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Analyzing the impact of wind and snow loads on long-span tensile membrane structures: investigating structural response and performance

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Abstract

Long-span structures are typical flexible structures that will produce significant responses when subjected to wind and snow loads. In recent years, the frequency of extreme weather events has been increasing, making it more likely to have adverse effects on long-span structures in windy and snowy weather. Long-span tensile membrane structures, due to their lightweight nature, are particularly sensitive to wind and snow loads. It is necessary to do research on their response under such loads. Firstly, the FLUENT software is utilized to numerically simulate the wind field and snowfall over the gymnasium, acquiring a non-uniform snow distribution on the roof surface. Subsequently, this non-uniform snow distribution is treated as vertical load and incorporated into a finite element model of the gymnasium for simulation analysis, aiming to investigate the response of the roof under the combined action of wind and snow loads. Under the combined influence of wind and snow loads, the vertical displacements at the roof edges exhibit relatively smaller magnitudes, while the central region displays larger vertical displacements.

Keywords: long-span structure, wind and snow loads, response

1. Introduction

In recent years, as the frequency of extreme weather events increasing, structure failures caused by wind and snow loads increases. Long-span structures have high flexibility, which is sensitive to wind and snow loads. Therefore, it is necessary to investigate the response of long-span structures under wind and snow loads.

The research method in snowdrift area can be divided into field measurement, wind tunnel test and numerical simulation. In recent years, with the development of numerical simulation, this method has received more and more attention from scholars. Zhou, XY[1] investigates the influence of roof slopes on the snow distribution of the gable roof. Through CFD simulations, it has been observed that the distribution of flow field around the gable roof and the friction velocity on snow surface vary with the roof slope, which lead to the increase of the upwind erosion flux and the leeward deposition flux with the increase of the incoming wind speed and the roof slope.

In the field of wind-induced vibration response studies, most scholars pay more attention to the structural response under wind loads, while there are relatively fewer studies addressing the structural response under the combined action of wind and snow loads. Xuanyi Zhou[2] designed an aeroelastic model for a lightweight roof structure, pre-depositing snow loads on the roof surface. Subsequently, wind tunnel tests are conducted to acquire the structural response under the combined action of wind and snow loads.

The study initially conducted a simulation to analyze the snow distribution on the roof of a gymnasium. Subsequently, wind tunnel tests are carried to obtain the wind load of the gymnasium. Non-uniform snow loads are applied as non-uniform vertical load to the finite element model of the gymnasium, and wind loads are also applied to the finite element model of the gymnasium to acquire its response under the combined wind and snow loads.

Figure 1: Photo of the gymnasium structure

2. Numerical simulation of snowdrift

In this study, FLUENT software is employed to investigate the snow distribution on the gymnasium. The mixed model in multiphase flow theory is adopted to simulate the snowdrift. It is assumed in this study that snowdrift occurs under the influence of wind loads, while the distribution of snow can not influence the wind field.

2.1. Basic theory

The governing equations consist of the mass continuity equation and the momentum conservation equation:

$$\frac{\partial \rho_m}{\partial t} + \nabla \bullet \left(\rho_m u_m \right) = 0 \tag{1}$$

$$\begin{gathered} \frac{\partial \left(\rho_m \mathbf{v_m} \right)}{\partial t} + \nabla \bullet \left(\rho_m v_m \mathbf{v_m} \right) = -\nabla p + \\ \nabla \bullet \left[\mu_m \left(\nabla \bullet \mathbf{v_m} + \nabla \bullet \mathbf{v_m}^T \right) \right] + \rho_m \mathbf{g} + F \end{gathered} \tag{2}$$

where ρ_m is the density of the mixture phase, which includes both snow and air, μ_m is the mixture dynamic viscosity, v_m is the velocity of the mixture phase of air and snow, F is the body force.

