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STUDY ON EQUIVALENT STATIC WIND LOAD ON LONG-SPAN ROOF BASED ON RESPONSE-RELATED SCALE

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Abstract: This paper proposes an equivalent static wind load calculation method based on response-related scale for the wind load calculation of large-span roof structures. The effectiveness of this method is verified by wind tunnel tests and finite element analysis of the roof of the east entrance of Hangzhou Convention and Exhibition Center. The research results show that the equivalent static wind load method based on response-related scale has high accuracy in reflecting the overall response characteristics of the structure, and its error in calculating the node displacement response is the smallest, only 4.6%, which is better than the traditional single-objective equivalent method and least squares method.
Keywords: Long-span roof; Static wind load; Response-related scale; Equivalent load; Hangzhou convention and exhibition center

INTRODUCTION

With the acceleration of urbanization and economic development, large-scale exhibitions play an increasingly important role in modern urban construction [1,2]. As the core area of Hangzhou Airport Economic Demonstration Zone, Hangzhou Convention and Exhibition Center project is not only the cover of the airport and an important window of Hangzhou city, but also a convention and exhibition base with complete facilities in the Yangtze River Delta region. In the design of large-scale roof structures of exhibitions, the accurate calculation of wind loads has an important impact on structural safety and economy. The traditional static wind load calculation method has certain limitations in large-span roof structures and it is difficult to fully reflect the complex response characteristics of the structure [3,4]. To this end, this study proposes an equivalent static wind load calculation method based on response-related scale to improve the accuracy and reliability of wind load calculation of large-span roof structures.

1 PROJECT OVERVIEW

The Hangzhou Convention and Exhibition Center project is located in Nanyang Street, Xiaoshan District, Hangzhou City, Zhejiang Province. It is located on the bank of Qiantang River and close to the Qiantang River estuary. Hangzhou Metro Line 1 crosses from the central corridor from east to west. The total land area of the project is about 740,000 m^2, and the total construction area is about 1.34 million m^2, of which the underground construction area is about 500,000 m^2 and the indoor net exhibition area is about 300,000 m^2. The volume ranks first in Zhejiang Province and fifth in the country. Hangzhou convention and exhibition center renderings can be seen in Figure 1.

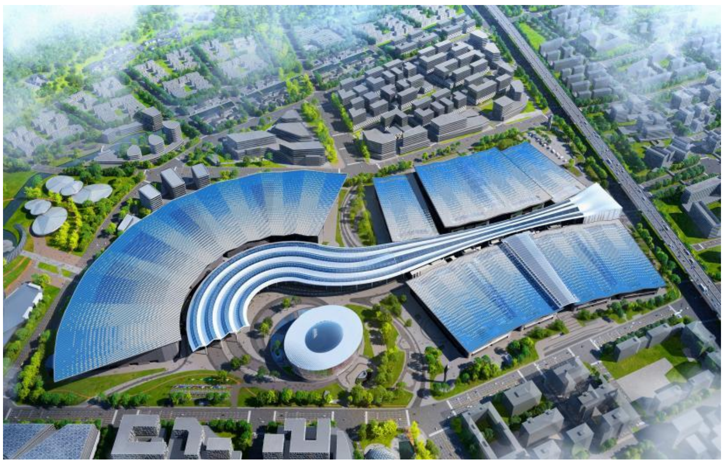


Figure 1 Hangzhou Convention and Exhibition Center renderings

2 RESEARCH METHODS

In order to calculate the equivalent static wind load of the large-span roof, a calculation method based on the response-related scale is proposed. The equivalent target that best reflects the overall effect of the structure is selected through the influence range of the response of a certain node of the structure. On this basis, the equivalent static wind load of the structure is determined by the dynamic load response correlation method. Taking the roof of the east entrance of the Hangzhou Convention and Exhibition Center as an example, a rigid model pressure wind tunnel test was carried out, and the equivalent static wind load was calculated by different methods.

