

# ***Study on Wind Pressure Distribution and Non-Gaussian Characteristics of a Long-Span Cylindrical Latticed Shell with a Small Rise-Span Ratio***

**Xiaolong Xu<sup>1, a</sup>, Zhuangzhuang Guo<sup>1, b</sup>, Anjie Chen<sup>1, c</sup>, Qun Yang<sup>1, 2, 3, d</sup>, Xiaobing Liu<sup>1, 2, 3, e, \*</sup>**

<sup>1</sup>*School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang, 050043, China*

<sup>2</sup>*Innovation Center for Wind Engineering and Wind Energy Technology of Hebei Province, Shijiazhuang, 050043, China*

<sup>3</sup>*Key Laboratory of the Ministry of Education for Road and Railway Engineering Safety Assurance, Shijiazhuang Tiedao University, Shijiazhuang, 050043, China*

<sup>a</sup>x\_x\_l\_long@163.com, <sup>b</sup>gzz0617@163.com, <sup>c</sup>chenanjiecaj@163.com, <sup>d</sup>quny123@126.com, <sup>e</sup>x\_b\_liu@126.com

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**Abstract:** In order to study the wind pressure distribution characteristics of large-span cylindrical reticulated shell structure with small rise-span ratio, the applicability of the current wind resistance code and the influence of non-Gaussian wind pressure effect, this paper takes the large-span cylindrical reticulated shell structure with a rise-span ratio of 1:6 as the research object, and carries out the wind tunnel pressure test of the rigid model. By comparing and analyzing the distribution of shape coefficient and overall force coefficient of small rise-span ratio and conventional rise-span ratio structures, the applicability of mainstream wind resistance design codes at home and abroad is analyzed, the non-Gaussian statistical characteristics of structural wind pressure are explored, and the underestimation error of extreme wind pressure under the action of non-Gaussian peak factor is quantified. The results show that the wind load distribution characteristics of the small rise-span ratio structure are different from those of the conventional structure, and there are potential safety hazards or economic deficiencies in the current code in different wind direction angle intervals. The non-Gaussian characteristics of the wind pressure of the low rise-span ratio structure are weaker than those of the conventional rise-span ratio structure, and the underestimation of the extreme wind pressure is reduced, but the wind pressure field of the structure still has significant peak and thick tail non-Gaussian characteristics. Ignoring non-gaussian will underestimate the extreme wind pressure of the structure, and even underestimate it by more than 50% at the edge of the roof. It can provide data support and theoretical basis for the wind-resistant design and specification revision of such small rise-span ratio cylindrical reticulated shell structures.

## 1. Introduction

Large-span cylindrical reticulated shell structure is widely used in large-span space buildings such as industrial coal storage sheds, stadiums and transportation hubs due to its beautiful architectural shape and reasonable structural mechanical performance. This kind of structure usually has the characteristics of light weight, large flexibility and small damping, and is very sensitive to wind load, so wind load often becomes one of the key loads to control its design. Among the many parameters that affect the wind load of cylindrical reticulated shell structures, the rise-span ratio has been proved to be a crucial factor by many scholars [1-3].

Domestic and foreign researchers such as Li et al. [4], Zhang et al. [5], Li et al. [6], Li and Tamura et al. [7] have carried out a lot of research on the wind load characteristics of cylindrical reticulated shell structures with different rise-span ratios. The research shows that the rise-span ratio changes the flow pattern, the large rise-span ratio structure has stronger airflow separation, and the shape coefficient is more unfavorable in the windward leading edge and the top value. Su et al. [8] obtained the wind pressure coefficient and overall force coefficient of the three-center cylindrical reticulated shell structure with a rise-span ratio of 0.326 through wind tunnel tests. The results show that the overall force coefficient of the structure increases first and then decreases under the wind direction angle of 0 to 90° and the most unfavorable wind pressure often does not appear in pure span or pure longitudinal inflow conditions, but is closely related to the wind direction angle.

Huang et al. [9] studied the wind pressure distribution of cylindrical reticulated shell structures with rise-span ratios of 0.38, 0.45 and 0.52 by wind tunnel test. It was found that with the decrease of rise-span ratio, the overall force coefficient of the structure and its variation range were significantly reduced, and the wind suction effect at the top was also weakened. The existing research on wind load analysis of three-center cylindrical reticulated shell mainly adopts wind tunnel test and numerical simulation method, among which wind tunnel test is the main means. The existing studies have analyzed the key parameters affecting the wind pressure distribution of dry coal shed roof, such as wind direction angle, rise-span ratio, length-width ratio and coal stacking state. The results show that the influence of wind direction angle and rise-span ratio on wind pressure distribution is more significant. In terms of rise-span ratio parameters, most of the existing studies focus on the conventional range of 0.2 ~ 0.5, and only a few studies involve small rise-span ratio conditions. The relevant results show that the shape coefficient of the reticulated shell structure with the rise-span ratio range of 0.2 ~ 0.4 is mostly in the range of -1.1 ~ 0.8 under the non-orthogonal flow, and the absolute value of the wind suction of the roof will increase under the non-orthogonal flow, about -0.6 ~ -1.4, and the wind load decreases first with the decrease of the rise-span ratio. However, for small rise-span ratio structures, the existing research has not yet clarified whether the current specifications can accurately reflect the actual wind pressure distribution characteristics. In addition, in terms of the overall force coefficient, the existing research has fully revealed its variation with the wind direction angle, but has not systematically compared the similarities and differences between the small rise-span ratio and the conventional rise-span ratio structure. It is difficult to directly provide a clear basis for engineering applications.

On the other hand, due to the complex flow field phenomena such as flow separation, reattachment and vortex shedding, the surface fluctuating wind pressure often does not obey the Gaussian distribution, showing significant non-Gaussian characteristics [10-13]. Zhang et al. [14] conducted wind tunnel tests on a large-span cylindrical reticulated shell structure with a rise-to-span ratio of about 0.27. The study shows that non-Gaussian characteristics must be considered when calculating the ultimate wind pressure of similar large-span cylindrical structures. Li [15] conducted wind tunnel tests on a large-span cylindrical reticulated shell structure with a rise-span ratio of about 0.39. The results show that the surface of the structure is significantly affected by the characteristic turbulence. The

non-Gaussian distribution characteristics of the fluctuating wind load at the measuring point are more prominent, and the large-scale vortex does not satisfy the independent and identical distribution, the correlation is strong, and the wind pressure signal is non-Gaussian.

Wei et al. <sup>[16]</sup> studied the skewness, kurtosis, peak factor and extreme value of the combined large-span cylindrical reticulated shell structure with a rise-span ratio of about 0.31 and 0.36. The results show that about 80% of the measuring points have a skewness less than  $-0.1$ , more than 90% of the kurtosis is greater than 3, and the peak factor is greater than 3.5 or even 11.5, indicating that ignoring non-Gaussian will lead to an underestimation of extreme wind pressure by 40-50%. Ye et al. <sup>[17]</sup> and Yang et al. <sup>[18]</sup> also studied the non-Gaussian characteristics and extreme values of various structural shapes such as large-span cylindrical reticulated shell structures or spheres. The results show that the airflow separation on the structural surface is closely related to the structural shape. In summary, the existing research has fully confirmed that the fluctuating wind pressure on the surface of the three-center cylindrical reticulated shell structure has significant non-Gaussian characteristics due to complex flow effects such as airflow separation, reattachment and vortex shedding. For the conventional rise-span ratio cylindrical reticulated shell structure, the study shows that the peak factor under the Gaussian assumption will lead to a serious underestimation of the average extreme wind pressure. Therefore, the non-Gaussian characteristic is a key factor that cannot be ignored in the calculation of the extreme wind pressure of the large-span cylindrical reticulated shell. At the same time, the existing research shows that the wind load of the structure decreases with the decrease of the rise-span ratio. However, there is still a lack of systematic research on small rise-span ratio conditions. For example, whether the influence of non-Gaussian effect on extreme wind pressure changes, how to change and how to change the amplitude are still unclear.

