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Wind Load Effects of Long-span Roof Structures Considering Wind Directionality

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Abstract

The wind-induced dynamic response (load effect) of long-span roof structures is contributed by multiple modes and there are multiple wind load effects that should be considered for the design. In this study, the peak wind load effects in terms of displacements of a long-span roof structure are determined through dynamic analysis with consideration of wind directionality. Firstly, the directionality characteristics and the dependence on mean wind speed of several typical load effects are discussed in detail. Secondly, these peak responses as functions of wind speed and direction are combined with directional wind information using the multivariate extremum theory. Lastly, some new insights on the directionality effect of long-span roof structures are provided. A simplified approach accounting for the directionality of multiple wind load effects is also proposed.

Introduction

Long-span roof structures have the characteristics of light weight, large flexibility, small damping and closely-spaced natural frequencies. The wind-induced dynamic response (load effect) is contributed by multiple modes and there are multiple wind load effects that should be considered for the design (e.g., Katsumura [3]). Furthermore, the load effects are functions of wind speed and direction. To estimate the wind load effects with various mean recurrence intervals, the extreme wind load effects as functions of wind speed and direction are combined with the directional wind climate model. Such a consideration of wind directionality effect has been well recognized in assessing wind load effects of structures (e.g., Isyumov et al. [2]; Zhang and Chen [4]). Various approaches have been developed to integrate the directional wind climate with the wind load effects at different wind directions. In design codes and standards, simplified procedures are often adopted. For examplw, in ASCE 7-10 [1], a single directionality factor of 0.85 is introduced.

In this study, the dynamic wind pressures on a long-span roof structure obtained from wind tunnel test at various wind directions are discussed. The peak wind load effects in terms of displacements are determined through dynamic analysis with consideration of multiple mode contributions. The directionality characteristics and the dependence on mean wind speed of several typical load effects are discussed in detail. These peak responses as functions of wind speed and direction are then combined with directional wind information using the approach developed in Zhang and Chen [5], which leads to the estimation of responses with various mean recurrence intervals (MRIs). New insights on the directionality effect of long-span roof structures are provided. A simplified approach for accounting for the directionality of multiple wind load effects is also proposed.

Wind Load Effect of Long-span Roof Structures

Wind Tunnel Experiments

The long-span roof structure has a long span of 167.5 m, a short span of 141.7 m and a height of 29.90 m. A series of wind tunnel experiments were carried out to measure the fluctuating pressure acting on the roof structure using a scaled model. The geometry scale of the model was 1:200. A total of 369 wind pressure measurement points were arranged on the roof surface, and the fluctuating wind pressures of these points were measured simultaneously. The sampling frequency of the pressure data was 300 Hz with a total sampling time of 60 s. The pressure taps were connected to the measurement system through PVC tubing. To avoid dynamic pressure distortion, signals were modified using the transfer function of tubing systems. Wind tunnel tests were performed at various wind directions with an increment of 22.5° .Wind direction was defined as 0° when wind blowing from narrower side and 180° from wider side, and increases clockwise.

The wind tunnel test was carried out using a boundary layer wind tunnel (XNJD-1 industrial wind tunnel) of the Research Center for Wind Engineering at Southwest Jiaotong University, as shown in figer 1. Spires and roughness elements were used to simulate a typical boundary layer wind flow of exposure Category B in accordance with the Load Code of China (MCPRC 2002). The reference wind speed is 8.0 m/s at a reference height of 0.15 m which is equivalent to 37.5 m/s at height of 30.0 m in full scale. The wind speed scale ratio is 0.213, and the frequency scale ratio is 42.6. The corresponding wind speed at the height of 10 m in full scale is 31.4 m/s, which is the basic wind speed with MRI of 50 years.

