WIND DIRECTIONALITY EFFECTS ON DESIGN WIND PRESSURES OF HONG KONG BUILDINGS

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ABSTRACT

Wind induced structural responses, including pressure, are directional dependent. First wind speed will not be uniform in all directions. Second the shape and structural properties of the structure will not be axi-symmetric. Consideration of the directionality effect will help to achieve an economical and safe design of structure. The current methods to take account the directionality effect in wind induced responses are discussed. Using wind data at Waglan Island, the application of the method of annual maximum response time series to Hong Kong has been described. A new simplified joint probability model has then been proposed. The application of this method to Hong Kong shows that the correlation among the directional responses is moderate.

KEYWORDS

Extreme wind speeds, direction dependence, wind pressure, joint probability.

INTRODUCTION

Wind speed at a location is directional dependent. In Hong Kong wind will be stronger from the East–South directional sector. The wind speed in a particular directional range for a given return period will be different from those in the other directional ranges. To determine the directional free extreme wind speed the annual maximum wind speed without consideration of direction are selected for the extreme values analysis. If a structure is cylindrical and with axi-symmetric structural properties, its response to wind will also be axi-symmetric and thus directional independent. The extreme structural response can be computed by using the direction-free extreme wind speed. However, if the structure is not axi-symmetric, its response to wind blow with a given speed will be directional dependent (e.g. the pressure coefficient of a rectangular prismatic structure will vary with the wind blow direction).

To take account the above-mentioned directionality effects, several methods have been proposed. The first method is to treat wind velocity by a stationary two-dimensional random vector process with speed and direction. The allowable extreme response is expressed as a function of direction. The cumulative probability is determined by a Poisson distribution with a parameter called mean crossing rate calculated from the wind spectra and the joint probability density function of wind speed and direction (Wen, 1984). The accuracy of the method is highly dependent on the reliable estimate of the wind spectra and the joint probability density function. This method is in general not recommended in structural design (Simiu and Scanlan, 1996).

The second method is based on the time series of the largest annual wind effects. The procedure is to express the wind effect (such as pressure, moment and etc.) in terms of a directional dependent function of wind velocity. In a particular year the annual maximum wind speed in each directional sector is first determined. The annual maximum wind effect in each directional sector can then by found. The direction free annual maximum wind effect is the maximum among all the wind effects in the directional sectors. By the same procedure a time series of the largest annual wind effects can be constructed. Standard extreme values analysis can then be performed to determine the extreme wind effects for any return periods. Details about this method can be found in Rigato, Chan and Simiu (2001), Li and Chan (2004).

The last method is to found the extreme value distribution of wind speed in each directional sector. Assuming there is no correlation between extreme wind speeds at any two directional sectors (e.g. Cook, 1983), the cumulative probability distribution of the largest annual wind effect will be equal to the product of the cumulative probabilities of the equivalent wind speeds in each directional sectors (Simiu et al., 1985).

The last method is simple, general and may be applied to any types of structure. The drawback of the method is that it is conservative, as the extreme wind speeds at two adjacent directional sectors are correlated. To resolve this problem, Itoi and Kanda (2002) presented two joint probability models for directional maximum wind speeds. One constraint of these models is that the scale parameter in each directional sector should be equal for consistency requirement. The models have been fitted by measured wind data in several stations in Japan. Payer and Küchenhoff (2004) implemented the method due to Coles and Walshaw (1994) to develop joint probability model of directional extreme wind speeds at a German weather station. The model is very general but has a lot of parameters required to be tuned.

In the present work a simplified joint probability model for directional extreme wind speeds is utilized. The model has only one free parameter which can be easily calibrated by available wind speed data. The model will be applied to fit the wind data of Waglan Island station of Hong Kong.

WIND DATA ANALYSIS

Wind data at Waglan Island for a period of 25 years (1975-1999) were obtained from the Hong Kong Observatory. The data include the hourly mean wind speed and mean wind flow direction in 10^o resolution at hourly interval. Annual maximum wind speed at 12 directional sectors, as well as the annual maximum wind speed among all the directions can be obtained for each year. A total of 12 time series of annual maximum wind speed at different directional sectors can be constructed for extreme values analysis.