In this paper, the long-span cylindrical reticulated shell structure with a rise-span ratio of 1:6 and a long-span ratio of 2:1 is taken as the research object, and the wind tunnel pressure test of the rigid model is carried out. The distribution law of the structural shape coefficient and the overall force coefficient is systematically analyzed, and the similarities and differences between the structure and the conventional rise-span ratio structure are summarized. Comparing and analyzing the measured shape coefficient and the existing specification values, the applicability of the specification is clarified; the non-Gaussian characteristics of wind pressure on the surface of the structure are studied, and the distribution characteristics of skewness and kurtosis are statistically analyzed. The improved Hermite method is used to calculate the peak factor, and the value of the peak factor and the underestimation of the extreme wind pressure are comprehensively analyzed.

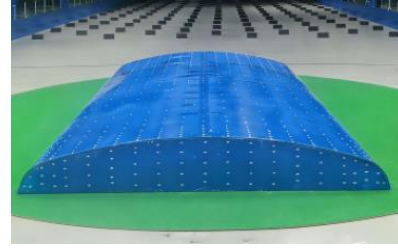
## 2. Wind Tunnel Test

### 2.1 General Overview of the Test

In this study, a long-span cylindrical lattice shell structure with a small rise-span ratio is taken as the research object. The structure has a rise-span ratio of 1:6, a length-span ratio of 2:1, a longitudinal length of 480 m, a span of 240 m, and a rise of 40 m. A rigid scaled model with a geometric scale ratio of 1:200 is adopted in the test, and the model is fabricated from ABS plate (as shown in Figure 1). A total of 825 pressure taps are arranged on the model surface, including 667 taps in the main region of the cylindrical lattice shell and 79 taps on each gable at both sides. Due to the symmetry of the model, the layout of pressure taps and wind directions are illustrated in Figure 2, where the rise, span and longitudinal length are denoted by  $f$ ,  $L$  and  $B$ , respectively. The model possesses sufficient strength and stiffness to avoid obvious deformation or vibration during the test, thereby meeting the accuracy requirements for surface pressure measurement.



(a) Overall view of the test.



(b) Partial view of the test.

Figure 1: Photos of the test model.

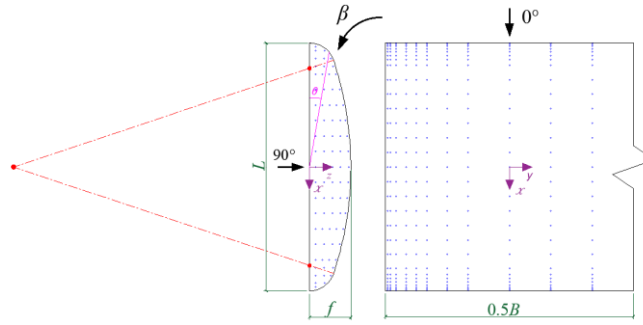


Figure 2: Schematic diagram of measurement point layout and wind direction angles.

The wind tunnel test was carried out in the low-speed test section of the STU-1 wind tunnel at the Wind Engineering Research Center, Shijiazhuang Tiedao University. This wind tunnel is a large-scale multifunctional boundary-layer wind tunnel with tandem double test sections capable of both closed-circuit and straight-through flow modes. The low-speed test section has a width of 4.4 m, a height of 3.0 m, and a length of 24.0 m, with a maximum wind speed exceeding 30.0 m/s. Under uniform flow, the turbulence intensity is controlled below 0.4%, and the flow field in the low-speed test section meets the high-quality standards for boundary-layer wind tunnels.

In accordance with the load code for building structures in China, spires and roughness elements were used in this test to simulate the Category B terrain specified in GB 50009-2012 Load Code for the Design of Building Structures<sup>[19]</sup>, as shown in Figure 3. Before the pressure measurement test, a three-dimensional fluctuating anemometer was used to measure the mean wind speed profile and turbulence intensity profile at the model location, with the results presented in Figure 4. It can be seen that the simulated wind speed profile and turbulence intensity profile are in good agreement with the theoretical values specified in the Chinese load code (2012 edition), verifying the validity of the flow field simulation.

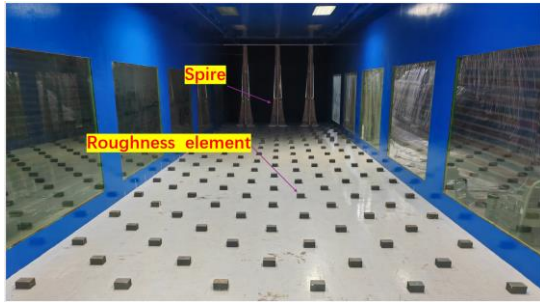


Figure 3: Terrain type B.

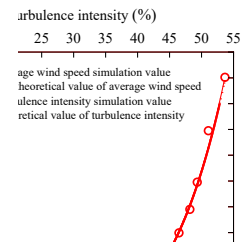


Figure 4: Mean wind profile and turbulence profile.

The wind tunnel laboratory is equipped with a complete set of wind load and response measurement equipment, which can meet various wind load testing and response measurement requirements. Multi-device coordinated data acquisition is adopted in the test: wind speed is measured by a pitot tube installed in front of the model; the pressure data acquisition system consists of ESP-64HD high-precision miniature pressure scanners and the DTC Initium data acquisition system (Figure 5). Among them, the ESP-64HD pressure scanner has a measuring range of  $\pm 2500$  Pa, a full-scale accuracy of  $\pm 0.03\%$ , and a scanning rate of up to 70000 Hz, enabling accurate capture of high-frequency fluctuations of fluctuating wind pressure. The DTC Initium data acquisition system has an accuracy of  $\pm 0.05\%$  and a scanning rate of 330 Hz. Each sampling duration is 30 seconds, yielding 9900 valid data points, and realizes synchronous data acquisition with the pressure scanners. Detailed technical parameters of the two devices are listed in Table 1 and Table 2. Before the test, the pressure measurement system was calibrated using the transfer function method to ensure the accuracy of pressure fluctuation measurement. In this test, only the effect of aerodynamic pressure on the structure is considered, and the influence of surface friction is neglected.



Figure 5: Measurement equipment.

Table 1: Parameters of ESP-64HD.

| Range         | Accuracy     | Working temperature | Scanning rate | Size                 |
|---------------|--------------|---------------------|---------------|----------------------|
| $\pm 2500$ Pa | $\pm 0.03\%$ | $-25-80$ °C         | 70 000 Hz     | 115.57×43.18×49.53mm |

Table 2: Specifications of the DTC Initium data acquisition system.

| Weight | Accuracy     | Working temperature | Scanning rate | Size          |
|--------|--------------|---------------------|---------------|---------------|
| 1.6 kg | $\pm 0.05\%$ | $0-70$ °C           | 330 Hz        | 254×178×89 mm |

The test model was fixed at the center of the turntable in the low-speed test section, and the wind direction was adjusted using the wind tunnel turntable. Considering symmetry, wind directions were selected from  $0^\circ$  to  $90^\circ$  at  $10^\circ$  intervals. The approaching wind speed was measured by a pitot tube at a height of 0.2 m upstream of the model, and the wind speed at the pitot tube position was controlled at 10 m/s during the test. Key parameters of the model and test cases are shown in Table 3.

