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Influence of wind directionality on wind loads and responses

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ABSTRACT

Different methods of allowing for wind directionality are discussed and their effects on predicted structural wind loads and responses of buildings and cladding pressures are examined. Results are presented for several tall buildings, for which wind tunnel model tests have been made, as well as for hypothetical buildings with generic aerodynamic signatures. Predictions of extreme wind loads and responses are made in both extra-tropical and tropical wind climates. Three of the analysis methods, namely the worst-case approach, the sector-by-sector method, and the up-crossings method are probabilistic procedures which rely on historical wind records. Also discussed is a time-domain analysis which tracks wind loads and responses during the passage of particular storms. This requires time histories of wind speed and direction that at this time are only available for tropical storms, where Monte Carlo simulations are used to determine time histories of the wind field. Directional factors are extracted from all predictions made in this study. These factors provide direct comparisons of extremes wind loads and effects predicted with particular methods of analysis to the corresponding predictions made with the worst-case method, which does not recognize the azimuthal variation of the aerodynamic data or the directional preferences of severe winds.

1. Introduction

This paper reviews commonly used methods that allow for wind directionality in the prediction of wind loads and responses of buildings and structures and compares their impact on design. Some codes of practice, including the National Building Code of Canada (NRCC, 2005), and the National Standard of the People's Republic of China (NSPRC, 2012), do not consider the directional preference of the local wind climate and specify design wind loads based on the assumption that the wind at its design speed will approach the building or structure from its most vulnerable direction. The design wind speed is arrived at through an analysis of extreme wind speeds, regardless of their direction. While this "worst case" approach of disregarding wind directionality is prudent in situations where information on wind direction is highly uncertain, it adds unnecessary conservatism in most situations. Other jurisdictions, like the British Standards Institute (British Standards Institution, 2002), and the Australian/New Zealand Standard, AS/NZS 1170.2.2002 (2011), have moved away from this worst case scenario by acknowledging that the wind speed exceeded for a specified probability can differ for different parts of the compass. This is done by specifying a reduction in the design speed for a particular azimuth sector, based on the analysis of extreme wind speeds on a sector-by-sector basis. These reduction factors are referred to as "directional factors" in BSI and as "wind direction multipliers" in AS/NZS 1170.2.2002.

Another approach is to use an across-the-board reduction of wind loads for structures whose aerodynamic properties are directionally sensitive. This is the approach taken by ASCE/SEI 7–10 (ASCE, 2010), which multiplies the design reference wind pressure by a directional factor. This factor is taken as $K_d=0.85$ for buildings and other structures with aerodynamics properties which differ with wind direction. ASCE/SEI 7-10 (ASCE 7) specifies $K_d=0.95$ for axi-symmetric chimneys, tanks and other structures which are not sensitive to wind direction. It is believed that the directional factors in ASCE 7 were arrived at through a calibration process which examined the dependence of aerodynamic data on wind direction and the overall reliability of the prescribed wind loads.

The sensitivity of buildings and structures to the direction of the wind is routinely examined in wind tunnel model tests, where data are acquired for all wind directions. The aerodynamic data obtained in different state-of-the-art wind tunnels tend to be generally similar. However, the processing of these aerodynamic data, in order to arrive at design wind loads and responses, can be quite different. While there is consensus on the minimum standards for carrying out wind tunnel model tests there is presently

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no consensus on the method of analysis for arriving at statistical predictions of prototype behavior. Depending on the procedures followed at a particular wind tunnel facility, the predicted design wind loads and responses for the same building or structure can be different. The potential for significant differences in the predicted wind loads has been noted in the technical literature (Sadek, 2005; Irwin et al., 2005). While ASCE 7 permits the use of results from wind tunnel model studies, it does not specify how wind directionality should be allowed for in the analysis of the wind tunnel test data. This lack of specificity has been raised in a recent critique of ASCE 7 procedures (Simiu et al., 2013).

2. Different analysis methods

The following methods for allowing for wind directionality in the analysis of wind tunnel model test data are considered.