In the realm of snowdrift, the erosion or deposition of snow particles is determined by the friction velocity u_* at the surface of the snow layer. Erosion occurs when the friction velocity u_* exceeds the threshold friction velocity u_{*_t}, while deposition occurs when the friction velocity u_* is smaller than the threshold friction velocity u_{*_t}. This is described by the following equation:

$$q_s \begin{cases} q_{ero} = A_{ero} \left(u_*^2 - u_{*_t}^2 \right) & u_* > u_{*_t} \\ q_{dep} = \rho_s f w_f \dfrac{u_{*_t}^2 - u_*^2}{u_{*_t}^2} & u_* \le u_{*_t} \end{cases} \tag{3}$$

where f is the snow concentration, A_{ero} is the empirical constant, w_f is snowfall velocity and ρ_s is the density of snow particle. The value of A_{ero} is set as 7.0×10^{-4}, the value of w_f is set as 0.2m/s and the value of ρ_s is set as 150kg/m^3.

In this study, the *k-kl-ω* model is employed to simulate the turbulent flow field around the building. The inlet wind speed wind speed profile follows the power-law distribution:

$$\bar{u}(z) = u_0 \left(\frac{z}{z_0} \right)^{\alpha} \tag{4}$$

where z_0 is the reference height and u_0 is the reference velocity. z_0 is set as 10m.

2.2. CFD model

The gymnasium has dimensions of 270m in length, 253m in width and 54m in height. With a flat shape coupled with significant span, the roof is low in vertical stiffness, which tends to generate noticeable vertical displacement under wind and snow loads. It is necessary to investigate the response of the roof under wind and snow loads.

The computational domain size is set as X×Y×Z=10L×21B×7H, which is large enough to ignore the boundary effects on the flow field. L, B and H refer to length, width and height of the structure respectively. In this research, the number of the unstructured mesh is approximately 4.8 million and the growth factor is set as 1.2. The threshold friction velocity u_{*_t} is set as 0.2m/s. The movement of snow particles is simulated using the SIMPLE algorithm in this study. Convergence is regarded to be achieved when all scaled residuals reached the steady state and reach a minimum value of 10^{-7} for continuity, x, y and z velocities.

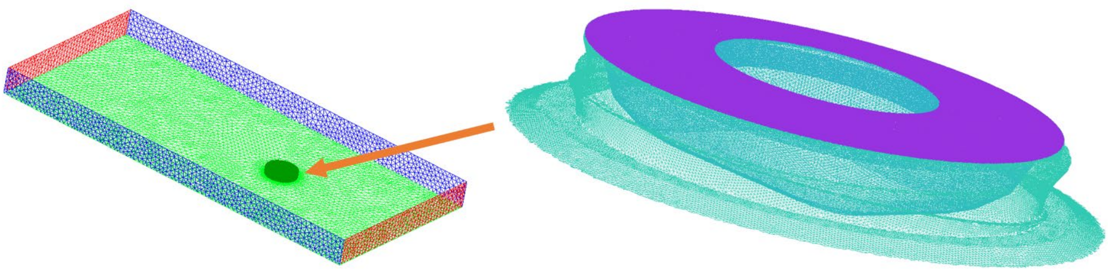
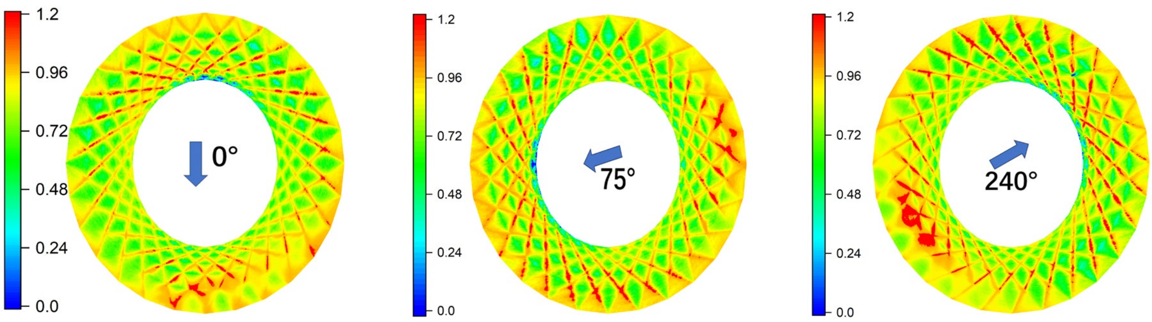


Figure 2: Computational region

According to Chinese load code GB50009-2012 for the design of building structures, the initial snow depth is set at 0.27m, corresponding to the basic snow load of 0.4 kN/m^2, which is the basic snow load corresponding to a 50-year return period in the Dalian region. Considering the symmetry of the gymnasium, three wind directions are selected at 0°, 75° and 240°. Generally, snowdrift occurs when the wind speed at the height of 10m exceeds 5m/s. However, most snow particles will occur suspension motion. In this study, the wind speed of 10 m/s is considered.