Table 3: Model parameters and test cases.

| $f$  | $L$  | $B$  | $f/L$ | $B/L$ | Number of measurement points |            | Wind direction angle                              | Wind speed |
|------|------|------|-------|-------|------------------------------|------------|---------------------------------------------------|------------|
|      |      |      |       |       | Cylindrical region           | End region |                                                   |            |
| 0.2m | 1.2m | 2.4m | 1/6   | 2/1   | 667                          | 79         | $0^\circ$ to $90^\circ$ , at $10^\circ$ intervals | 10 m/s     |

## 2.2 Data Processing

The dimensionless wind pressure coefficient, mean wind pressure coefficient, and fluctuating wind

pressure coefficient are defined as follows:

$$C_{pi} = \frac{p_i - p_s}{p_t - p_s} = \frac{p_i - p_s}{1/2 \rho U_r^2} \quad (1)$$

$$\bar{C}_p = \frac{\sum_{i=1}^N C_{pi}}{N} \quad (2)$$

$$C'_p = \sqrt{\frac{\sum_{i=1}^N (C_{pi} - \bar{C}_p)^2}{N-1}} \quad (3)$$

where:  $C_{pi}$  wind pressure coefficient at point I,  $\bar{C}_p$  mean wind pressure coefficient,  $C'_p$  fluctuating wind pressure coefficient,  $p_i$  measured pressure at tap I,  $p_s$  static pressure at the reference point,  $p_t$  total pressure at the reference point,  $\rho=1.225\text{kg/m}^3$  mean air density,  $U_r$  approaching wind speed at the reference height (corresponding to 10 m above ground for the full-scale structure)  $N=9900$  number of effective samples (sampling frequency 330 Hz  $\times$  sampling duration 30 s).

In addition, the shape coefficient of pressure taps is defined as shown in Equation (4). The overall force coefficient of the structure is given in Equation (5).

$$\mu_s = \frac{C_{pi}}{(Z_i/10)^{2\alpha}} \quad (4)$$

In which,  $\mu_s$  is the shape coefficient of measuring points,  $C_{pi}$  is the wind pressure coefficient corresponding to measuring point  $i$ ,  $Z_i$  is the height at measuring point  $i$ ,  $\alpha$  is the terrain roughness index with a value of 0.15.

$$C_{Fq} = \sum_i \bar{C}_{pdi} A_i \cos \gamma_{qi} / A_q \quad (5)$$

In which,  $C_{Fq}$  is the overall force coefficient of the structure in  $q$  direction,  $q=x$ ,  $y$  and  $z$  represent  $x$  direction,  $y$  direction and  $z$  direction respectively. The positive directions of  $x$ ,  $y$  and  $z$  are shown in Figure 2.  $A_i$  is the area corresponding to measuring point  $i$ ,  $A_q$  is the projection area of the structure in  $q$  direction,  $\gamma_{qi}$  is the direction angle of the normal vector at measuring point  $i$  in  $q$  direction.

The skewness (third order moment) and kurtosis (fourth order moment) of fluctuating wind pressure are widely used to describe the deviation degree of fluctuating wind pressure from Gaussian distribution. They are important parameters to judge whether wind pressure signals follow non Gaussian distribution [20-22]. For non Gaussian distribution, when the skewness is positive, the long tail on the right represents positive skewness, and when the skewness is negative, the long tail on the left represents negative skewness. The calculation formulas of skewness ( $\gamma_3$ ) and kurtosis ( $\gamma_4$ ) are given as follows:

$$\gamma_3 = \frac{1}{N} \sum_{i=1}^N \left[ \left( \frac{C_{pi} - \bar{C}_p}{C'_p} \right)^3 \right] \quad (6)$$

$$\gamma_4 = \frac{1}{N} \sum_{i=1}^N \left[ \left( \frac{C_{pi} - \bar{C}_p}{C'_p} \right)^4 \right] \quad (7)$$

The peak factor is a key parameter in the calculation of extreme wind pressure. Based on the peak factor method proposed by Davenport <sup>[23]</sup>, this method has been adopted in codes of many countries and organizations in the world <sup>[24-27]</sup>, and the peak factor calculated by this method is basically between 2.5 and 3.5. Considering that the Davenport peak factor method is not suitable for non Gaussian processes, Winterstein <sup>[28]</sup> put forward the Hermite model method. According to the transformation theory, the Gaussian process and non Gaussian process can be related by mapping functions. However, the Sadek Simiu method <sup>[29]</sup> cannot provide explicit solutions of the mapping relations, while Winterstein can obtain explicit solutions by means of orthogonal Hermite polynomial approximation. In addition, the Hermite model method does not require the probability distribution of non Gaussian wind pressure to follow the Gamma distribution. However, the original Hermite method does not provide a solution formula for the peak factor of extreme wind pressure, which is not convenient in application. Besides, because this method does not consider the effect of the bandwidth factor, it will lead to overestimated extreme values. On this basis, Kwon and Kareem <sup>[30]</sup>, Yang et al. <sup>[31]</sup>, Yang and Tian <sup>[32]</sup> proposed more accurate and improved Hermite formulas for calculating non Gaussian peak factors, which have been widely used in engineering practice. The definition of non Gaussian peak factor is given as follows:

$$g_{,NG} = \kappa \left\{ \left( \beta + \frac{\gamma}{\beta} \right) + h_3 \left[ \beta^2 + (2\gamma - 1) + \frac{1.98}{\beta^2} \right] + h_4 \left[ \beta^3 + 3\beta(\gamma - 1) + \frac{3}{\beta} \left( \frac{\pi^2}{6} - \gamma + \gamma^2 \right) + \frac{5.44}{\beta^3} \right] \right\} \quad (8)$$

$$\kappa = \frac{1}{\sqrt{1 + 2h_3^2 + 6h_4^2}} \quad (9)$$

$$h_3 = p1 \cdot \gamma_3 + p2 \cdot \gamma_3 \gamma_4 + p3 \cdot \gamma_3^3 + p4 \cdot \gamma_3 \gamma_4^2 + p5 \cdot \gamma_3^3 \gamma_4 + p6 \cdot \gamma_3 \gamma_4^3 + p7 \cdot \gamma_3^5 + p8 \cdot \gamma_3^3 \gamma_4^2 + p9 \cdot \gamma_3 \gamma_4^4 \quad (10)$$

$$h_4 = p1 + p2 \cdot \gamma_4 + p3 \cdot \gamma_3^2 + p4 \cdot \gamma_4^2 + p5 \cdot \gamma_3^2 \gamma_4 + p6 \cdot \gamma_4^3 + p7 \cdot \gamma_3^4 + p8 \cdot \gamma_3^2 \gamma_4^2 + p9 \cdot \gamma_4^4 + p10 \cdot \gamma_3^4 \gamma_4 + p11 \cdot \gamma_4^2 \gamma_4^3 + p12 \cdot \gamma_4^5 \quad (11)$$

In which, the corresponding parameters in the formula are listed in Table 4.

Table 4: Coefficient Values of Improved Hermite Method

| Coefficient | $h_3$     | $h_4$     |
|-------------|-----------|-----------|
| $p1$        | 0.1967    | -0.0721   |
| $p2$        | -1.646e-2 | 0.03176   |
| $p3$        | 1.809e-2  | -0.02942  |
| $p4$        | 7.438e-4  | -0.00179  |
| $p5$        | -9.209e-4 | 0.002348  |
| $p6$        | -1.366e-5 | 5.965e-5  |
| $p7$        | 1.527e-4  | -6.282e-4 |
| $p8$        | 1.07e-5   | -6.355e-5 |
| $p9$        | 8.823e-8  | -9.692e-7 |
| $p10$       | \         | 1.497e-5  |
| $p11$       | \         | 5.457e-7  |
| $p12$       | \         | 6.049e-9  |

The extreme wind pressure coefficient is defined as the superposition of the mean wind pressure coefficient and the fluctuating wind pressure coefficient multiplied by the peak factor, and the formula is given as follows:

$$C_{P, peak}^{\pm} = \bar{C}_p \pm gC_p' \quad (12)$$

In which,  $C_{P, peak}^{\pm}$  represents the extreme wind pressure coefficient of measuring point  $i$ ,  $\bar{C}_p$  is the mean wind pressure coefficient,  $C_p'$  is the fluctuating wind pressure coefficient;  $g$  is the corresponding peak factor.

### 3. Analysis of Shape Coefficients and Global Force Coefficients

#### 3.1 Analysis of Shape Coefficients

The variation of shape coefficients at the measurement points of the structure is shown in Figure 6. Wind pressure is defined as positive when it acts normal to the structural surface toward the structure, and negative otherwise.

