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A conceptual model for wind and debris impact loading of structures due to tornadoes

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ABSTRACT

This paper presents a novel conceptual design framework which takes into account the direct wind loads and pressure loads acting on a structure due to the passing of a tornado. Furthermore, for the first time, the potential damage due to debris impact has been incorporated enabling a holistic assessment of structural loading to be considered. The model is built on a recently developed wind and pressure field model that captures the main features of tornadoes, which is used to generate a large number of tornado wind and pressure field realisations from which values of particular load effects can be determined. A cumulative distribution function of load effect is thus derived, which can be combined with tornado climatology probabilities to determine load effects at a particular risk level. This use of this framework is illustrated through two examples – the direct wind and pressure loads on a low-rise portal frame structure, and the debris loads on a medium rise rectangular structure.

1. Introduction

Since wind engineering was first defined as a discipline in the 1960s, most attention has been focussed on the effects of large-scale windstorms on structures – particularly tropical and extra-tropical cyclones. This has resulted in a robust set of wind engineering tools for design, encapsulated in codified design methods for a wide variety of structures using the results of extensive wind tunnel and full scale testing, within a conceptual framework first developed by Davenport and the other early pioneers of wind engineering (Davenport, 1982). In recent years however it has come to be realised that the effects of smaller, transient wind storms can be of significance – frontal gusts, thunderstorm downbursts and tornadoes in particular – and there is significant ongoing research in this area. Much of this work has been focussed on full-scale observations of such wind systems (eg Bluestein et al., 2003; Orwig and Schroeder, 2007; Duranona et al., 2006) and physical and numerical modelling (eg Haan et al., 2008; Mishra et al., 2008a, b; Case et al., 2013; Jesson et al. 2015a, b). Only very recently have methodologies begun to emerge to incorporate these transient wind effects into the design process - see De Gaetano et al. (2014) and Solari (2014) for a discussion of loading due to thunderstorm downbursts, and Kareem et al. (2016) for a more general structure to incorporate transient effects into design, which reduces to the Davenport methodology for statistically stationary wind events. Design for such transient winds usually requires a time series approach, as the traditional spectral based methods make the assumption that the wind loading is statistically stationary. In a review by Letchford and Lombardo (2015), the wide range of issues that arise from codification of non-synoptic winds are discussed and a framework is proposed based on the "design response spectrum" methodology used in earthquake engineering. This utilises a range of real earthquake time histories applied to a range of structures of different natural frequencies to specify displacements, velocities and accelerations that can be used for design purposes. The major problem of applying either this method or time history based methods for downbursts and tornadoes is the lack of full-scale wind velocity and pressure time histories, particularly with regard to tornadoes.

This paper is specifically concerned with the wind loads due to tornadoes. Now, tornadoes are widely classified using the Fujita or enhanced Fujita scales (Fujita, 1991; WERC, 2006) which allocates tornadoes to one of five categories. This essentially classifies tornadoes by the damage they cause and thus effectively integrates both the wind loading and the building vulnerability, and inevitably the range of wind speeds associated with any one Fujita classification is large. Whilst a useful descriptor, this classification does not actually specify the parameters required for a wind loading design. Now, the wind loading due to tornadoes is particularly complex and consists of a number of components. Firstly we have what might be termed direct wind loads – loads caused by the variable surface pressures on the structures due to the local

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velocities, in a similar manner to the loads caused by synoptic winds, although it can be expected that these loads will be transitory in terms of time, magnitude and direction, and cannot be regarded as stationary. Also, close to the core of the tornado, the vertical component of the wind speed may be of significance and effect these surface pressures. Secondly there will be loads caused by the differences between the low atmospheric pressure in the core of the tornado, and the non-equalised internal pressure within the structure. The magnitude of the latter will be dependent on the nature of the envelope porosity and the presence, or otherwise, of any dominant opening, and again can be expected to be highly transitory. Finally, within tornadoes there can be expected to be significant impact loads from flying debris from either natural sources (trees, soil and gravel etc.) or from damaged buildings (roof and wall components etc.). Such debris can be observed in tornadoes and effectively visualise the tornado funnel cloud (Noda, 2015).

Tornado loading is usually taken into account only for highly sensitive structures such as nuclear power plants. The methodology used in the US nuclear industry is given in USNRC (2007). There, a design wind speed is given which has a probability of occurrence of 10^{-7} for each of three regions of the USA, and the pressure loads are then calculated from the application of a very simple Rankine vortex model. Debris impact velocities are also given for a small range of debris types (pipes. automobiles and metal spheres), taken from a numerical solution of trajectories, using a different wind field model developed by Simiu and Scanlan (1996). However, a conceptual method of how all these essentially time varying loading effects could be incorporated into design for a range of risk levels is yet to be developed, although there is some ongoing work by Tamura et al. (2015) that is attempting to build a tornado database for use in design in Japan. It is nonetheless clear that a pre-requisite of such a method is a consistent and simple description of the tornado flow field that could be used in design to predict velocity and pressure time histories and to enable debris trajectories to be calculated. Further, to enable such a formulation to be used to generate the large number of cases needed for either a time history method or the design response spectrum method described above, requires that it be relatively simple and quick to apply (i.e. not a complex numerical calculation). Such a wind field/debris trajectory model has recently been developed by the authors and is reported in Baker (2016).