2.1 Dynamic Load Response Correlation Method

The motion equation of the large-span spatial structure based on the node degree of freedom is formula (1):

$$[Q]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \quad (1)$$

Where, $[Q]$、$[C]$、$[K]$ are the mass matrix, damping matrix and stiffness matrix of the corresponding node degree of freedom respectively; $\{x\}$、$\{\dot{x}\}$、$\{\ddot{x}\}$ are the displacement, velocity and acceleration of each node degree of freedom respectively; and $\{F(t)\}$ are the wind load time history of each node degree of freedom respectively.

Define $[K]\{x\}$ in formula (1) as the structural wind vibration force, which comprehensively reflects the combined effect of wind load, damping force and inertia force. From the definition, it can be seen that the structural wind vibration force and the structural displacement response are linearly related. The response of the large-span spatial structure can be regarded as a quasi-static response under the action of the structural wind vibration force. Therefore, after obtaining the response time history of each degree of freedom of the structure through random vibration analysis, the equivalent static wind load of the large-span roof structure can be obtained based on the structural wind vibration force using the LRC method. Since the equivalent wind vibration force contains the structural dynamic characteristics, this method is called the dynamic load response correlation method.

The equivalent static wind load in the modal space can be expressed as formula (2)-formula (4):

$$F_{eq} = \bar{F} + \tilde{F}_{eq} \quad (2)$$

$$\tilde{F}_{eq} = g \sum j \left(W_j \tilde{F}_{eq,j}\right) \quad (3)$$

$$\tilde{F}_{eq,j} = \omega_j^2 [Q] \sigma_{qj} \varphi_j \quad (4)$$

$$W_j = \frac{\sum \rho_{q,ij} \sigma_{Tq,i} \varphi_j}{\sigma_T} \quad (5)$$

Where: F_{eq} is the equivalent static wind load of the structure; F is the average wind load of each degree of freedom; $\tilde{F}_{eq}$ is the pulsating equivalent static wind load; g is the peak factor, which can be taken as 2.5 for the main structure; $\tilde{F}_{eq,j}$ is the root mean square of the j-th order pulsating wind load; W_j is the participation coefficient of the j-th order wind load; ω_j is the i-th order natural circular frequency of the structure; φ_j is the i-th order vibration mode; σ_{qj} is the i-th order generalized displacement root mean square; $\rho_{q,ij}$ is the correlation coefficient between the i-th order modal response and the j-th order modal response; σ_T is the root mean square of the equivalent target; $\sigma_{Tq,i}$ is the i-th order root mean square value of the equivalent target; $\sum(\cdot)$ is the summation symbol.

To calculate the modal wind load participation coefficient of formula (5), the equivalent target must be selected first. Equivalent targets are generally selected based on engineering needs and experience, such as structural displacement or base force response. For large-span spatial structures, due to the complexity of structural response, there are often more than one representative equivalent target. When multiple equivalent targets are selected, the equivalent target can be replaced by a consistent equivalent target. The consistent equivalent target is expressed as a linear combination of all equivalent targets, namely:

$$T = I^T\{T_i\} \quad (6)$$

Where: T is the consistent equivalent target; $\{T_i\}$ is the column vector composed of each equivalent target; $(\cdot)^T$ represents transposition, I represents the distribution coefficient vector of each equivalent target, calculated as follows:

$$I = \left[P_{ij}\right]^{-1}\{1\} \quad (7)$$

Where $\left[P_{ij}\right]$ is the correlation coefficient matrix of each equivalent target time series.

2.2 Response Related Scale

The response related scale reflects the affected size of the response at a specified position under random load. Since the vertical structural size of the roof structure is much smaller than the plane size, the area can be expressed as follows.

$$E_i = \sum\nolimits_j \left|\rho_{ij}\right| M_j \quad (8)$$

Where: E_i represents the response correlation scale of the i node position; ρ_{ij} represents the correlation coefficient of the structural response at i and j; M_j represents the node subordinate area at i position, $|\cdot|$ represents the absolute value. Since the responses at different positions may have a negative correlation, in order to ensure that the affected area is a positive value, the absolute value of the correlation coefficient is used when calculating the response correlation scale.