The vertical wind profile is generally expressed by power law relationship and can be described by the following equation:

$$\frac{v_z}{v_g} = \left(\frac{z}{z_g}\right)^{\alpha} \tag{1}$$

where z=height

z_g=gradient height

v_z=hourly mean wind speed at height z

v_g=gradient wind speed

Recent field measurement results showed that for open sea condition the gradient height is about 500m and the wind speed variation with height can be approximated by a power law profile with exponent equal to 0.1 to 0.11.

As Waglan Island is exposed to open sea in most of the directions, the wind profile at Waglan will probably follow the open sea type wind profile, i.e. the gradient height is 500m and the power law exponent is 0.1-0.11. Using these parameters the wind speed at Waglan v_w can be converted to the gradient wind speed v_g by

$$v_g = 1.2\, v_w \tag{2}$$

For extreme values analysis of directional wind speed, the wind climate is defined by annual maximum wind speeds blowing from N directions. N directional time series are then formed. Extreme values analysis yields N extreme values $U_T(\theta_i)$, $_{i=1,2,\ldots N}$ where T denotes the return period and θ denotes the wind blow direction.

If wind direction is not accounted for, the N time series can be combined into a single series of the largest wind speed:

$$U_j^{\max} = \max_i [U_j(\theta_i)] \qquad _{j=1,2,....M} \tag{3}$$

where $U_j^{\max}$ is the annual maximum wind speed disregarding the direction in year j, and $U_j(\theta_i)$ is the annual maximum wind speed at direction θ_i in year j. Using the extreme values analysis, the non-directional estimate of the T-year wind speed U_T can be obtained. Since each of the terms of the time series $U_j^{\max}$ is equal to or greater than its counterpart in the N directional time series, $U_T > U_T(\theta_i)$.

The Gumbel probability distribution function is used to fit the extreme wind speed data U. The cumulative probability function is given by:

$$P(U_0 < U) = \exp[-\exp\frac{-(U - A)}{B}] \tag{4}$$

The coefficients A, B are called the location and scale coefficient respectively. The exceedance probability is

$$P(U_0 \geq U) = 1 - P(U_0 < U) \tag{5}$$

The relationship between return period T and exceedance probability is

$$P(U_0 \ge U) = 1/(\lambda T) \qquad (6)$$

where λ = the average number of data used per year.

In the fitting a plotting exceedance probability P_m is assigned to each datum U_m. In this work P_m is given by the Weibull Formula. Least squares method is used to determine the parameters A and B by fitting a line through the data pairs (U_m, $-\ln(-\ln(1-P_m))$).

Fig. 1 displays the 50 year return period direction-free gradient wind speed by extrapolation of the results on extreme values analysis of wind data at Waglan as well as the results with directional variation. It can be seen that wind blows most strongly from the range of directions from East to South. By employing 12 directional sectors, the extreme wind speed in any sector is 13%-60% smaller than the corresponding direction-free wind speed. The confidence intervals of the results are expressed in terms of the standard deviations which are around 15% of the mean values. It is also of interest to show the return periods in each directional sector corresponding to a 50 year direction-free scaled-up wind seed of 59.5m/s (Table 1).

It is observed that in the range of direction from West to North, the gradient wind speed extrapolated from Waglan data is smaller. One of the reasons is due to topographic effect, wind blowing from this range of directions is partly sheltered by the mountains of Hong Kong.