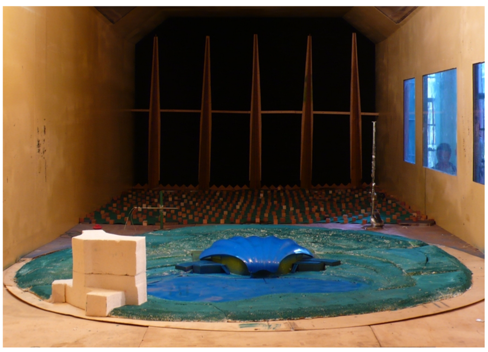

Figure 1. Rigid model of the roof structure in wind tunnel

Analysis of Wind Load Effects

The roof structure is a steel spatial truss with a total of 3,049 nodes and 11,991 elements. The finite element model is shown in Figer 2. The structural modal damping ratio is assumed as 0.01. The fundamental frequency of this structure is 0.88 Hz. The frequencies of first 50 modes range from 0.88 Hz to 9.95 Hz. The dynamic response analysis was carried out in the time domain by using Newmark integration method. In order to obtain accurate estimation of these modal responses, the wind pressure time histories with a time step of 1/300=0.0033 s in the model scale, i.e., 0.0033×42.6=0.141 s in the prototype, were linearly interpolated. Thus, the actual calculation step is 0.0141 s, which is less than $1/(10 f_{\max}) = 0.0174\ s$.

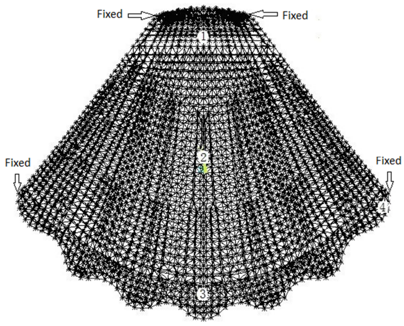

Figure 2. Finite element model of the roof structure

The displacements at four nodes indicated in figure 2 are considered here. The mean and STD values of these responses are calculated directly from the response time history. The maximum response is then determined as $r_i = \overline{r_i} + \operatorname{sgn}(\overline{r_i}) g\sigma_{r_i}$, where g is the peak factor generally ranging from 3 to 4; $\operatorname{sgn}(\cdot)$ is the sign function. As an example, Table 1 shows the mean, STD and maximum displacement at the central node (No. 2) at different wind speeds ranging from 20 to 50 m/s at 0° wind direction. The peak factor g is taken as 3.5. Figer 3 shows the power spectral density (PSD) function of the displacement at wind speed of 35 m/s. It can be seen that the background and resonant responses are at the similar level, and the resonant response is primarily contributed by the 1st and 4th modal responses.

Wind speed (m/s)	20	25	30	35	40	45	50
Mean (mm)	19.19	29.84	42.27	58.14	74.80	95.50	117.18
STD (mm)	6.78	11.26	16.78	24.36	31.24	41.48	52.50
Maximum (mm)	42.91	69.25	101.00	143.39	184.16	240.68	300.92

Table 1. Displacement of the central node (No. 2) at different wind speeds in 0° wind direction

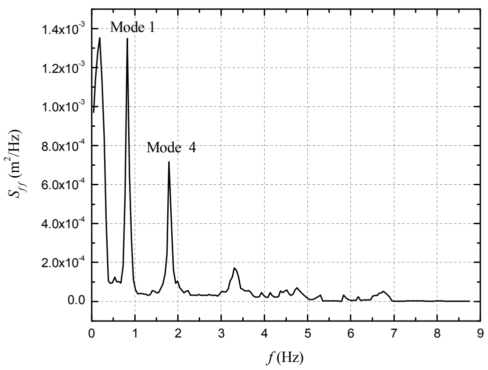

Figure 3. PSD function of the displacement of node 2

The extreme response at i-th wind direction can be curve-fitted as a power function of wind speed as

$$x_i(V_i) = \frac{1}{2}\rho V_i^2 C_i(V_i) = \frac{1}{2}\rho V_i^{2+b_i} C_{i0} \qquad (1)$$

where $C_i(V_i)$ is wind load effect coefficient; C_{i0} and b_i are two constants; V_i is mean wind speed in i-th direction. For very rigid structures, the background response is dominant and resonant response is negligibly small, b_i is close to zero. In general, $b_i > 0$ for flexible structures due to dynamic amplification effect from the resonant component.

Figer 4 shows the results of curve-fitting of extreme displacements at the four nodes as power function of wind speed. It is observed that the power function serves well. It is noted that other type of functions can also be used in necessary, which will not affect the discussion of the directionality effect. Figer 5 is the results for the normalized constant as a function of wind direction. It is observed that these four displacements have different directionality feature: (1) Node 1: There are two dominant directions, i.e., 90° and 180°, which are not adjacent; (2) Node 2: All of the directions have the similar level of response; (3) Node 3: There are three dominant directions, i.e., 157.5°, 180° and 202.5°, which are adjacent. (4) Node 4: There are only one dominant direction, i.e., 112.5°, and responses of other directions are much smaller.