2.3. Simulation result

Figure 3 shows the snow distribution under different wind directions. It is evident that under the influence of wind load, the windward area of the roof presents erosion while the leeward area shows deposition. The maximum normalized snow depth reaches 1.2.



(a) 0° (b) 75° (c) 240°

Figure 3: Non-uniform distribution of snow on the roof

3. Wind tunnel test

In this study, wind pressure of the structural roof is obtained through wind tunnel tests of rigid model. Non-uniform snow load is applied on the roof of the structure as vertical load, and wind pressure load is applied to the structure simultaneously. This approach can acquire theresponse of the roof under wind and snow loads. The initial assumption of this study is that the non-uniform snow has no impact on the wind pressure of the roof.

Wind tunnel test of the rigid model is conducted at the Joint laboratory of wind tunnel and water flume in Harbin Institute of Technology. The model, fabricated from photosensitive resin and ABS sheets, has sufficient stiffness to prevent vibration at the test wind speeds, which guarantees sufficient accuracy in wind pressure measurement.

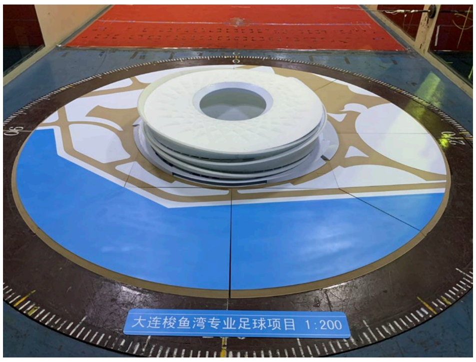


Figure 4: Rigid model of the gymnasium

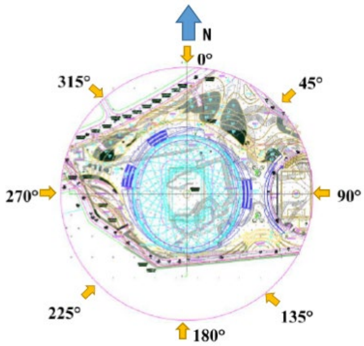


Figure 5: Definition of wind direction

The geometric scale ratio of the model is set at 1:200, and the blocking radio of wind tunnel tests are below 5%.

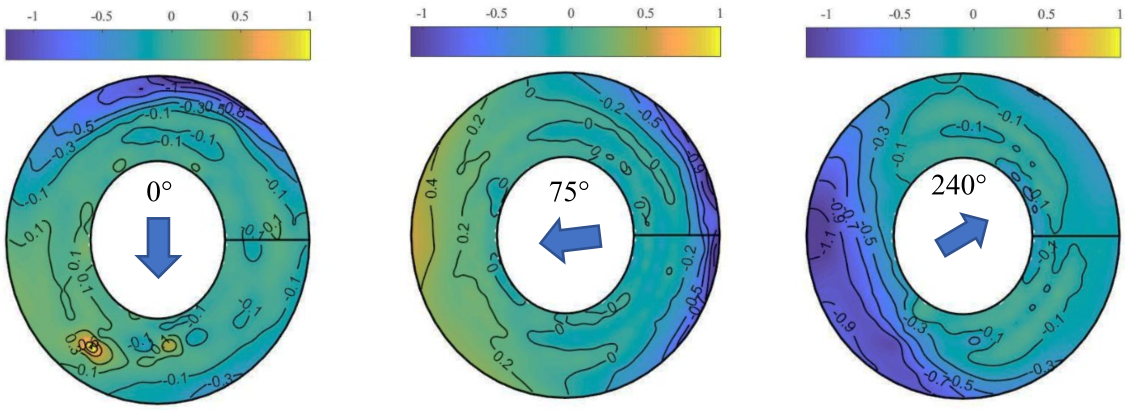
The type A roughness category in Chinese load code GB50009-2012 is modeled to simulate the atmospheric boundary layer. The reference height of the test is set as 100m(corresponding to the model height of 0.5m). The wind speed of the test is set as 10m/s. The frequency of the pressure measurement signals is 625Hz. Each test is sampled for a duration of 20s. Wind tunnel tests are conducted at wind direction of 0°, 75° and 240°.