It can be seen from Figure 6(a) that the shape coefficients are positive at the bottom of the windward side. With increasing height, the wind pressure gradually changes from positive to negative, reaching the maximum negative value at the top of the structure, and varies sharply along the spanwise direction. The shape coefficients are negative at the bottom of the leeward side, and the negative pressure gradually increases with height. It can be observed that the maximum and minimum shape coefficients at the measuring points on the windward surface and roof area of the structure are 0.6 and -0.4, respectively. In contrast, the maximum and minimum values at the corresponding positions for structures with conventional rise-span ratios are approximately 0.8 and -1. The results indicate that, under the  $0^\circ$  wind direction, the wind load on the roof gradually decreases as the rise-span ratio decreases. At the positions near the windward side of the two gables, the shape coefficient reaches a minimum negative value of -1.8. The absolute value of this coefficient is approximately 0.2~0.3 larger than that of the conventional rise-span ratio, indicating that the roof corner near the gable end experiences stronger wind suction under small wind angles (i.e., when the oncoming flow forms a large angle with the gable wall).

It can be seen from Figure 6(b) that the shape coefficients show large negative pressure at the end region on the incident flow side, while the values in the middle and leeward regions are close to zero. Under longitudinal incident flow, the windward side of the gables forms positive pressure due to airflow impingement, with shape coefficients mainly ranging from 0.4 to 0.8. The pressure is largest in the central region and gradually decreases toward the edges. The airflow then climbs upward, the absolute value of the shape coefficient gradually decreases, and eventually becomes negative. At the top region of the latticed shell, negative pressure vortices formed by flow separation cause wind suction, which is mainly concentrated in the near-end region close to the bottom of the structure, with a minimum shape coefficient of -1. In the wake region, the airflow reattaches to the top and leeward surface of the structure, and the absolute value of the negative pressure gradually decreases.

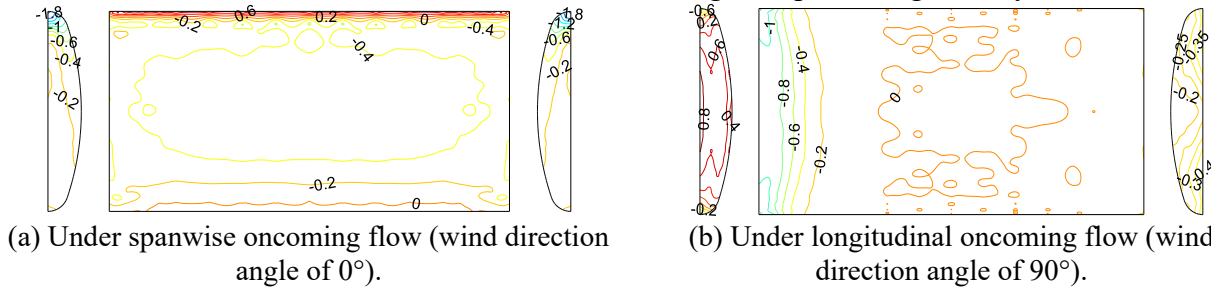


Figure 6: Contours of shape coefficients at measurement points of the cylindrical latticed shell under oncoming flows from different directions.

### 3.2 Analysis of Global Force Coefficients

The variation laws of the global force coefficients of the long-span cylindrical latticed shell structure in three directions are shown in Figure 7. The x, y, and z directions are defined as the spanwise, longitudinal, and vertical directions, respectively. A positive value indicates that the global force coefficient is consistent with the positive direction of the coordinate axis, while a negative value indicates the opposite.

In the Figure 7,  $C_{Fx}$ ,  $C_{Fy}$  and  $C_{Fz}$  are the measured data studied in this paper, while  $CFx'$ ,  $CFy'$  and  $CFz'$  are based on the contents and conclusions studied by some scholars in the introduction, such as Su, and then transformed into the same definition and direction as this paper. The overall force coefficients in the three directions under the conventional rise-span ratio are comprehensively considered.

Figure 7: Global force coefficients and fitting curves.

According to the analysis of Figure 7, for the overall force coefficient, in the range of  $0^\circ \sim 90^\circ$  wind direction angle, the change trend of the overall force coefficient with the wind direction angle is similar to that of the conventional rise-span ratio structure, which increases first and then decreases. However, there are also some differences between them. Firstly, the overall value is slightly smaller than that of the conventional rise-span ratio. Secondly, the overall force coefficient of the small rise-span ratio structure reaches the maximum value near the  $50^\circ$  wind angle, while the maximum value of the conventional rise-span ratio structure appears at the  $30^\circ$  wind angle. This shows that as the rise-span ratio decreases, the maximum value of the overall force coefficient decreases gradually, and the wind direction angle corresponding to the peak value shifts to a high angle, and the overall change tends to be gentle.

In terms of the longitudinal overall force coefficient, the small rise-span ratio structure increases monotonously with the increase of the wind direction angle, and the maximum value appears near the  $80^\circ$  wind direction angle. The conventional rise-span ratio structure shows a trend of increasing first and then decreasing, and the peak value is located at  $60^\circ$  wind direction angle. The comparison shows that the decrease of the rise-span ratio will lead to the peak position of the longitudinal overall force coefficient moving to a higher wind direction angle.

In terms of the vertical overall force coefficient, the vertical overall force coefficient of the small rise-span ratio structure decreases monotonously with the increase of the wind direction angle, while the conventional rise-span ratio structure increases first and then decreases, and the maximum value

appears near the wind direction angle of  $30^\circ$ . On the other hand, its numerical value is also reduced compared with the conventional rise-span ratio. This shows that as the rise-span ratio decreases, the vertical overall force coefficient gradually decreases and the peak wind direction angle shifts to a low angle.

## 4. Distribution and Non-Gaussian Characteristics of Fluctuating Wind Pressure

### 4.1 Wind Pressure Distribution

To facilitate the regionalized analysis of non-Gaussian distribution characteristics of wind pressure and ensure that the subzones cover key structural regions with reasonable area weights, the main part of the cylindrical latticed shell is divided into 48 blocks based on the analyses of shape coefficients and global force coefficients. The length ratios of each block along the spanwise and longitudinal directions of the structure are shown in Figure 8.