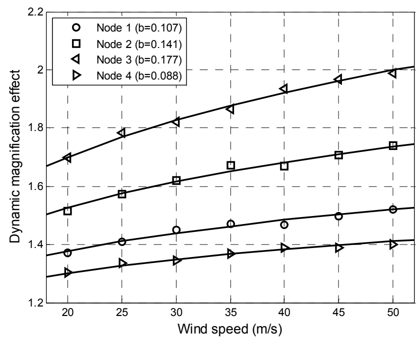

Figure 4. Curve-fitting of extreme response as power function of wind speed at 0° wind direction

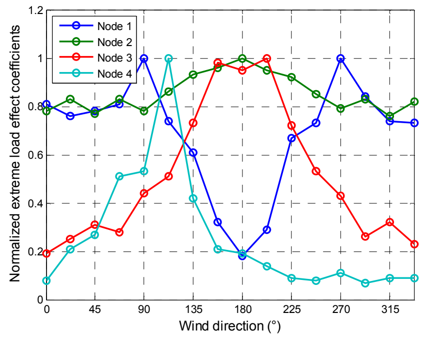

Figure 5. Normalized extreme response coefficients

Distributions of Directional Extreme Wind Speed

Distribution of Extreme Wind Speed at Each Direction

The directional hourly mean wind speed data used in this study was processed based on the data set 6405 from Automated Surface Observation System (ASOS, NOAA) at Chicago, IL, USA, dated from January 1st, 2000 to April 30th, 2016. To model the multivariate directional extreme wind speeds, the first step is to determine the extreme value distribution of wind speed in each direction, which is assumed to follow Gumbel (Type I) distribution. For simplicity, these directional hourly mean wind speeds are partitioned into sixteen directional sectors. Each sector swepts an area from $\alpha_i - 11.25°$ to $\alpha_i + 11.25°$ and are denoted by its central direction, where $\alpha_i = 0°, 22.5°, \cdots, 337.5°$, representing directions of N, ENE, NE…, WNW. The drawback of using yearly maximum wind speed is the small sample size which leads to large statistical error. Use of block maxima, e.g., monthly maximum or storm maximum wind speeds, can reduce the statistical error due to the increased sample size. In this study, the monthly maximum hourly mean wind speed data are used. In each direction, there are altogether 196 monthly maxima available. All the monthly maximum wind speeds are first sorted in an ascending order and the *m*-th wind speed corresponds to a probability of nonexceedance in a month or cumulative probability function (CFD) value, $\Psi_m = (m - 0.44)/(n + 0.12)$, where n is the number of months. The corresponding CDF of yearly maximum is then estimated as $(\Psi_m)^{12}$ by assuming that the monthly maximums are independent and identically distributed, which are then fitted into Gumbel distribution.

Modeling of Multivariate Directional Extreme Wind Speeds

The joint probability distribution of directional extreme wind speeds can be determined using multivariate extreme value theory. The Gaussian copula model is adopted in this study (e.g. Zhang and Chen [5]). The joint probability distribution of directional extreme wind speeds are given as

$$H(v_1, v_2, \ldots, v_n) = G_n(y_1, y_2, \ldots, y_n) \tag{2}$$

Where $y_t = \Phi^{-1}\left(\Psi_{V_i}(V_i)\right)$ is the value of underlying Gaussian variable Y_i; Φ is the CDF of standard Gaussain distribution; G_n is the CDF of n-dimensional Gaussian distribution with mean 0 and covariance matrix Σ and $\Sigma_{ij} = \Sigma_{ji} = \rho_{ij}$; and ρ_{ij} is the correlation coefficient of Y_i and Y_j. In the case where $\Psi_{V_i}(v_i)$ is Type I extreme value distribution, the relationship between correlation coefficient, $r_{ij} = r_{ji}$, and $\rho_{ij} = \rho_{ji}$, is given by Zhang and Chen [4]:

$$r_{ij} = \frac{6}{\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left\{-\ln\left[-\ln\left(\Phi(y_i)\right)\right]-\gamma\right\} \left\{-\ln\left[-\ln\left(\Phi(y_j)\right)\right]-\gamma\right\}\phi(y_i, y_j; \rho_{ij})\, d_{yi} d_{yj} \tag{3}$$

where $\gamma = 0.5772$ is Euler constant; $\phi(y_i, y_j; \rho_{ij})$ is the joint probability density function (JPDF) of bivariate Gaussian distribution with correlation coefficient ρ_{ij}.