The wind pressure coefficient at measurement point *i* on the structure surface at time *t* is $C_{pi}(t)$:

$$C_{pi}(t) = \frac{P_i(t) - P_0}{\frac{1}{2}\rho U_H^2} \tag{5}$$

where C_{pi} is the wind pressure coefficient at measurement point *i*, P_i is the wind pressure at measurement point *i*, P_0 is the static pressure at reference height, ρ is the density of air, U_H is the average wind speed at the reference height.

Figure 6 shows the average wind pressure coefficient distribution on the roof at different wind directions. It is evident from the figure that negative pressure appears in the windward region of the roof, while positive pressure is prevalent in other regions.



(a) 0°　　(b) 75°　　(c) 240°

Figure 6: Average wind pressure coefficient on the roof

4. Response analysis

4.1. Computational parameters and model

In this study, wind loads and snow loads are simultaneously applied to the finite element model of the gymnasium to investigate the response of the structure. The distribution forms of wind and snow are different from Chinese load code, which can not be directly combined according to the load combination procedures. In this research, the magnitude of the snow load is calculated by the normalized snow depth multiplied by the basic snow pressure, and the wind load is calculated by the average wind pressure coefficient multiplied by the basic wind pressure. According to Chinese load code GB50009-2012, the basic wind pressure for the 50-year return period in Dalian region is 0.65 kN/m².

In this study, the response of the gymnasium to wind and snow loads is investigated using ANSYS software. In the finite element model, Beam44 elements are utilized to simulate trusses and columns, Link8 and Link10 elements are utilized to simulate vertical poles and cables, Mass21 elements are utilized to simulate the self-weight of the gymnasium. The upper cable net was prestressed to 5000 kN, while the lower cable net was prestressed to 7000 kN. Figure 7 shows the finite element model of the gymnasium. The structure is subjected to full-span, half-span and wind-induced non-uniform snow loads. Wind-induced non-uniform snow load is obtained from snowdrift simulation in Section 2.3.

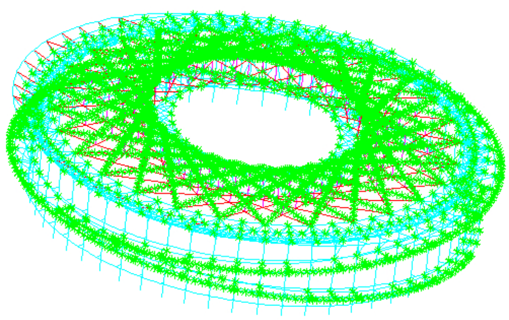
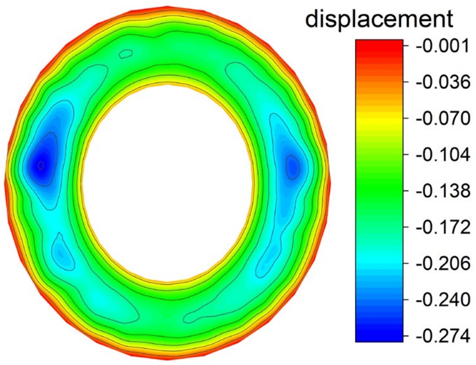


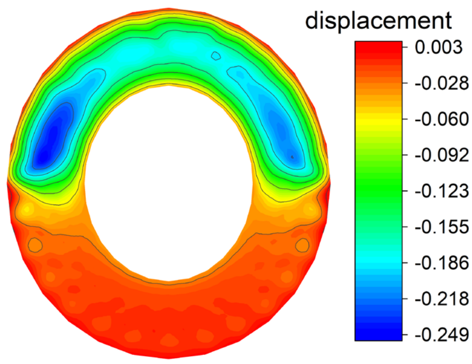
Figure 7: Finite element model of the gymnasium