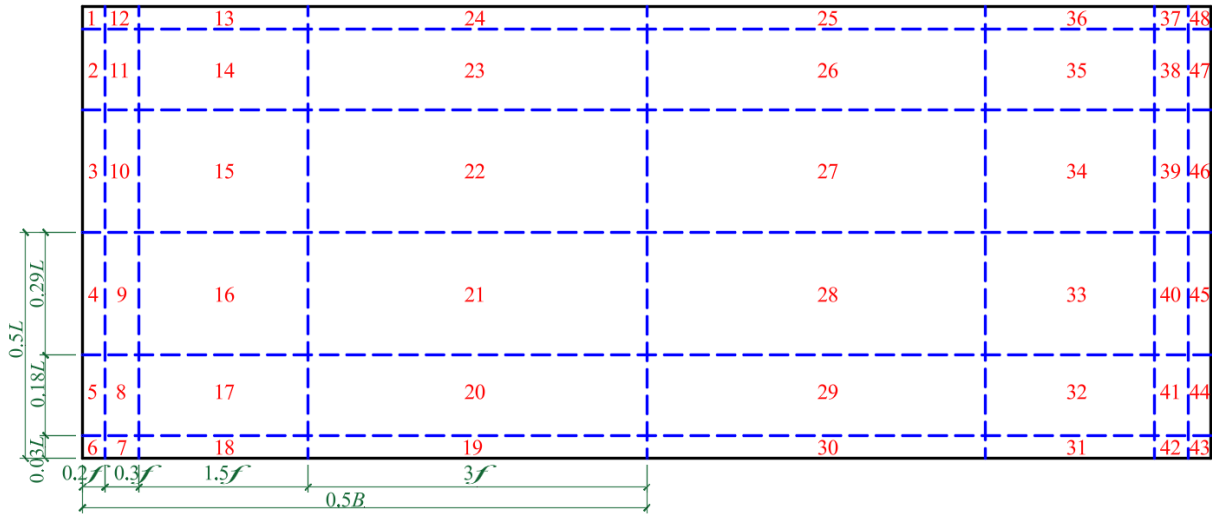


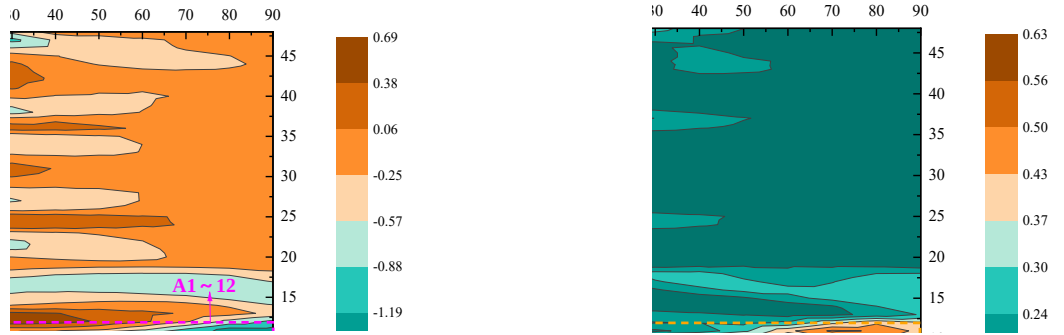
Figure 8: Schematic diagram of model zoning.

To comprehensively investigate the non-Gaussian characteristics of wind pressure on the structural surface, it is essential to analyze the distributions of the mean wind pressure coefficient and fluctuating wind pressure coefficient. These distributions help identify whether the regions of interest lie within flow separation zones and determine the unfavorable regions and corresponding wind direction angles under wind action. Therefore, based on the area-weighted average results of 48 subzones, the distribution patterns of the zonal mean wind pressure coefficient and zonal fluctuating wind pressure coefficient are analyzed, as shown in Figure 9.

It can be seen from Figure 9(a) that the distribution of the mean wind pressure coefficient of the cylindrical latticed shell presents significant regional differences and wind direction dependence. Zones 1, 12, 13, 24, 25, 36, 37, and 48 show positive values under most wind direction angles, indicating that these regions are subjected to positive wind pressure. Among them, the positive wind pressure is most significant for Zone 1 at  $10^\circ\sim 40^\circ$ , Zones 12 and 13 at  $0^\circ\sim 50^\circ$ , and Zones 24 and 25 at  $0^\circ\sim 30^\circ$ , with the maximum zonal mean wind pressure coefficient reaching 0.69. This phenomenon occurs because the oncoming flow impinges directly on the structural surface (i.e., the windward side) without flow separation, forming a positive pressure zone. The remaining zones show negative values under most wind direction angles, indicating that these regions are subjected to wind suction. Among them, the wind suction is the strongest for Zones 1 and 12 at  $50^\circ\sim 90^\circ$ , Zones 2~11 at  $10^\circ\sim 90^\circ$ , and Zones 15, 16, 21, 22, 27, 28, 33, and 34 under most wind direction angles, with the minimum negative mean wind pressure coefficient reaching -1.82. This is mainly because these regions are located on

the leeward side or edges of the structure, where low-pressure zones form after the oncoming flow undergoes flow separation.

Figure 9(b) shows that the distribution of the fluctuating wind pressure coefficient is somewhat correlated with that of the mean wind pressure coefficient: regions with larger absolute values of the mean wind pressure coefficient usually correspond to larger fluctuating wind pressure coefficients. The fluctuating wind pressure coefficients are significantly higher than those in other regions for Zones 1~3 at  $40^\circ\sim 90^\circ$ , Zones 4~9 at  $70^\circ\sim 90^\circ$ , and Zones 10~12 at  $30^\circ\sim 90^\circ$ , with the maximum value reaching approximately 0.63. This is mainly because these regions lie in the transition zone between the windward and crosswind sides of the structure and are associated with intense flow separation. Vortex shedding inside the separation bubble intensifies wind pressure fluctuations, resulting in high flow disorder and strong wind pressure fluctuations, thus enhancing the fluctuating characteristics.



(a) Zonal mean wind pressure coefficient      (b) Zonal fluctuating wind pressure coefficient

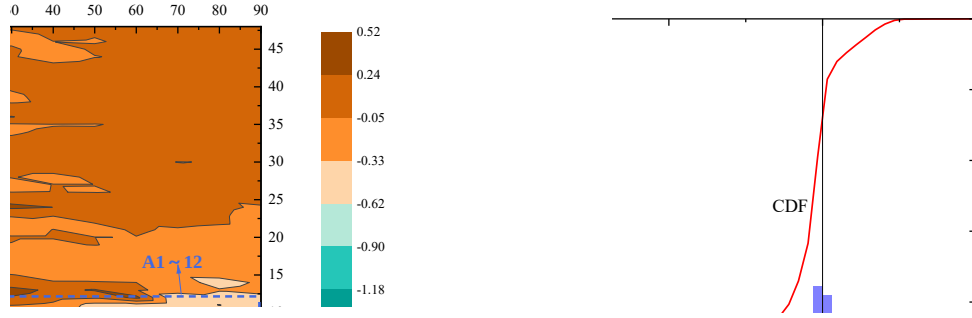
Figure 9: Statistical distribution of zonal wind pressures under all wind direction angles.

#### 4.2 Non-Gaussian Characteristics of Fluctuating Wind Pressure

Mean values, medians, maxima and minima alone are insufficient. Skewness and kurtosis are widely adopted as important parameters to judge whether wind pressure signals follow a non-Gaussian distribution, serving as core indicators for quantifying non-Gaussian characteristics. For a standard Gaussian distribution, skewness and kurtosis are 0 and 3, respectively. For non-Gaussian distributions, positive skewness indicates right-skewed distribution (long tail on the right), while negative skewness indicates left-skewed distribution (long tail on the left). When kurtosis is greater than 3, the distribution shows a leptokurtic and heavy-tailed feature; when less than 3, it is platykurtic and light-tailed. In this study, the skewness and kurtosis coefficients for each block are obtained based on the area-weighted average results of the 48 subzones.

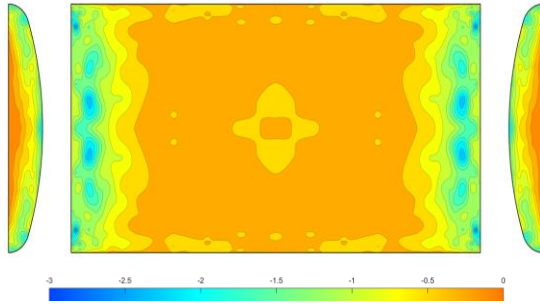
Figure 10(a) shows the zonal skewness coefficients of the cylindrical latticed shell. Skewness values of most blocks are negative. In particular, blocks 1~12 exhibit more pronounced negative skewness at wind directions of  $10^\circ\sim 90^\circ$ , revealing obvious negative skewness characteristics. These regions are located at the edges or leeward side of the structure. As shown in the CDF plot in Figure 10(b), more than 60% of the skewness values across the cylindrical latticed shell are less than 0, indicating that the fluctuating wind pressure distribution is generally left-skewed with long tails concentrated on the negative wind pressure side. Meanwhile, the CDF of minimum skewness in Figure 10(d) shows that most minimum skewness values of measurement points range from -2 to 0. Figure 10(c) presents the contour distribution of the minimum skewness at measurement points under all wind directions from a statistical perspective. It can be seen that the minimum skewness values of

all measurement points are negative, demonstrating significant negative skewness.

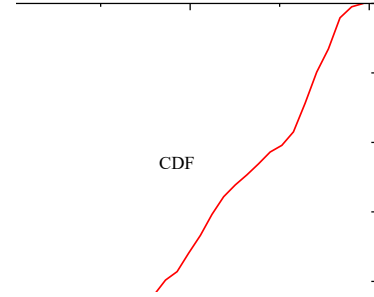


(a) Skewness

(b) CDF histogram of skewness



(c) Minimum skewness at measurement points under all wind directions



(d) CDF histogram of minimum skewness

Figure 10: Skewness analysis.