The value of ρ_{ij} relies only on r_{ij}, and is irrelevant to the parameters of Type I distribution. The translation function has its limit in negatively correlated case, e.g., the lower bound $r_{ij} = -0.89$ corresponds to $\rho_{ij} = -1$. The correlation coefficient r_{ij} can be directly calculated from the wind speed data. It can be assumed that the correlation coefficient among directional monthly maximum wind speed is identical to that of yearly maximum wind speeds (Zhang and Chen [4]). A convenient fitting formula for the correlation coefficient ρ_{ij} is given by

$$\rho_{ij} = r_{ij}\left(1.064 - 0.069 r_{ij} + 0.005 r_{ij}^2\right) \tag{4}$$

Extreme Wind Speed Regardless of Wind Direction

The CDF of extreme wind speed regardless of wind direction is determined from the posed multivariate model as $\Psi_V(v) = H(v, v, \cdots, v)$. It can also be obtained directly by fitting the yearly maximum data regardless of wind direction, which is denoted as $\Psi_{Vnon}(v)$. Figer 6 shows their compassion along with the CDFs of extreme wind speed in each direction. It is proved that, theoretically, $\Psi_V(v) \neq \Psi_{Vnon}(v)$ unless the marginal distributions of each direction are identical. The property that $\Psi_V(v) < \Psi_{V_i}(v)$ ensures that the directionless wind speed estimated from the multivariate model is always larger than any of the directional wind speeds for any MRI level. However, it is possible to have unrealistic result that $\Psi_{Vnon}(v) > \Psi_{V_i}(v)$ at higher MRIs, which is due to modeling error. In this study, the distribution of yearly maximum wind speed regardless of direction obtained from the multivariate model will be used.

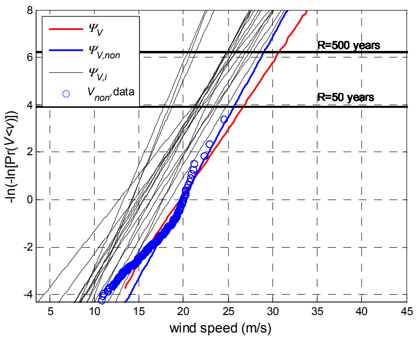

Figure 6. Distribution of yearly maximum wind speed regardless of wind direction

Distribution of Extreme Wind Load Effect with Directionality Effect

Distribution of Yearly Maximum Wind Load Effect

The CDF of yearly maximum wind load effect with consideration of wind directionality can be calculated as follows

$$\Psi_X(x) = H(v_{x1}, v_{x2}, \cdots, v_{xn}) \tag{5}$$

where $v_{xi}\ (i = 1, 2, \cdots, n; n = 16)$ is the wind speed in i-th direction cause the wind load effect level x, which can be readily determined from the relationship of extreme response with wind speed and direction as discussed before, i.e., $v_{xi} = (2x/\rho C_{\alpha i})^{\frac{1}{b_{\alpha i}+2}}\ (i = 1, 2, \cdots, n)$.

Clearly, when directional extreme wind speeds are independent, we have

$$\Psi_X(x) = \Psi_{V1}(v_{x1})\Psi_{V2}(v_{x2})\cdots\Psi_{Vn}(v_{xn}) \tag{6}$$

The wind effect with MRI of R years, x_R is determined as

$$R = 1 - \frac{1}{1 - \Psi_X(x_R)} \tag{7}$$

When wind directionality effect is not considered, the wind effect with MRI of R years is calculated as

$$x_{R0} = \max(x_{1R0}, x_{R20}, \cdots, x_{Rn0}) \tag{8}$$

where x_{Ri0} is wind effect caused by wind speed V_R, i.e., $x_{Ri0} = 0.5\rho V_R^{2+b_i} C_{i0}\ (i = 1, 2, \cdots, n)$; and V_R is R-year wind speed regardless of wind direction. The direction factor is defined as $K_d = x_R / x_{R0}$, which is less than unity.