4.2. Simulation Results and Analysis

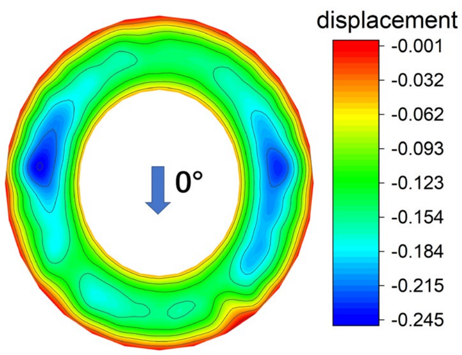
Figure 8 presents the contour plots of the roof displacement under snow loads with different distribution patterns. Positive values mean upward displacement, while negative values mean downward displacement. Under full span loading conditions, the maximum vertical displacement of the roof reaches 0.274 meters; under half span loading conditions, the maximum vertical displacement is smaller at 0.249 meters. The vertical displacements induced by both full span and half span loading conditions comply with the requirements of Chinese standard JGJ 7-2010 (1/250 of the span). The vertical displacements induced by full span and half span snow loads exceed those caused by simulated snow loads under 0° wind load. This is attributed to snow erosion on the roof surface under simulated snow loads, leading to a reduction in the total snow load acting on the structure. Under 0° and 75° wind load, the locations of maximum vertical displacement along the longitudinal axis of the roof are in the middle region, measuring 0.245m and 0.266m, respectively. This phenomenon can be attributed to the longer dimension along the longitudinal axis, resulting in lower roof stiffness. Under 240° wind load, the region of maximum vertical displacement is located in the upper left corner of the roof, reaching 0.31 m, which is likely influenced by the non-uniform distribution of snow.