From the definition of E_i, it can be seen that the larger E_i, the response at i position is, the higher the correlation between the response at other positions is, and the stronger the integrity of the response at i position is. Calculating the equivalent static wind load of the structure with the response at the maximum position as the equivalent target can reflect the overall characteristics of the large-span space structure. For large-span space structures, since the structure is in an over-static form, the roof may have multiple local extreme values. For such cases, the equivalent static wind load should be calculated with the responses at all local extreme value locations as multiple targets.

3 ENGINEERING EXAMPLES

3.1 Wind Tunnel Test

The overall layout of the exhibition hall of the Grand Convention and Exhibition Center is in the form of "fishbone + semi-enclosed" and the roof has a unique shape. In order to ensure its safety performance, its wind load is determined by wind tunnel tests. The following figure 2 shows the wind tunnel test model and ground roughness simulation picture (north-facing flow). The wind tunnel test uses a 1:300 model with a ground roughness of Class B. The wind tunnel test takes north as the 0° direction and rotates clockwise to complete a total of 36 wind load tests in wind directions.

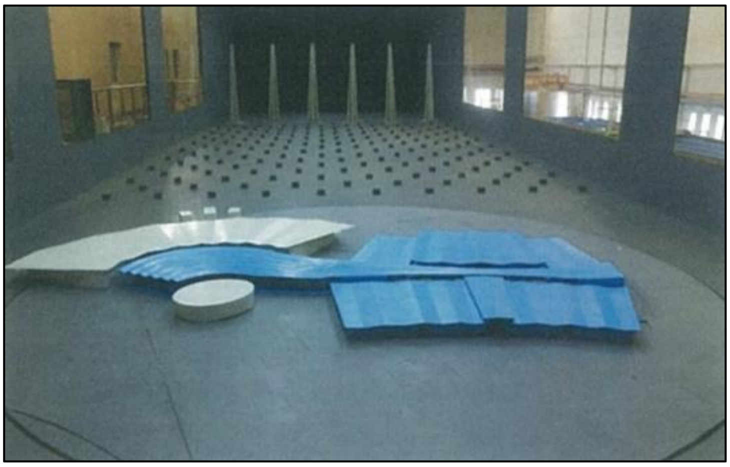


Figure 2 Wind tunnel test of Hangzhou Convention and Exhibition Center

From the wind tunnel test results, the middle corridor is disturbed by the surrounding venues, and the wind load is relatively small in most wind directions. The mean value of the wind pressure coefficient is defined as formula (9), and the root mean square value of the wind pressure coefficient is defined as formula (10).

$$W_P = \frac{p}{0.5\rho v^2} \tag{9}$$

$$\widetilde{W}_P = \frac{\tilde{p}}{0.5\rho v^2} \tag{10}$$

Where: W_P is the mean value of the wind pressure coefficient; $\widetilde{W}_P$ is the root mean square value of the wind pressure coefficient; p is the mean wind pressure at the measuring point; $\tilde{p}$ is the root mean square value of the wind pressure at the measuring point. v is the incoming wind speed at a height of 10m corresponding to the prototype; ρ is the air density.

When the corridor is at 90°, the interference in front is small. The following figure 3 and 4 shows the mean value of the wind pressure coefficient and the root mean square value of the wind pressure coefficient in the middle corridor under this wind direction. Since the roof of the east entrance is significantly higher than the interfering buildings on both sides, and the elevation of the edge of the entrance is higher than the elevation of the middle corridor, the wind load at the end is large, while the wind load in the middle is small due to the existence of reattachment. The maximum negative wind pressure coefficient of the entrance can reach -1.7; the root mean square value of the wind pressure coefficient can reach 0.3.