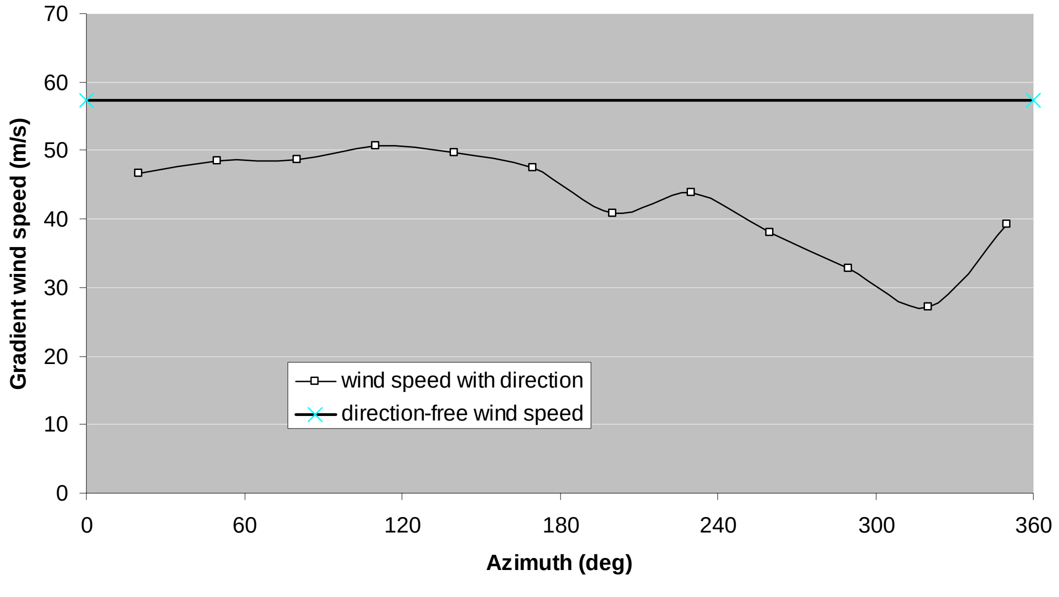

Fig. 1 Directional variation of the 50 year return period gradient wind speed

Table 1 Return periods for scaled-up wind speed of 59.5m/s at different directional sectors

Wind speed	Direction Free	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	270-300	300-330	330-360
59.5(m/s)	50yr	264	199	215	130	129	189	815	399	2689	11869	385253	1452

EXTREME WIND PRESSURES

i) Annual maximum response time series

The structural response of a building to wind refers to the pressure, force, deflection, acceleration, or based-moment due to wind blow. Owing to the shape of the building, the structural response will depend on the direction of wind blow. There is usually a critical direction in which the response is the maximum for a constant wind speed irrespective of direction. If the direction-free wind speed for a given return period (say 50 years) is chosen as the reference wind speed and the wind blow direction is specified as the critical direction (i.e. the code-type approach), the response will be conservative and has a return period greater than the corresponding return period of wind speed (50 years).

To obtain the direction-free maximum pressure, a time series of the annual maximum pressure is first constructed. The relationship between pressure P and wind speed U at direction i and year j can be expressed generally as

$$P_j(\theta_i) = a(\theta_i)U_j(\theta_i)^{b(\theta_i)} \qquad (7)$$

where a, b are empirical coefficients, with $2 \le b \le 3$. Also, an equivalent wind speed r can be obtained.

$$r(\theta) = \left(a(\theta)U^{b(\theta)}\right)^{1/B} \qquad (8)$$

where B can be defined to be the average of all the b values. Extreme values analysis can be performed to this series and the T year return period equivalent wind speed and hence the corresponding pressure can then be found. The purpose of using the equivalent wind speed is to achieve a better fitting of the data to the extreme probability distribution.

In the code-type approach, the direction-free maximum pressure P^C is determined by choosing the maximum wind speed and maximum coefficients among all directions. For year j

$$P_j^C = \max_i \left\{a(\theta_i)\max_i\left[U_j(\theta_i)\right]^{b(\theta_i)}\right\} \qquad (9)$$

By comparing eqs (4) and (6), it is obvious that $P_j^c \ge P_j(\theta_i)$.

There is a limiting case of interest. If a, b are constant, i.e. direction-free, then the maximum response will be induced by the annual maximum direction-free wind speed and $P_j^c = P_j(\theta_i)$

For the other cases, a time series of annual maximum pressure must be formed and extreme values analysis has to be carried out. For illustrative purpose, consider wind blowing against a very tall building (Fig. 2). The effect of wind blow direction on the pressure coefficient (an explicit function of a) has been measured and shown in Fig. 3. Using the data at Waglan, the annual maximum pressure and its equivalence speed can be determined by eqs. (8) and (9) with b=2. The pressure variation with return period is then obtained and displayed in Fig. 4.

In the figure the corresponding pressure using the code-type approach (upper bound) is also displayed. It can be seen that about 15% reduction in design pressure can be achieved.

It should be noted that the directionality reduction effect depends on several factors. First is the directional variation of the structural response (force coefficients, pressure coefficients, momentum coefficients, deflections, accelerations and etc.). Second is the directional variation of the extreme wind speed. Third is the orientation of the building. However, it is sure that the code-type approach will give the upper bound of the structural response.