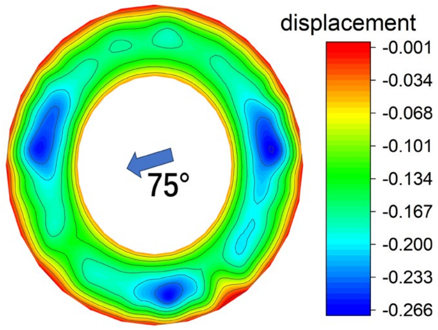
(a) Full span uniform snow load



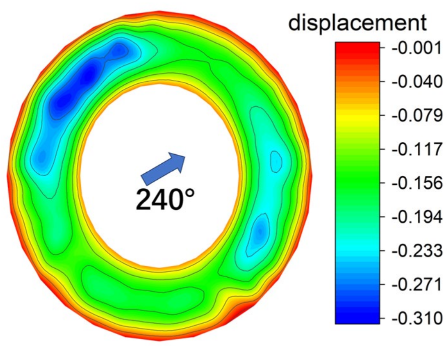
(b) Half span uniform snow load



(c) Simulated snow load under 0° wind



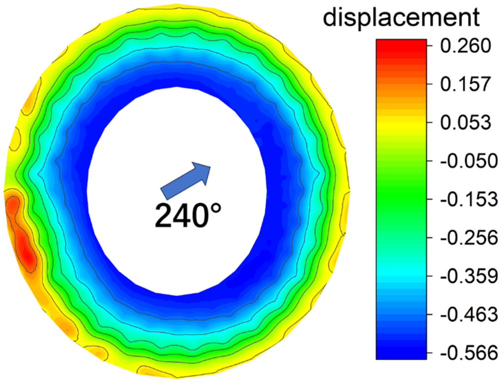
(d) Simulated snow load under 75° wind



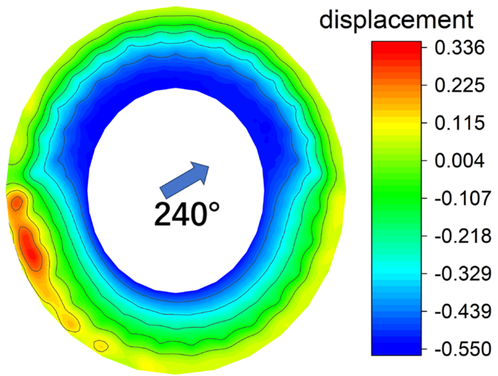
(e) Simulated snow load under 240° wind

Figure 8: Contour plot of the roof displacement under snow load

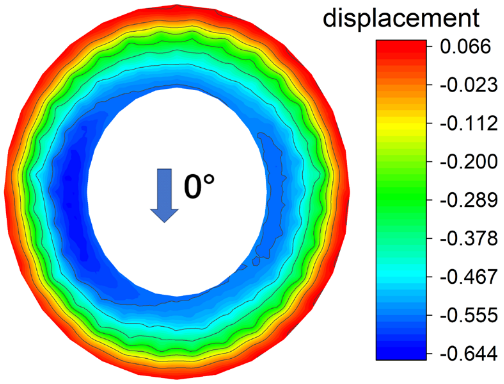
Figure 9 presents the contour plot of the displacement on the roof under the combination action of wind and snow. Apparently, the windward region of the roof generates upward displacement. This phenomenon can be explained that the flow separation occurs at the windward edge, which generates wind suction force. However this region is close to the supports, which possess higher vertical stiffness. Consequently, the vertical displacement in this region is relatively small. The combined action of wind and snow change the distribution of roof displacement response and the maximum displacement magnitude. The differences in maximum vertical displacements of the roof under different wind directions and simulated snow loads are relatively small. Under 0° wind load, the maximum vertical displacement of the roof is 0.644m; under 240° wind load, the maximum vertical displacement of the roof is 0.61m; under 75° wind load, the vertical displacement of the roof is highest, reaching 0.678m.



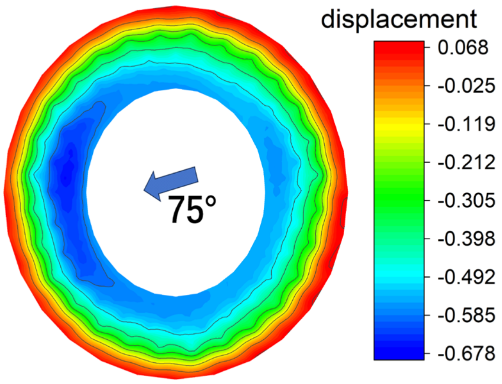
(a) full span uniform snow load and 240° wind load



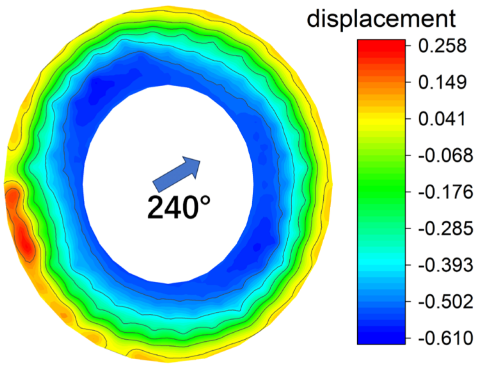
(b) half span uniform snow load and 240° wind load



(c) simulated snow load under 0° snow and 0° wind load



(d) simulated snow load under 75° snow and 75° wind load



(e) simulated snow load under 240° snow and 240° wind load

Figure 9: contour plot of the roof displacement under snow and wind load

Due to the vertical displacement of the roof induced by simulated snow loads at 240° wind load exceeds those at 0° and 75° wind load, calculations for the vertical displacement of the structure are conducted under full span and half span snow load at 240° wind load. In comparison to the effects of wind load and simulated snow load, the differences in vertical displacements induced by full span snow load and simulated snow load are relatively small. Under half span uniform snow load and 240° wind load, the maximum upward displacement of the roof is greater, reaching 0.336 m. This is attributed to the absence of vertical snow load application in the region below the roof's central axis.

5. Conclusion

This study investigates the snowdrift on the roof of a gymnasium and the structural response of the roof under the combination of wind and snow loads. The snow accumulation pattern of roof is significantly influenced by wind direction. Compared to snow load alone, the displacement response of the roof is more intense under the combination of wind and snow loads, highlighting the necessity for further research on the response of such structures under wind and snow loads.

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[2] X. Zhou, S. Qiang, Y. Peng, and M. Gu, “Wind tunnel test on responses of a lightweight roof structure under joint action of wind and snow loads,” *Cold Reg. Sci. Technol.*, vol. 132, pp. 19–32, Dec. 2016, doi: 10.1016/j.coldregions.2016.09.011.