2.1. Worst case method – method 1

In this method the predictions of wind loads and responses are made by assuming that the wind at its design speed approaches the building or structure from the direction for which its aerodynamic data are greatest. The design wind speed is usually determined from an extreme value analysis of the recorded annual extremes, regardless of wind direction. Fig. 1 shows a plot of annual extreme wind speeds versus probability level. Different methods of fitting are used for arriving at an analytical description. A commonly used technique at the Boundary Layer Wind Tunnel Laboratory (BLWTL) is to fit observed values with a Type 1 extreme value distribution, with the Gumbel parameters determined with a weighted least square fit. This is a straightforward approach for individual stations; however, difficulties arise when data from two or more stations are combined to create a "superstation", as done in the development of the ASCE 7 wind map (Peterka, 1992). The approach used assumes that annual extremes at the individual stations are independent, and the records are added or "stacked" together. The upside of this approach is an increase in record length. The downside is that due to lack of complete independence, predictions from stacked data will underestimate the extremes at one or more of the component stations. This is apparent from Fig. 1, where the predicted wind speeds at return periods of interest tend to be the lower bound.

Following the worst case method, the wind-induced pressure at a location of interest for an average recurrence interval or return period R, becomes

$$p(R) = 1/2\rho V(R)^2 (C_p(\alpha))_{MAX} \tag{1}$$

where $V(R)$ is the design wind speed for return period R and $C_p(\alpha)_{MAX}$ is the largest value of the azimuth dependent pressure coefficients.

This method disregards any dependence that the aerodynamic data have on wind direction, as well as any directional preferences of the local wind climate. Once the aerodynamic data have been determined, it is only necessary to define the design wind speed.

2.2. Sector-by-sector method – method 2

With this method the loads and responses for a particular sector of the compass are calculated using the highest aerodynamic data determined within that sector in conjunction with the design wind speed which has been multiplied by a speed factor determined for that sector. This speed factor is defined as the ratio of the extreme wind speed for that sector, determined from an analysis of extreme winds from that sector, to the largest extreme wind speed amongst all sectors. The speed factors are normalized by the largest sector extreme. The sector extreme wind speeds are determined using the same approach as described for Fig. 1. The difficulties which arise in this process are discussed later in the paper. The speed ratios are then determined for return periods of interest.

The various wind sectors are usually taken to be statistically independent and the largest value is used for design. Therefore the wind-induced pressure for return period, R, becomes:

$$p(R) = [1/2\rho (V(R)\beta(\alpha))^2 C_p(\alpha)]_{MAX} \tag{2}$$

where $\beta(\alpha)$ is the speed factor for sector α, defined as the ratio of the extreme wind speed for this sector for return period R to the design wind speed $V(R)$, regardless of wind direction.

This method recognizes the directional dependence of the aerodynamic data, however, the assumption of statistical independence and equality of wind events for all sectors are conservative

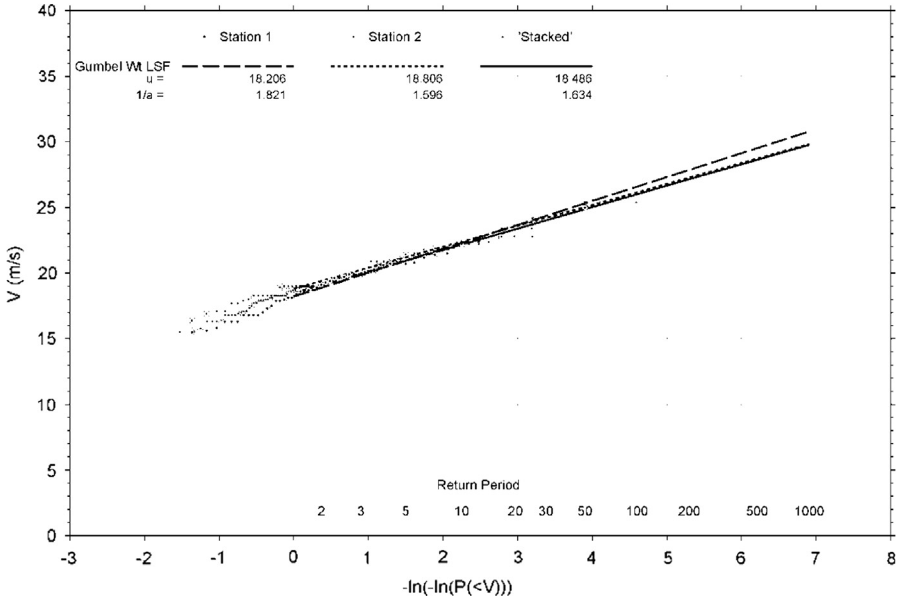

Fig. 1. Analysis of annual extreme wind speeds.