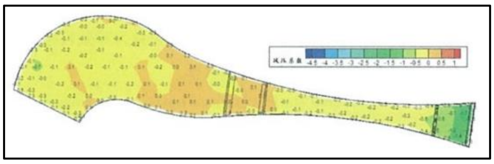


Figure 3 Average Value of Wind Pressure

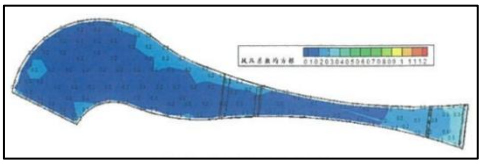


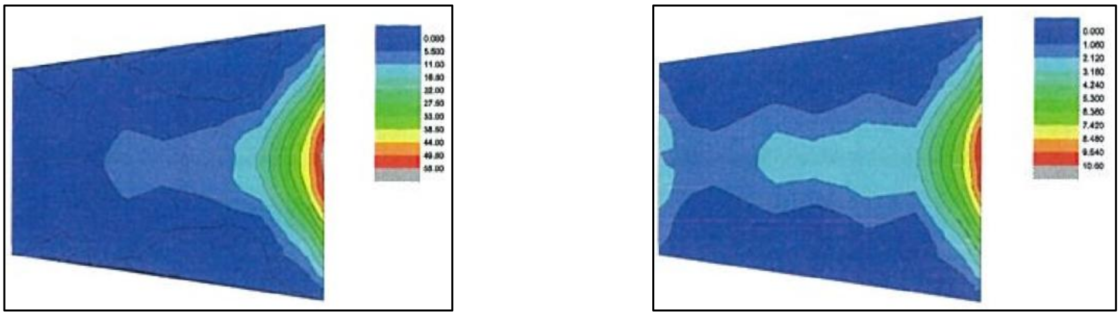
Figure 4 Root Mean Square Value of Wind Pressure Coefficient

Coefficient

3.2 Structural Response and Response-Related Scales

The total length of the corridor can reach 960m. In order to ensure the coordination of the structure under the action of temperature, the structure is divided into multiple substructures for design during structural design. Among them, the wind load at the east entrance is large, so this part of the structure is selected for key analysis. The roof of the east entrance is trapezoidal, with a structural length of 86m and a maximum span of 95m. The typical vertical vibration mode of the structure and the first 500 natural vibration periods of the structural period are obtained through finite element analysis.

The 90° wind direction flow load is applied to the structure, and the response of the structure under the action of average wind and pulsating wind is shown in the figure 5 below. Obviously, the position where the maximum displacement of the structure occurs is the same as the distribution form of wind load. The maximum average displacement and the maximum pulsating displacement of the structure are both located at the center of the east end of the login port, and the maximum average displacement and the maximum pulsating displacement are 55mm and 10mm respectively.



(a) Mean (b) Root Mean Square Value

Figure 5 Wind-Induced Displacement Response

The relevant scale of the structural displacement response is calculated using formula (8), and the relevant scale distribution diagram at any node of the model can be obtained, as shown in the figure 6 below. The maximum position of the response-related scale is located near the center of the roof plane, and three local extreme values appear, which deviate greatly from the maximum position of the structural displacement, indicating that the maximum displacement of the structure is a local response caused by local loads. If the maximum displacement of the structure is used as a single equivalent target, it cannot fully reflect the structural response to other areas with smaller displacements.

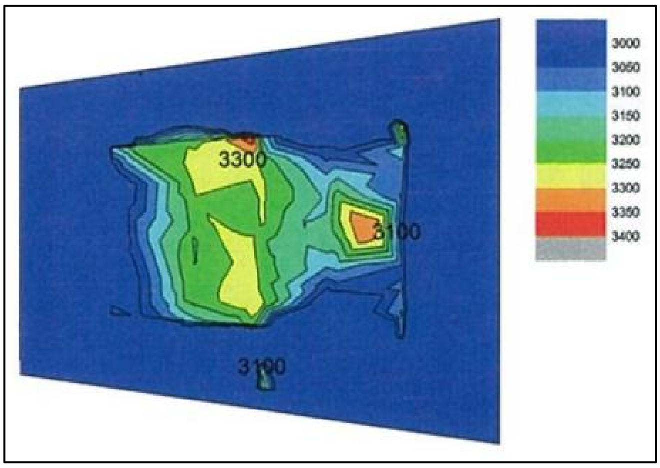


Figure 6 Displacement Response Related Scale

Equivalent static wind load: In order to compare the difference of equivalent static wind loads with different equivalent targets, the dynamic load response related method is used with the maximum displacement as the equivalent target, the dynamic load response related method is used with the structural displacement at the extreme position of the response integral scale as the multi-target equivalent, and the least square method is used with the response of all roof nodes as the equivalent target to calculate the equivalent static wind load. The distribution of equivalent static wind load is shown in the figure 7-9 below.