Figure 11(a) shows the zonal kurtosis coefficients of the cylindrical latticed shell. The zonal kurtosis of most blocks is greater than 3. In particular, the kurtosis values of blocks 1~12 are significantly larger than those of other regions under most wind directions, exhibiting obvious leptokurtic and heavy-tailed characteristics. These regions are located at the edges or leeward side of the structure, and the high-kurtosis regions are highly consistent with the regions of high absolute skewness.

As shown in the 1-CDF plot in Figure 11(b), more than 70% of the kurtosis values across the cylindrical latticed shell are greater than 3, indicating that the fluctuating wind pressure distribution generally shows leptokurtic and heavy-tailed features, and the probability of extreme wind pressure is significantly higher than that of the Gaussian distribution.

From the 1-CDF plot of maximum kurtosis shown in Figure 11(d), it can be seen that the maximum kurtosis values of measurement points are concentrated between 3 and 8. Figure 11(c) presents the contour distribution of the maximum kurtosis at measurement points under all wind directions from a statistical perspective. It can be observed that the maximum kurtosis of most measurement points is greater than 3, moreover, the structural edges are much larger than other parts, demonstrating distinct leptokurtic and heavy-tailed characteristics.

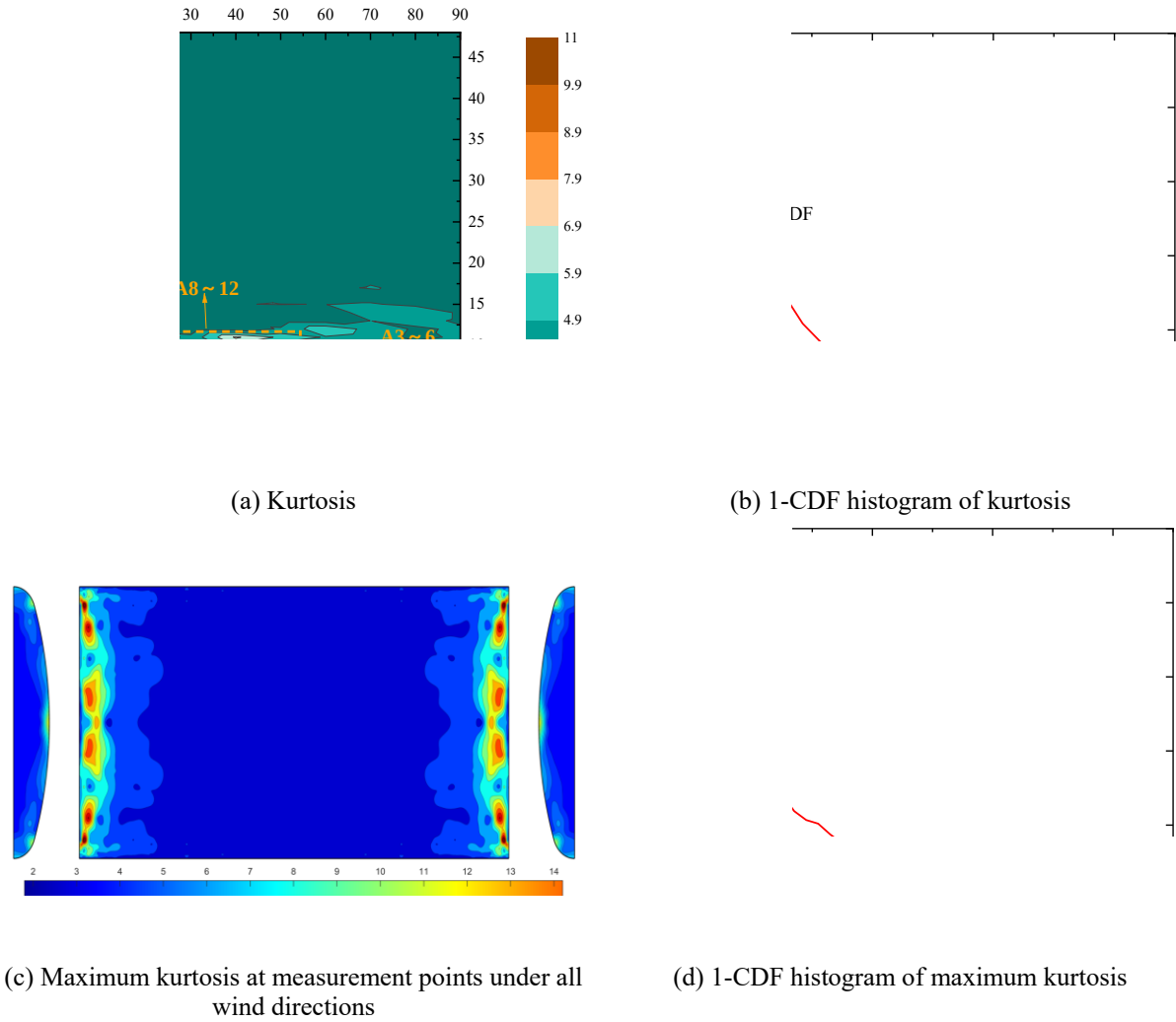
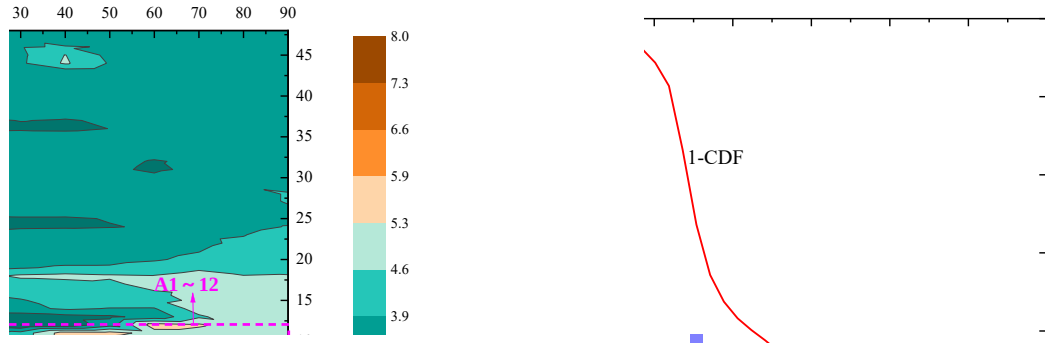


Figure 11: Kurtosis analysis.

In terms of the statistical characteristic parameters of wind pressure, the skewness and kurtosis distribution of wind pressure on structural surfaces exhibit a significant correlation difference with the rise-to-span ratio. Compared with structures adopting conventional rise-to-span ratios, structures with small rise-to-span ratios present an obvious improvement in the statistical parameter distribution of wind pressure measurement points. Specifically, the proportion of measurement points with skewness less than  $-0.1$  and kurtosis greater than 3, which represent typical non-Gaussian characteristics, decreases by approximately 20 percentage points. Existing studies have demonstrated that for conventional rise-to-span ratio structures, the proportions of measurement points with skewness below  $-0.1$  and kurtosis above 3 are approximately 80% and 90%, respectively. This indicates that the wind pressure field of conventional structures features widespread and intense non-Gaussian distribution characteristics. In contrast, the corresponding proportions of such characteristic measurement points are considerably reduced for small rise-to-span ratio structures, which effectively mitigates the non-Gaussian deviation of wind pressure distribution. Nevertheless, the overall wind pressure field fails to conform to the Gaussian normal distribution. Obvious and non-negligible non-Gaussian characteristics still dominate the global wind pressure distribution. Therefore, the non-Gaussian effect should be fully considered in wind load determination and extreme wind pressure calculation for structural design and analysis, and the simplified calculation based on the Gaussian assumption is not applicable.