In practice, the sector-by-sector approach is often used, which estimate the R-$year$ wind effect as

$$x_R = \max\left(x_{R1}, x_{R2}, \cdots, x_{Rn}\right) \tag{9}$$

where x_{Ri} is wind effect caused by wind speed V_{Ri}, i.e., x_{Ri}=$0.5\rho V_{Ri}^{2+b_i} C_{i0}$ $\left(i = 1, 2, \cdots, n\right)$; and V_{Ri} is $R-year$ wind speed in i-th direction.

Figer 7 shows the distributions of yearly maximum wind effect of node 3 calculated from directional wind speed, i.e., $\Psi_{vi}\left(v_{xi}\right), \left(i = 1, 2, \cdots, n\right)$; $\Psi_X\left(x\right)$ based on joint distribution of directional wind speeds, i.e., equation (5); $\Psi_{X,SBS}\left(x\right)$ based on sector-by-sector approach, i.e., equation (9); $\Psi_{X,Ind}\left(x\right)$ based on independent assumption of directional wind speed, i.e., equation (6).

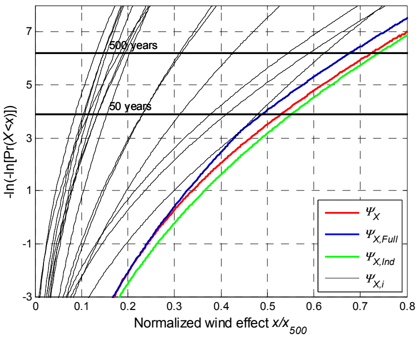

Figure 7. Distribution of yearly maximum wind effect of node 3

A simplified approach accounting for the directionality of multiple wind load effects

The prediction made by taking correlation into consideration should fall into the region bounded by $\Psi_{X,SBS}\left(x\right)$ and $\Psi_{X,Ind}\left(x\right)$. It can be seen that the extreme responses based on sector-by-sector approach which come from the maximum valve of all directions leads to an underestimate of wind load effect. The differences are 13.21% and 9.09% corresponding to $R = 50$ *and* 500 *years*, respectively. However, the extreme responses based on independent assumption of directional wind speed have relatively small differences with the valves of 4.23% and 2.33% corresponding to $R = 50$ *and* 500 *years*, respectively. Of course, one may also consider the differences to be unacceptable. In this study, a modified factor is given to deal with this condition:

$$\alpha_s = x_{\rho,R} / x_{Ind,R} \tag{10}$$

where α_s is the modified factor with the valve of $0 < \alpha_s \le 1$; $x_{\rho,R}$ and $x_{Ind,R}$ are the extreme responses by multivariate approach and sector-by-sector approach, respectively.

Theoretically, it is most accurate for giving each node a modified factor. However, it is reasonable to give a uniform modified factor because these modified factors are closer to each other. In this study, a uniform modified factor, α_u, for all of the wind load effects is given by the multiple extreme value theory:

$$\begin{aligned}&\Pr\left[X_1 < \alpha_u x_{Ind,1}, X_2 < \alpha_u x_{Ind,2}, \cdots, X_n < \alpha_u x_{Ind,n}\right]\\ &= \Pr\left[X_1 < \alpha_{s,1} x_{Ind,1}, X_2 < \alpha_{s,2} x_{Ind,2}, \cdots, X_n < \alpha_{s,n} x_{Ind,n}\right]\end{aligned} \tag{11}$$

Based on the above statements, the following modified process is developed to serve the purposes of accurate solutions for the long-span roof structures:

1) Estimate all of the extreme responses based on independent assumption of directional wind speed;

2) Obtain all of the modified factors corresponding to these extreme responses by the multivariate approach. Then, calculate the uniform modified factor by the multiple extreme value theory.

3) Determine the final extreme responses by multiplying the results by the uniform modified factor.

Conclusions

This study analysed the wind load effects in terms of displacements of a long-span roof structure through dynamic analysis with consideration of wind directionality. The main conclusions are as follows:

(1) The dynamic wind pressures on a long-span roof structure are obtained from wind tunnel test at various wind directions. Then, the peak wind load effects in terms of displacements are determined through dynamic analysis with consideration of multiple mode contributions.

(2) The directionality characteristics and the dependence on mean wind speed of several typical load effects are discussed in detail.

(3) These peak responses as functions of wind speed and direction are combined with directional wind information using the multivariate extremum theory considering the dependence of directional wind speeds.

(4) A simplified approach with the uniform modified factor accounting for the directionality of multiple wind load effects is proposed.

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