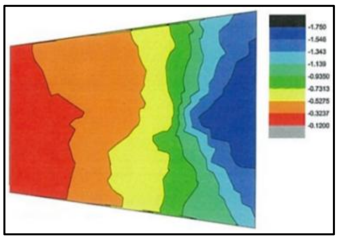


Figure 7 Equivalent Static Wind Load with a Single Displacement Extreme Value as the Equivalent Target

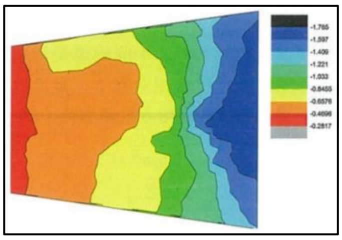


Figure 8 Equivalent Static Wind Load with all Displacement Extreme Values as the Equivalent Target

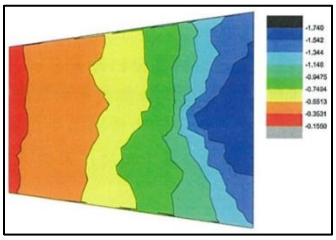


Figure 9 Equivalent Static Wind Load with the Displacement Corresponding to the Position of the Response-Related Scale Extreme Value as the Equivalent Target

From the overall distribution point of view, the equivalent static wind loads corresponding to different methods are close to the distribution form of the average wind load of the structure. The wind load on the west side is small and the wind load on the east side is large, but there are obvious differences in the distribution range of local wind loads. When the maximum displacement is used as a single target equivalent, the correlation between the wind load on the west side and the maximum displacement on the east side is poor, so the range of the small wind load on the west side is significantly higher than the multi-target equivalent static wind load.

Each equivalent static wind load is applied to the structural model, and the structural displacement response at the 1-12 node positions is calculated respectively, as shown in the figure 10 below. It can be seen that different equivalent static wind loads can accurately reflect the extreme displacement response of point 11, but the displacements of positions 1-9 obtained based on the single-target equivalent static wind load are quite different from the maximum displacement, and the maximum relative error at point 2 can reach more than 50%. The accuracy of the response-related scale method with fewer equivalent targets is close to that of the least squares method with all responses as equivalent targets, and the error at point 2 is the largest, about 7%.