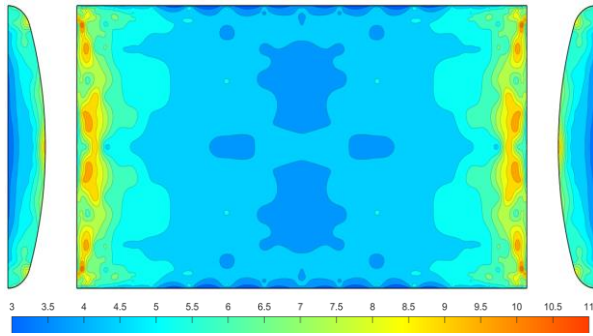
### 4.3 Peak Factor and Extreme Value Analysis

Based on the above analysis, the non-Gaussian characteristics of the cylindrical latticed shell have been identified. Therefore, the non-Gaussian peak factors for all measurement points under each wind direction are calculated using the modified Hermite method. Meanwhile, the peak factor for each block is determined based on the area-weighted average of each subzone. Figure 12(a) shows the zonal peak factor coefficients of the cylindrical latticed shell. It can be seen that regions with pronounced non-Gaussian characteristics generally exhibit higher peak factors. The strong similarity between the peak factor distribution shown in Figure 12(a) and the skewness and kurtosis distributions in Figures 10(a) and 11(a) can be attributed to the fact that the derivation of the non-Gaussian peak factor is intricately linked to the higher-order moments.

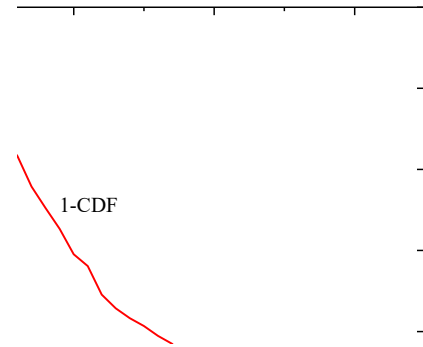


(a) Peak factor

(b) 1-CDF histogram of peak factor



(c) Maximum peak factor at measurement points under all wind directions



(d) 1-CDF histogram of maximum peak factor

Figure 12: Peak factor analysis.

It can be observed from Figure 12(a) that the zonal peak factors in most regions are greater than 3. In particular, the peak factor values of blocks 1~12 are significantly larger than those of other regions under most wind directions. As shown in the 1-CDF histogram in Figure 12(b), more than 80% of the peak factors across the cylindrical latticed shell are greater than 3. From the 1-CDF histogram of the maximum peak factor in Figure 12(d), it can be seen that the maximum peak factor values of measurement points are concentrated between 4 and 7. In practical engineering, extreme wind

pressures are relevant to the wind-resistant design of envelope structures. Meanwhile, since the wind-resistant design of envelope components is dominated by wind suction, only negative extreme values are considered. Figure 12(c) presents the contour distribution of the maximum peak factor at measurement points under all wind directions from a statistical perspective. It can be seen that the maximum peak factor of almost all measurement points is greater than 4, with a maximum value of up to 10.3. Compared with the conventional rise-to-span ratio, both the regional scope and overall maximum amplitude of the non-Gaussian peak factor of wind pressure for the structure decrease slightly. However, numerous measuring points with high peak factors still exist under all wind directions, and the non-Gaussian amplification effect induced by wind pressure remains remarkable.

Therefore, in the wind load design of envelope structures for long-span cylindrical latticed shells with a small rise-span ratio, it is inappropriate to adopt the Gaussian assumption (with a value of approximately 3) or the code-specified peak factor of 2.5 as the basis for determining the peak factor of fluctuating wind pressure.

Tables 5~8 present the extreme wind pressure coefficients calculated based on different peak factors (code-specified 2.5, Gaussian, and non-Gaussian). Comparisons are conducted for typical measurement points under wind directions of 0°, 30°, 60°, and 90°.

The extreme wind pressure coefficients ( $\mu-2.5\sigma$ ) computed using the code peak factor of 2.5 are generally smaller than those obtained from the non-Gaussian peak factor ( $\mu-g_{NG}\sigma$ ). The underestimation ratio ranges from 13% to 66%, with an average of approximately 28%. Moreover, the underestimation ratio is even higher in regions with pronounced non-Gaussian characteristics, such as the structural edges and leeward sides. For instance, the value at Tap64 under 60° is underestimated by 66%.

The extreme wind pressure coefficients ( $\mu-g_G\sigma$ ) derived from the Gaussian peak factor are also lower than the non-Gaussian results, with an underestimation ratio of 0-54% and an average of about 19%. Compared with the mean underestimation range of extreme wind pressure for structures with conventional rise-to-span ratios (40%~50%), the average underestimation ratio of structures with small rise-to-span ratios is generally lower than that of conventional ones. Nevertheless, the non-Gaussian characteristics cannot be neglected under extreme working conditions.

Table 5: Comparison of extreme wind pressure coefficients at several measurement points under 0° wind direction.

| Tap <i>i</i> | $\beta/(^{\circ})$ | $\mu$ | $\sigma$ | (i) $\mu-2.5\sigma$ | (ii) $\mu-g_G\sigma$ | (iii) $\mu-g_{NG}\sigma$ | (i)/(iii) | (ii)/(iii) |
|--------------|--------------------|-------|----------|---------------------|----------------------|--------------------------|-----------|------------|
| 5            | 0                  | -0.40 | 0.17     | -0.83               | -0.99                | -1.38                    | 0.60      | 0.72       |
| 44           | 0                  | -0.44 | 0.15     | -0.82               | -0.97                | -1.21                    | 0.68      | 0.80       |
| 56           | 0                  | -0.17 | 0.21     | -0.68               | -0.88                | -1.45                    | 0.47      | 0.61       |
| 64           | 0                  | -0.49 | 0.21     | -1.01               | -1.22                | -1.28                    | 0.79      | 0.95       |
| 327          | 0                  | -0.49 | 0.13     | -0.80               | -0.93                | -0.98                    | 0.82      | 0.94       |
| 333          | 0                  | -0.86 | 0.12     | -1.16               | -1.27                | -1.33                    | 0.87      | 0.95       |

Table 6: Comparison of extreme wind pressure coefficients at several measurement points under 30° wind direction.

| Tap <i>i</i> | $\beta/(^{\circ})$ | $\mu$ | $\sigma$ | (i) $\mu-2.5\sigma$ | (ii) $\mu-g_G\sigma$ | (iii) $\mu-g_{NG}\sigma$ | (i)/(iii) | (ii)/(iii) |
|--------------|--------------------|-------|----------|---------------------|----------------------|--------------------------|-----------|------------|
| 5            | 30                 | -1.48 | 0.32     | -2.28               | -2.57                | -3.00                    | 0.76      | 0.86       |
| 44           | 30                 | -1.64 | 0.41     | -2.67               | -3.05                | -3.39                    | 0.79      | 0.90       |
| 56           | 30                 | -0.64 | 0.26     | -1.29               | -1.54                | -1.91                    | 0.67      | 0.81       |
| 68           | 30                 | -0.20 | 0.19     | -0.68               | -0.86                | -1.86                    | 0.36      | 0.46       |
| 102          | 30                 | -0.47 | 0.24     | -1.06               | -1.29                | -2.74                    | 0.39      | 0.47       |

Table 7: Comparison of extreme wind pressure coefficients at several measurement points under 60° wind direction.

