado simulator. The deterministic time-varying mean pressure component is extracted from the time history record using discrete wavelet transformation (DWT) approach. A continuous wavelet transformation (CWT) based approach is employed for determining the evolutionary power spectral density (EPSD) functions and time-varying standard deviation (STD) as well as covariance of dynamic pressures. The results showed that the characteristics of dynamic pressures are strongly affected by the location of tornado, and are very different from those under straight-line wind. The pressure drop caused by tornado vortex plays a key role in defining the pressure characteristics. The building frame responses are also calculated from the statistics of pressures. The equivalent static wind loads (ESWLs) causing peak responses are defined by using the gust response factor approach. The effect of translation speed of tornado vortex is also investigated. The translating tornado vortex leads to a delay of occurrence of maximum time-varying mean and STD, and reduction in maximum STD thus peak response. It also makes the energy distribution of pressure fluctuations shifted to higher frequencies with a broader power spectrum. Finally, it is shown that the tornado-induced responses are significantly higher than those from ASCE 7-10.

1. Introduction

Tornados cause a great deal of damage on buildings, especially low-rise buildings. Tornado-induced pressures on low-rise buildings have different characteristics as compared to those under straight-line winds. Nowadays, a growing number of tornado simulators have been built to simulate tornado-like vortices (e.g., [6,13,18]), and to quantify dynamic wind pressures and load effects on structures under stationary and translating tornado-like vortices (e.g., [12,16,7,8,15,19,21,11,3,2,14,20]).

Sengupta et al. [16] compared tornado-induced peak loads of both cubic building and tall building at two different translation speeds and quasi-steady case. Haan et al. [7] studied tornado loads of a one-story, gable-roofed building in different translation speeds and different vortex core diameters. It was shown that the magnitudes of integrated forces reduce with the increase in the translation speed, and the vortex profile slants to translation direction. The peak uplift force did not have a significant variation with respect to building orientation, probably due to the fact that the uplift force is dominated by pressure drop of tornado instead of the aerodynamic interaction of the roof with flow. In most cases, the integrated forces are higher for a smaller-diameter tornado vortex. Mishra et al. [12] and Sabareesh et al. [15] studied dynamic pressures on a cubical model under stationary tornado-like vortices. Hu et al. [8] studied the flow-structure interactions between a low-rise building and tornado-like winds at different fixed locations from tornado center. Kumar et al. [11] also showed that the smaller diameter of tornado causes higher peak stress, and slower translating tornado causes earlier failure of a wood frame. The effect of building geometry [3] and the influence of internal pressure due to building openings [19] on tornado-induced loads of low-rise buildings were also investigated. Roueche et al. [14] examined the tornado loads on a wood-frame building using one case study of the experimental pressure data reported in Haan et al. [7] with a translation speed of 0.15 m/s. It showed that the peak shear forces under tornado loads are 1.8 times and 2 times larger for roof-to-wall and wall-to-foundation connections, respectively, and the vertical tornado load is 4 times greater, as compared to those from ASCE 7-10 for a fully sealed low-rise building. Dynamic pressures on a cooling tower due tornado-like vortices were studied by Cao et al. [2] and Wang et al. [20].

This study presents an analysis and characterization of dynamic pressures and internal forces on a low-rise building frame using measurement data obtained from the tornado simulator at Iowa State University [7]. The deterministic time-varying mean pressure

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component is extracted from the time history record using discrete wavelet transformation (DWT) approach. The stochastic fluctuation component around the time-varying mean is then characterized in terms of time-varying standard variation (STD) and evolutionary power spectral density (EPSD) function, determined by a continuous wavelet transformation (CWT) based approach [9]. The correlation structures of pressures are analyzed by using proper orthogonal decomposition (POD). The analysis and characterization are also carried out for internal forces of the building frame. The equivalent static wind loads (ESWLs) for tornado loading are proposed based on gust response factor approach. The effects of tornado translation speed on the time-varying mean, STD and EPSD of pressures and internal forces are also quantified. Finally, tornado-induced responses are compared with those determined using wind loads specified in ASCE 7-10. The results of this study help in developing better understanding of the characteristics of translating tornado-induced pressures and load effects on low-rise buildings.