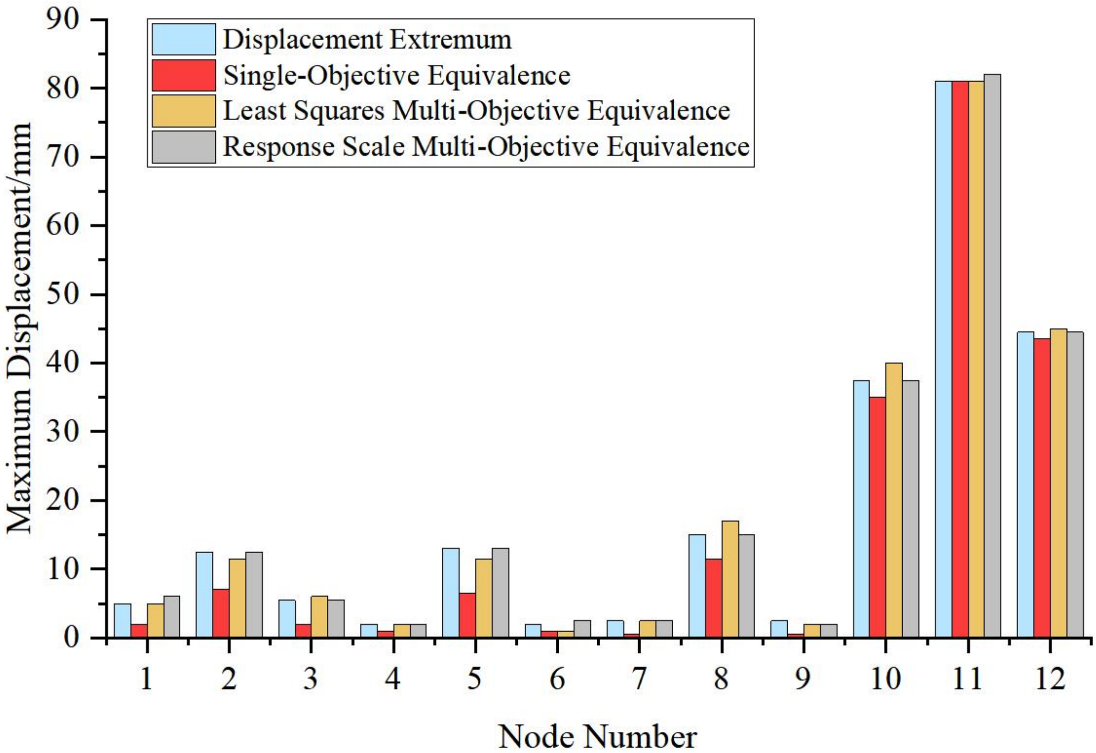


Figure 10 Comparison of Node Displacements Corresponding to Different Equivalent Static Wind Loads

The following table 1 shows the vertical resultant forces of the structure corresponding to different equivalent static wind loads. The calculation result based on the single-target equivalent has the largest error, while the relative error based on the response-related scale method is the smallest.

Table 1 Vertical Resultant Force Corresponding to Different Equivalent Static Wind Loads

Equivalent target	Equivalent method	Vertical load resultant/10^6N	Maximum vertical load/10^6N	Relative error
Maximum displacement	Dynamic load response	3.75	5.26	-28.7%

	correlation method			
Total displacement of the roof	Least square method	5.82	5.26	10.6%
Displacement of the maximum position of the response-related scale	Dynamic load response correlation method	5.50	5.26	4.6%

Based on the above research, a large-span roof wind load calculation method based on response correlation scale is proposed. The response correlation scale reflects the range of influence of the overall structure on the response of a certain node position of the structure. The larger the index, the stronger the overall structure response of the position. Since the large-span roof structure is an over-static system, multiple response correlation scale extreme values are often required to determine the equivalent target that fully reflects the overall response of the structure. Based on the selected equivalent target, the equivalent static wind load of the structure is determined by the dynamic load response correlation method. The experimental analysis based on the roof of the east entrance of Hangzhou Convention and Exhibition Center shows that both the multi-objective equivalent static wind load and the single-objective equivalent static wind load can reflect the wind load of the main wind-exposed area on the surface of the structure, but the distribution shapes of the equivalent static wind loads of different methods are different in the area with small average wind load, and the multi-objective equivalent results are greater than the single-objective equivalent results; the equivalent static wind load method based on the response-related scale is used, and the accuracy of the calculated node displacement response is close to that of the least squares equivalent static wind load calculation method, but the vertical force accuracy is higher than the least squares method, and the maximum error is only 4.6%.

4 CONCLUSION

This paper proposes an equivalent static wind load calculation method based on the response-related scale for the calculation of the wind load of the east entrance of Hangzhou Convention and Exhibition Center. Through wind tunnel tests and finite element analysis, this method has significant advantages in reflecting the overall response characteristics of large-span roof structures. The research results show that the equivalent static wind load method based on the response-related scale can not only accurately reflect the wind load distribution in the main wind-exposed area, but also effectively control the calculation error of the displacement response of each node, with a maximum error of only 4.6%. Therefore, this method has broad application prospects and promotion value in the calculation of wind loads on large-span roofs.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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