| Tap $i$ | $\beta/(^{\circ})$ | $\mu$ | $\sigma$ | (i) $\mu-2.5\sigma$ | (ii) $\mu-g_G\sigma$ | (iii) $\mu-g_{NG}\sigma$ | (i)/(iii) | (ii)/(iii) |
|---------|--------------------|-------|----------|---------------------|----------------------|--------------------------|-----------|------------|
| 2       | 60                 | -0.21 | 0.54     | -1.57               | -2.07                | -2.79                    | 0.56      | 0.74       |
| 31      | 60                 | 0.01  | 0.45     | -1.12               | -1.54                | -2.29                    | 0.49      | 0.67       |
| 44      | 60                 | -1.75 | 0.35     | -2.63               | -2.97                | -3.60                    | 0.73      | 0.82       |
| 64      | 60                 | -0.11 | 0.34     | -0.96               | -1.30                | -2.84                    | 0.34      | 0.46       |
| 68      | 60                 | -1.54 | 0.59     | -3.01               | -3.58                | -3.99                    | 0.76      | 0.90       |
| 102     | 60                 | -1.67 | 0.46     | -2.81               | -3.25                | -3.44                    | 0.82      | 0.95       |

Table 8: Comparison of extreme wind pressure coefficients at several measurement points under 90° wind direction.

| Tap $i$ | $\beta/(^{\circ})$ | $\mu$ | $\sigma$ | (i) $\mu-2.5\sigma$ | (ii) $\mu-g_G\sigma$ | (iii) $\mu-g_{NG}\sigma$ | (i)/(iii) | (ii)/(iii) |
|---------|--------------------|-------|----------|---------------------|----------------------|--------------------------|-----------|------------|
| 2       | 90                 | -0.94 | 0.41     | -1.96               | -2.34                | -3.59                    | 0.55      | 0.65       |
| 31      | 90                 | -0.95 | 0.40     | -1.95               | -2.33                | -3.16                    | 0.62      | 0.74       |
| 56      | 90                 | -1.12 | 0.45     | -2.25               | -2.67                | -3.75                    | 0.60      | 0.71       |
| 68      | 90                 | -1.39 | 0.39     | -2.36               | -2.72                | -3.57                    | 0.66      | 0.76       |
| 146     | 90                 | -0.31 | 0.20     | -0.82               | -0.98                | -1.02                    | 0.80      | 0.96       |
| 333     | 90                 | 0.03  | 0.11     | -0.26               | -0.37                | -0.46                    | 0.56      | 0.82       |

## 5. Conclusions

Based on the pressure measurement wind tunnel test of the rigid model of the large-span cylindrical reticulated shell structure with small rise-span ratio, the multi-dimensional analysis of the shape coefficient distribution, the variation law of the overall force coefficient, the non-Gaussian statistical characteristics of the fluctuating wind pressure, the non-Gaussian peak factor and the estimation of the extreme wind pressure are systematically carried out. The main conclusions are as follows:

(1) The distribution of the shape coefficient of the small rise-span ratio structure is similar to that of the conventional rise-span ratio structure. The difference is that compared with the conventional rise-span ratio, when the wind direction angle is small (the angle between the incoming wind and the gable is large), the wind suction at the corner of the gable is larger. At other wind directions, the smaller the rise-span ratio, the smaller the wind suction on the roof.

(2) In terms of the overall force coefficient, in the range of 0° to 90° wind direction angle, with the decrease of the rise-span ratio, the overall force coefficient of the span is still increasing first and then decreasing, but the peak value is reduced, and the wind direction angle is moved from 30° to 50°, and the change tends to be gentle. The longitudinal overall force coefficient increases first and then decreases to a monotonous increase, and the peak wind direction angle moves from 60° to 80°. The vertical overall force coefficient increases first and then decreases to a monotonous decrease, the peak wind direction angle moves forward from 30°, and the overall value is lower than that of the conventional rise-span ratio structure.

(3) Under the condition of full wind direction angle, the skewness value of the over 60% wind pressure measuring point of the structure is negative, indicating that the overall distribution of wind pressure is left-skewed, and the probability long tail is mainly concentrated in the negative pressure interval. The kurtosis value of more than 70% of the measuring points is greater than 3, showing the typical non-Gaussian distribution characteristics of peak and thick tail. The high value areas of wind pressure skewness and kurtosis are mainly concentrated on the edge, corner and leeward side of the structure. Compared with the conventional rise-span ratio structure, the proportion of measuring points with structural skewness less than -0.1 and kurtosis greater than 3 decreased by about 20

percentage points (the corresponding proportion of the conventional structure was about 80% and 90%, respectively), but the overall wind pressure field still showed significant non-Gaussian characteristics.

(4) At all wind directions, the non-Gaussian peak factor is significantly higher than the standard value and the Gaussian hypothesis value. The peak factor of wind pressure at more than 80% of the measuring points is greater than 3, and the maximum value of the peak factor can reach 10.3. The peak factor of the conventional rise-span ratio structure is greater than 3.5, and the maximum peak factor is 11.5. In general, the overall amplitude of the wind pressure peak factor of the structure is slightly reduced, but there are still a large number of peak factor measuring points in the whole wind direction, and the non-Gaussian amplification effect of wind pressure is still significant. The calculation results of extreme wind pressure coefficient of low rise-span ratio structure based on non-Gaussian peak factor show that when the standard peak factor is 2.5, the underestimation of extreme wind pressure is 13% ~ 66%, with an average underestimation of about 28%. Under the Gaussian assumption, the underestimation range is 0 ~ 54%, with an average underestimation of 19%. In contrast, the extreme wind pressure of the conventional rise-span ratio structure is underestimated by 40% ~ 50% on average. Although the average underestimation ratio of the small rise-span ratio structure is lower than that of the conventional rise-span ratio structure, both the specification value and the Gaussian assumption are obviously underestimated, and the underestimation range of the roof edge area is more than 50%. The non-Gaussian characteristics are significant, and its influence on the extreme wind pressure cannot be ignored. It is suggested that the peak factor value should be appropriately increased in the revision of the specification to ensure the safety of the structure.

## Nomenclature

|                     |                                                                                         |            |                                                            |
|---------------------|-----------------------------------------------------------------------------------------|------------|------------------------------------------------------------|
| $B$                 | Length                                                                                  | $C_{Fq}$   | The overall force coefficient of the q-direction structure |
| $B/L$               | Length-to-span ratio                                                                    | $A_i$      | Area of measuring tap $i$                                  |
| $C_{pi}$            | Wind pressure coefficient at $i$ tap                                                    | $A_q$      | The projection area in the $q$ direction                   |
| $\bar{C}_p$         | Mean wind pressure coefficient                                                          | $U_r$      | Approaching wind speed                                     |
| $C'_p$              | Fluctuating pressure coefficient                                                        | $U_g$      | The wind speed at a height of $Z_g$                        |
| $C_{p, peak}^{\pm}$ | Extreme wind pressure coefficient                                                       | $Z$        | Actual height                                              |
| $f$                 | Rise                                                                                    | $Z_g$      | Corresponding to an actual height of 200 m                 |
| $f/L$               | Rise-to-span ratio                                                                      | $Z_i$      | Height at tap $i$                                          |
| $g$                 | Peak factor                                                                             | $\alpha$   | Geomorphologic roughness index                             |
| $g_{,G}$            | Peak factors based on Gaussian assumption                                               | $\beta$    | Wind direction angle                                       |
| $g_{,NG}$           | Peak factors based on non-Gaussian assumption                                           | $\gamma$   | Euler's constant, approximately 0.5772                     |
| $L$                 | Span                                                                                    | $\gamma_3$ | Skewness                                                   |
| $N$                 | Number of valid sampling points                                                         | $\gamma_4$ | Kurtosis                                                   |
| $p_t$               | Total pressure of reference tap                                                         | $\theta$   | Sectional Azimuth Angle                                    |
| $p_s$               | Reference tap static pressure                                                           | $\mu_s$    | Shape coefficient                                          |
| $p_i$               | Pressure at measuring tap $i$                                                           | $\rho$     | Air density                                                |
| $\gamma_{qi}$       | The direction angle of the normal vector of the measuring taps $i$ in the $q$ direction |            |                                                            |

## Credit authorship contribution statement

Xiaolong Xu: Data curation, Formal analysis, Software, Writing – original draft, Writing – review & editing. Zhuangzhuang Guo: Supervision, Validation. Anjie Chen: Supervision, Validation. Qun Yang: Resources, Supervision. Xiaobing Liu: Funding acquisition, Resources, Supervision.

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