Section 2 summarises the main points of this wind and debris trajectory model. We then build on this to develop a consistent risk based approach to tornado wind loading due to the three mechanisms described above. Section 3 considers the wind and pressure fields in translating tornadoes and section 4 sets out a conceptual framework for the tornado wind load design process. The calculation of direct wind loads and pressure loads is then described and illustrated in section 5, and the calculation of debris impact loads in tornadoes is set out and similarly illustrated in section 6. The model is discussed and concluding remarks made in section 7.

2. The tornado wind field and debris trajectory model

The model outlined in Baker (2016) starts by assuming the following expression for the radial velocity of a single celled tornado vortex.

$$\overline{U} = \frac{-4\overline{r}\overline{z}}{(1+\overline{r}^2)(1+\overline{z}^2)} \tag{1}$$

where $\overline{U} = U/U_m$; U and U_m are the radial velocity and maximum radial velocity respectively; $\overline{r} = r/r_m$; r and $r_m$are the radial distance from the centre of the vortex and a radial length scale respectively; $\overline{z} = z/z_m$; z and $z_m$are the vertical distance from the centre of the vortex and vertical length scale respectively. This expression thus gives a peak in the radial inflow velocity in both the radial and vertical directions and thus seems physically plausible. It effectively aims to model the tornado ground boundary layer, through forcing a velocity reduction close to the ground. By substituting this expression into the continuity equation and the circumferential and radial momentum equations one obtains the following expressions for the normalised circumferential velocity $\overline{V} = V/U_m$ and normalised pressure $\overline{P} = p/\rho u_m^2$

$$\overline{V} = \frac{2.88S\overline{r}[\ln(1+\overline{z}^2)]}{(1+\overline{r}^2)} \tag{2}$$

$$\overline{P} = -\frac{8\overline{r}^2\overline{z}}{(1+\overline{r}^2)^2(1+\overline{z}^2)^2} - \frac{4.15S^2(ln(1+\overline{z}^2))^2}{(1+\overline{r}^2)} - \frac{4ln(1+\overline{z}^2)(1-\overline{z}^2)}{(1+\overline{r}^2)^2(1+\overline{z}^2)^2} \tag{3}$$

where V is the circumferential velocity, p is the pressure, ρ is the density of the flow and S is the swirl ratio, the ratio of the maximum circumferential velocity to the maximum radial velocity.

$$S = \frac{V_M}{U_M} \tag{4}$$

Expressions can also be derived for the vertical velocity and buoyancy force but are not be considered here. In this paper we will define the parameters that will be used in the loading as the velocities and pressures at the edge of the boundary layer i.e., $\overline{z} = 1$. This results in the rather simpler expressions which will be used in what follows.

$$\overline{U} = \frac{-2\overline{r}}{(1+\overline{r}^2)} \tag{5}$$

$$\overline{V} = \frac{2S\overline{r}}{(1+\overline{r}^2)} \tag{6}$$

$$\overline{P} = -\frac{2\overline{r}^2}{(1+\overline{r}^2)^2} - \frac{2S^2}{(1+\overline{r}^2)} \tag{7}$$

Using the debris theory developed by Baker (2016), the debris trajectory analysis was carried out for compact debris only i.e. for debris where the aerodynamic forces are characterised by a drag coefficient (C_D) only, on the basis that such a formulation is appropriate for the large time behaviour of both compact and sheet debris. The analysis revealed that the trajectory is dependent upon the swirl ratio S, the initial debris trajectory positions $\overline{r}_o$ and $\overline{z}_o$ and two further parameters given by

$$\Phi = \frac{0.5\rho A r_m}{M} \qquad C_D\Psi = \frac{g r_m}{u_m^2} \tag{8}$$

where A is the debris area, M is the debris mass, and C_D is the debris drag coefficient. The first group in equation (8) is the buoyancy parameter, whilst the second is an inverse tornado Froude number. The Tachikawa number, which is normally used to characterise debris flight (Holmes et al. (2006)) is given by the ratio Φ/Ψ. In broad terms, the debris trajectories are much more dependent upon S and Φ than on $\overline{r}_o, \overline{z}_o$ and Ψ - for example whether or not debris flies or falls in a tornado is largely a function of its position in the S/ Φ plane. This will be seen to be of significance in what follows.

3. Tornado translation

To be able to use the above vortex model in any design methodology, we need to allow for vortex translation in some way. To do this we make the following assumptions.

- The structure under consideration is at (0, $\overline{Y}$), where $\overline{Y} = Y/r_m$ and Y being the lateral distance from the tornado track centre line;
- The tornado moves at a dimensionless speed $\overline{Q} = Q/U_m$ along the x axis, where Q is the dimensional speed, and passes through the origin at a normalised time $\overline{t} = tr_m/U_m = 0$ (t represents the actual time);
- The total dimensionless wind speed $\overline{\mathscr{V}}$ at the structure, is the vector sum of tornado wind speeds and tornado translational speed $\overline{Q}$;