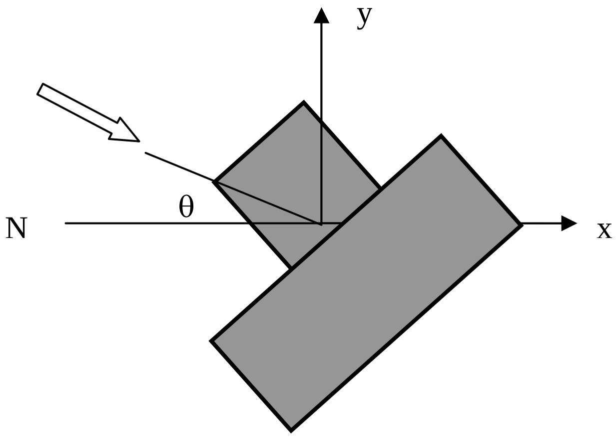

Fig. 2 Definition sketch of wind blow against a building

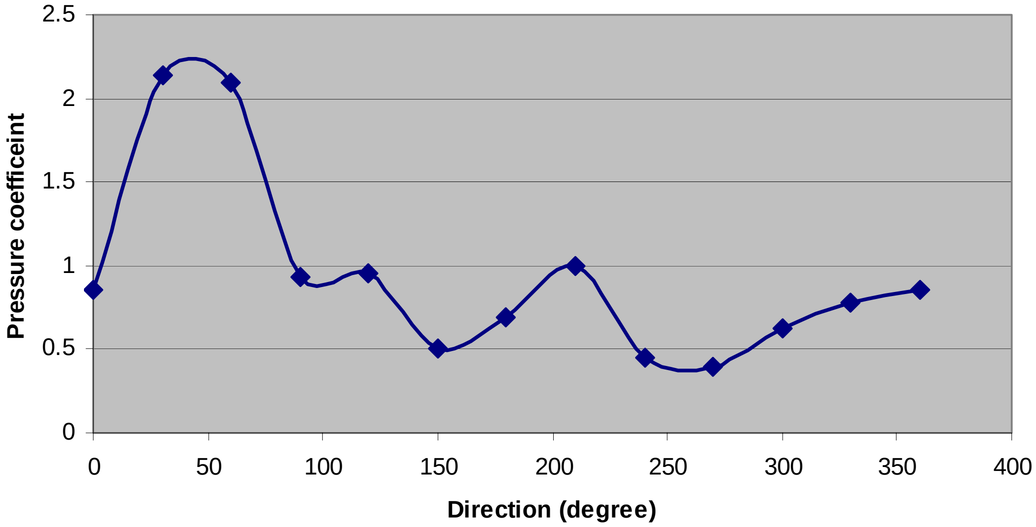

Fig. 3 Variation of absolute pressure coefficient with direction of wind blow

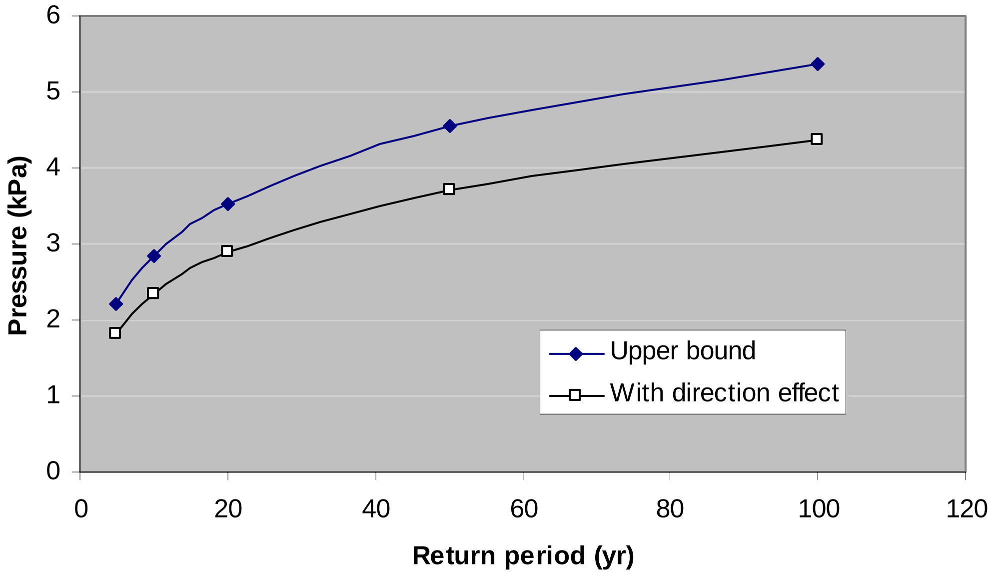

Fig. 4 Variation of extreme structural response with return period

ii) Joint Probability Model

The proposed joint probability model is based on the observation that if the directional wind speeds are mutually independent, then the joint cumulative probability of all directional wind speeds should be given by

$$\begin{aligned}\Pr ob(v < U) &= \Pr ob(v_1 < U, v_2 < U, \ldots, v_n < U) \\ &= \Pr ob(v_1 < U)\Pr ob(v_2 < U)\ldots\Pr ob(v_n < U)\end{aligned} \tag{10}$$

where n=number of sectors for the 360^0 circle.

On the contrary, if the directional wind speeds are mutually dependent, all the events will be perfectly correlated. The joint cumulative probability of all directional wind speeds should then be

$$\begin{aligned}\Pr ob(v < U) &= \Pr ob(v_1 < U, v_2 < U, \ldots, v_n < U) \\ &= \min[\Pr ob(v_1 < U), \Pr ob(v_2 < U), \ldots, \Pr ob(v_n < U)]\end{aligned} \tag{11}$$

In reality the directional wind speeds should be partially dependent. The joint cumulative probability should be bounded between the about two functions. A very simple joint cumulative probability model can be constructed as follows.

$$\begin{aligned}\Pr ob(v < U) = {} & \alpha \min[\Pr ob(v_1 < U), \Pr ob(v_2 < U), \ldots, \Pr ob(v_n < U)] + \\ & (1-\alpha)\Pr ob(v_1 < U)\Pr ob(v_2 < U)\ldots\Pr ob(v_n < U)\end{aligned} \tag{12}$$

where α=free parameter to reflect the degree of dependence among the directional wind speeds. When α=1, the directional wind speeds are fully dependent. When α=0, the directional wind speeds are fully independent. The present model excludes the rare case that the directional wind speeds are negatively correlated.

For each directional sector the cumulative probability has been determined by using the Gumbel distribution. The value of α is unknown and need to be determined empirically. One way is to fit the model with the direction-free annual maximum wind data at Waglan. Fig. 5 shows that the joint probability with α=0.6 gives the best fit.

