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A concept for a design tornado in wind load provisions

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SUMMARY

The concept of a design tornado for use in building codes and design standards is proposed, along with discussion of the potential benefits and limitations of such an approach.

Keywords: *tornadoes, wind loads, design standards*

1. INTRODUCTION

The development of wind load provisions in building codes or design standards for synoptic-scale windstorms involves establishing:

- probabilistic values for the design wind speed;
- deterministic velocity profiles to account for terrain variations and the height of the building, through the exposure factor, K_z;
- probabilistic values for the aerodynamic effects of the building using either the gust effect factor, G, with a mean pressure coefficient, Cp, or a combined peak coefficient, (GCp), using the terminology of ASCE 7-22;
- a probabilistic directionality factor, K_d, to account for the non-alignment of the directions of the design wind speed, when it occurs, with the worst aerodynamic direction.

In ASCE 7-22, the aerodynamic load coefficients are from the worst direction and are the expected peak values (57th percentile values from a Gumbel distribution) that occur in a 1-hr duration. The probability of occurrence of the design wind speed is set through a reliability analysis.

ASCE 7-22 (2022) is currently the only consensus-based load standard to consider tornadoes. The approach used is similar to that for synoptic wind loads with a probabilistic tornado wind speed along with exposure and directionality factors that account for the uniqueness of tornado wind fields. The aerodynamic coefficients for tornadoes are the same as synoptic wind fields but with the addition of a new factor, K_{vT}, that accounts for the vertical wind directions, which are more prominent in tornadoes than in atmospheric boundary layers. One can view this formulation as being essentially the same as that for synoptic wind loads but with a series of different factors.

The advantage of the ASCE 7 tornado loads formulation is its simplicity, which derives from the similarity to the synoptic wind loads approach. There are some disadvantages, however, which derive from the distinct features of tornado wind fields including:

- sizes that are comparable to those of buildings, such that static pressure drop effects in the tornado wind field are significant;
- sizes that are comparable to those of buildings, such that the uniformity of the wind over the building is reduced;
- swirling winds and vertical angles of attack, which alter flow patterns and building-generated vortices.

These parameters alter the wind loads but only the vertical wind directions are explicitly considered. In particular, the range of tornado-to-building size ratios, R/L, where R is the core radius of the tornado (i.e., radius of maximum winds) and L is the largest plan dimension of the building, and swirl ratios that can occur indicate that tornado loads have many more parameter variations than synoptic wind loads do, increasing the complexity in analysis. In fact, there has not been a single tornado-simulator experiment to date that has covered all of the cases such that the design loads were determined by this method. The ASCE 7-22 design loads were established via Monte Carlo simulations, which required the development of aerodynamic models used with tornado wind field statistics and models. The objective of this paper is to propose and examine an alternative formulation that uses a direct concept for the tornado wind field.

2. DESIGN TORNADO CONCEPT

In 1991, Michael Newark, the father of tornado research in Canada, published a paper entitled "A design basis tornado", which inspired the current work. In this paper, Newark (1991) presents a series of characteristic parameters obtained from field observations including:

- median damage length, median damage width, and median damage area;
- maximum rotational speed;
- average translation speed;
- dynamic wind pressure;
- maximum static pressure drop;
- rate of change of static pressure.

Each of these values were presented as a function of Fujita Scale category, from F-scale = 0 to 4. While modern tornado damage surveys have led to significantly improved methods and updated values, and some of the parameters, such as the rate of change of static pressure, are suspect, the concept is useful. Of particular importance are (i) the design tornado wind speed, V, (ii) the maximum static pressure drop, where Cp_s is the gauge pressure coefficient of the minimum pressure in the core, relative to the outer static pressure and referenced to the maximum rotational velocity, (iii) the shape of the static pressure drop as a function of radial position in the tornado vortex, $f_s(r/R)$, (iv) the tornado core radius (i.e., radius of maximum speed of the vortex), R, and (v) the translational speed of the tornado vortex.

2.1. Design Tornado Wind Speed

The methods for determining the design tornado wind speed are well established, being similar in approach to those for hurricanes/tropical-cyclones (e.g., Li et al., 2024). Statistical models for the occurrence, intensity, path lengths, and path widths are used together with a wind field model in a Monte Carlo simulation to obtain probabilistic wind speeds. Figure 1 provides an example of the results of such analyses for Canada.