2. Tornado-induced pressures on a low-rise building frame

2.1. Statistics of tornado-induced pressures

The dynamic pressures on a low-rise building frame are analyzed, which were collected using the tornado simulator at Iowa State University as shown in Fig. 1 [7]. The arrow pointing to the right and arcing arrow counter-clockwise indicate the vortex translation and rotation directions, respectively. The simulated tornadoes had a swirl ratio of 0.08, a diameter to maximum wind speed of $D = 0.46$ m and a mean horizontal velocity at building height of $U_H = 8.3$ m/s. While currently there is no unified definition of swirl ratio, the tornado-like vortex consider here has a smaller swirl ratio with small vortex radius. Three translation speeds of $U_{TS} = 0.15$, 0.46 and 0.61 m/s were considered. Each translation speed involved 10 repeated runs of measurements. The time scale was 1:13.8 and velocity scale was 1:7.25, which was selected based on real tornado observations [7]. The equivalent prototype mean horizontal wind speed was 60.2 m/s which was corresponding to an F2 tornado. The translation speed in prototype was 1.09, 3.34 and 4.42 m/s, respectively, which was in lower side of translation speed of tornados. These relatively lower translation speeds give a conservative tornado loading. The tornado-induced pressures were measured on a one-story gable roof building (length scale 1:100) with 91 mm by 91 mm plan and an eave height of 36 mm. The gable roof angle was 35° and the maximum height of model was 66 mm. The sampling frequency of pressure data was $f_s = 430$ Hz. The surface pressures at 89 locations in Fig. 1 were simultaneously measured, which were denoted as $p_j(t) = 0.5\rho U_H^2 C_{pj}(t)$, where ρ is air density, and $C_{pj}(t)$ is pressure coefficient. Internal pressures were not measured thus not considered in the analysis.

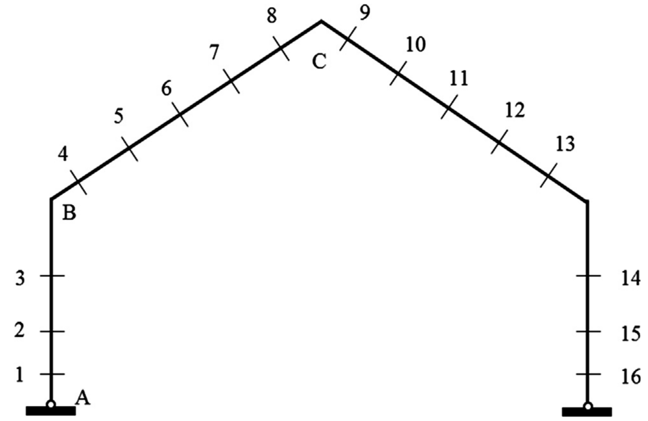

Fig. 2. Building frame and pressure tap locations.

The wind load effects of a building frame are considered in this analysis, which are affected by the wind pressures in the red box in Fig. 1. The pressure taps are re-numbered from Taps #1 to #16 starting from section A shown in Fig. 2. Fig. 1 also shows the location of sections A, B and C. In this study, the time-varying character of tornado loads and responses are plotted with respect to nondimensional distance x/D instead of time t, where x is distance from the center of tornado vortex to the center of building model. The following analysis is on the case of translation speed of 0.15 m/s. The analysis of other translation speeds will be presented in later section. The dynamic pressure is modeled as a nonstationary random process with a deterministic time-varying mean and random fluctuation components. Wavelet transform (WT) can be used to decompose a nonstationary process into several sub-processes

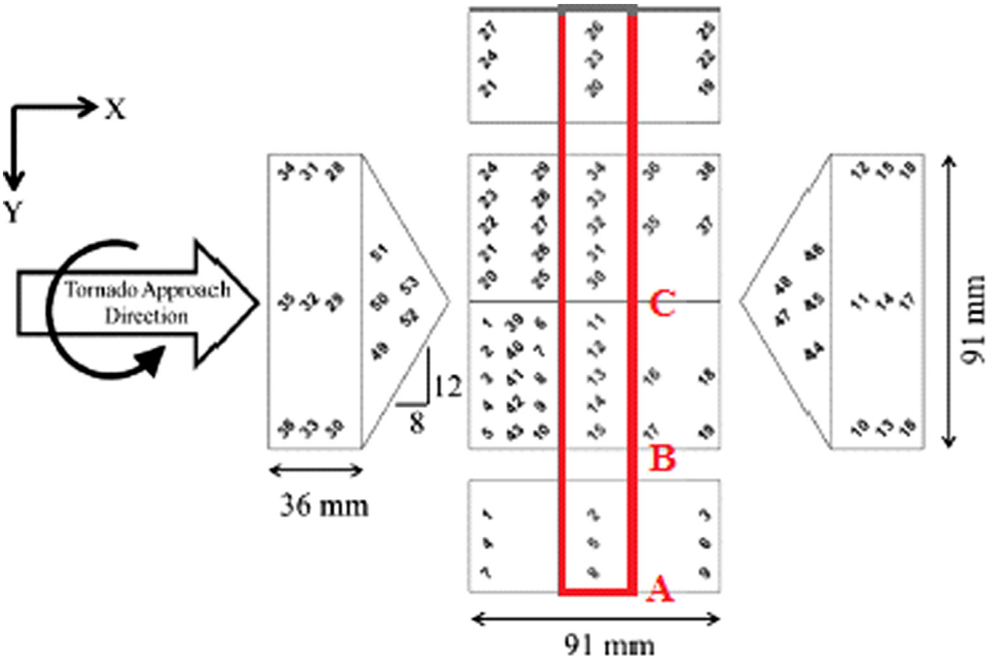

Fig. 1. Layout and dimensions of building model [7,14].