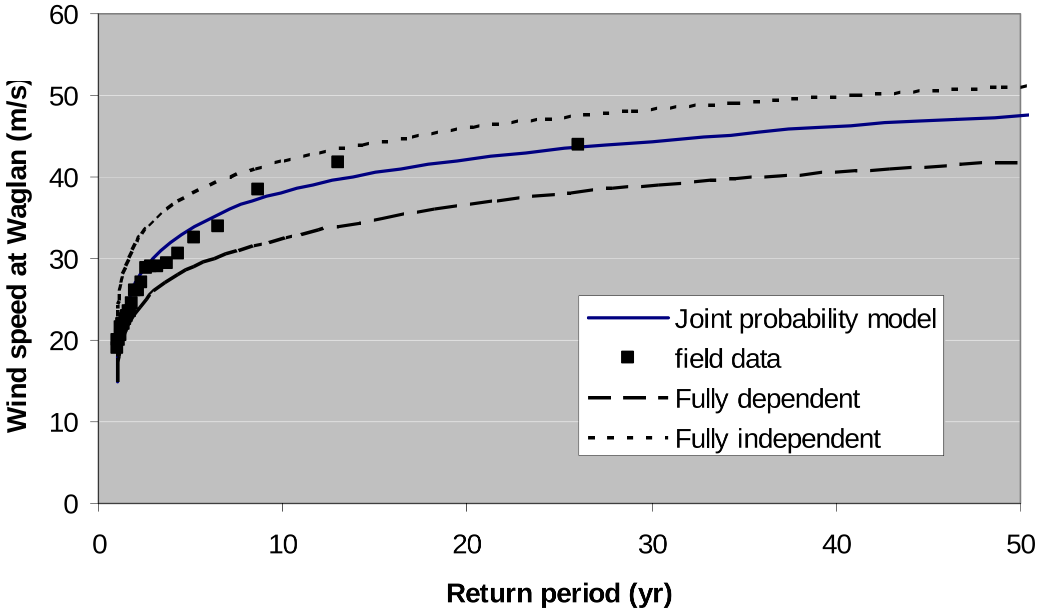

Fig. 5 Joint probability model for reconstruction of maximum wind at Waglan

When the model is applied to analyze pressure response, the equivalent wind speed U_i at directional sector i corresponding to a given value of pressure P is first determined using eq. (8). The cumulative probability is determined as follow.

$$\begin{aligned}\Pr ob(p < P) = \alpha \min[\Pr ob(v_1 < U_1), \Pr ob(v_2 < U_2), ..., \Pr ob(v_n < U_n)] + \\ (1-\alpha)\Pr ob(v_1 < U_1)\Pr ob(v_2 < U_2) .... \Pr ob(v_n < U_n)\end{aligned} \tag{13}$$

The value of α is case dependent but changes only moderately. This is mainly due to data sampling variability. Also the joint probability function is not very sensitive to the value of α. By comparing with the method using annual maximum time series of response, the value of α changes to 0.4 for best fitting in the present case (Fig. 6). The value of α will be a function of the directional variation of the pressure coefficient. For pressure or other responses there is in general a directional range within which the response is much larger. The correlation among the directional responses will thus be lower than that in the case of directional wind speeds. Changing the value of α from 0.6 to 0.4 only changes the 50-year return period pressure by about 5%.

CONCLUSIONS

Methods dealing with the wind directionality effect on the response of a structure have been briefly reviewed. The application of the method based on annual maximum response time series to Hong Kong has been described. A new simplified joint probability model has then been proposed. The application of this method to Hong Kong shows that the correlation among the directional responses is moderate.

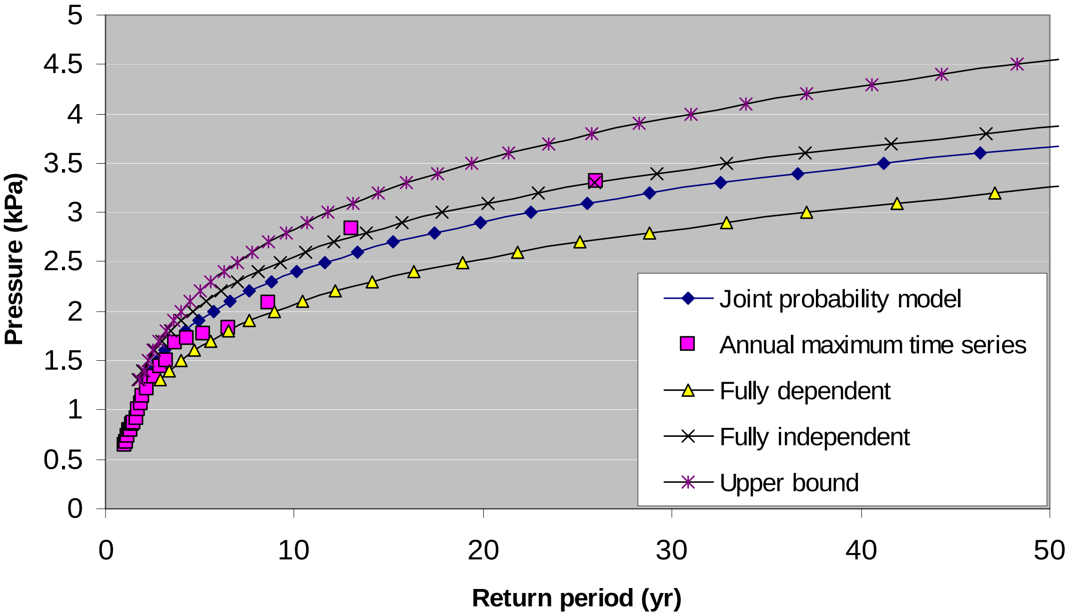

Fig. 6 Joint probability model for maximum pressure response

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