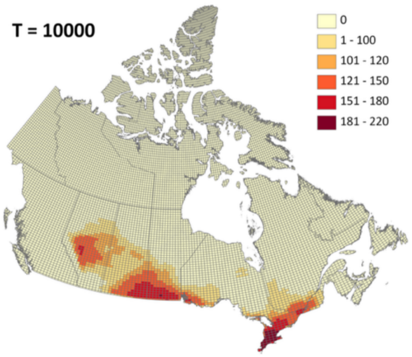

Figure 1: Tornado design wind speeds for Canada for plan areas of 1,000,000 ft^2 and a return period of 10,000 years.

All of these analyses have the wind speed model in common – that developed by Twisdale (1978). This is an empirical model which has the benefit of using a probabilistic distribution of input parameters, which include path length, width and direction, maximum tornado intensity and intensity variation along the path, and occurrence. Such statistical models have not yet been developed for other common wind field models, such as the Baker-Sterling model, which is based on simplified solutions to the Navier-Stokes equations. Using the design tornado wind speed and an appropriately-chosen translation speed, V_t, the maximum rotational speed of the vortex can be determined.

2.2. Static Pressure Distribution

Static pressure distributions in tornado wind field models depend on the rotational wind speed, V_r, the core radius, and the swirl ratio. In the Twisdale model, the inflow ratio is used for the swirl ratio. Figure 2 depicts the static pressure coefficients as a function of the non-dimensional radial position, r/R, and inflow ratio.

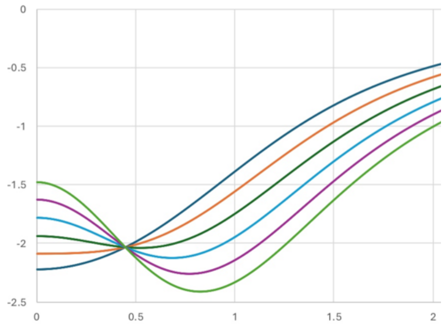

Figure 2: Static pressure distributions versus r/R as a function of inflow ratio for the Twisdale wind field model.

For the design scenario, a single static pressure distribution is required in order to calculate the loads since the swirl ratio would be a random parameter in the field. It is important to note that for the net design loads, it is the static pressure differences that are important, not the absolute magnitude. Hernandez (2024) has shown that the largest loads are between $\sim 0.5 < r/R < \sim 1.0$. As can be seen in Figure 2, the slopes for different swirl ratios are similar in this range such that the actual functions will not alter the critical (worst-case) loads significantly.

2.3. Tornado Core Radius

The other parameter of importance for the static pressure distribution is the core radius, R. The core radius is related to the path width of the tornado. Path widths are a function of the EF-Scale rating, being wider on average for more intense tornadoes. Adding to the complexity, the radius and path width will vary in similar, although not identical, ways. For design, a single statistically-based value is needed. This should be related to the EF-Scale range for the design wind speed, V.

3. TORNADO LOADS USING THE DESIGN TORNADO

Using the five parameters of the design tornado, the tornado-induced pressures can be determined on the faces of the building. The concept is that the net loading is made up of two components: (i) the aerodynamic portion and (ii) the static pressure portion. For example, the external pressure is:

$$(p_e - p_o) = (p_e - p_s) + (p_s - p_o) = Cp_a(0.5\rho V_h^2) + Cp_s(0.5\rho V_r{}^2) f_s(\tfrac{r}{R}) \qquad (1)$$

where p_e is the external pressure, p_o is the static pressure outside the tornado wind field, p_s is the static pressure in the tornado, Cp_a is the aerodynamic pressure coefficient, and ρ is the air density. In this formulation, the aerodynamic pressure is determined as the difference between the pressure on the building surface less the local static pressure in the tornado wind field. Internal pressures, p_i, can be determined in the same way.

For design the aerodynamic coefficients can be determined as modified values of the code coefficients, as done in ASCE 7-22. This formulation leads to larger net load coefficients than the current ASCE 7 formulation by bringing in the additional net loading caused by the static pressure differences across the various building surfaces. For example, for base shears (and neglecting various factors including the directionality, elevation angle, and exposure factors):

$$\left(p_{e,w} - p_{e,l}\right)/q_h = (GCp_w - GCp_l) + Cp_s\left(f_s\left(\frac{r_w}{R}\right) - f_s\left(\frac{r_l}{R}\right)\right) \qquad (2)$$

where the subscripts w and l indicate windward and leeward surfaces, respectively.

4. CONCLUSIONS

The concept of a design tornado is investigated. This framework has several advantages: (i) it should be useful for an extended period of time, even as new knowledge is developed, (ii) it allows for implementation of the current state of knowledge, and, most importantly, (iii) defines the tornado loads in a way that captures the actual physics of tornado loading. The conference presentation will include discussion of the detailed analysis and parameter choices.

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