Study on the Characteristics of Local Wind Pressure Variations in Open Circular Arc Large-Span Roofs

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Abstract. The wind tunnel test research on the open ring-arched large-span roof, based on the wind tunnel test results, analyzed in the wall under different opening rate of the ring-arched local roof shape factor change rule. The results show that: As the opening rate increases, wind pressure on the outer edge of the roof decreases. When the opening rate is 74% or more, its effect on wind pressure is minimal, with a shape factor difference of around 0.7 between closed and open states. Openings near the outer edge can reduce high negative pressure areas.

Keywords: circular roof, wind tunnel tests, openings, shape factor.

1 Introduction

With the rapid development of society, large-span roofs are widely used in various types of large public buildings, such as stadiums and airports [1]. Depending on their function and aesthetic requirements, large-span structures feature different open forms [2]. However, open large-span roofs have two main characteristics: first, they have low damping and lightweight properties, making them wind-sensitive structures. Current load standards do not fully apply to the actual conditions of open large-span buildings [3]. Second, the wind load mechanism for open large-span roofs is more complex than that of typical enclosed large-span roofs, as there are both upper and lower windward surfaces influenced by internal and external pressures. As a result, the engineering design is more challenging [4].

In recent years, numerous wind resistance experiments on open large-span roofs have been conducted by domestic and international scholars. For example, Pan Dan [5] conducted wind tunnel model tests on both unperforated and perforated open-type semi-circular arch large-span roofs. Under wind angles of 30°, 60°, and 90°, due to the airflow moving against the slope, there was significant flow separation at the windward side, resulting in the highest negative wind pressure coefficient. However, after perforating the wind-sensitive areas of the roof, the wind pressure at the windward edge was reduced, with a maximum reduction rate of 53.5%. Killen et al. [6] studied the effect of the ventilation rate between a canopy roof and the stands on wind loads on the canopy roof, finding that ventilation slightly reduced the canopy wind load by approximately 10%. Kim et al. [7] investigated the wind pressure variations

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on an open dome roof with different opening rates and found that the minimum wind pressure coefficient at the outer edge of the roof interior increased as the opening rate increased. Open large-span roofs often face uneven and rapidly changing wind pressure distribution due to their open nature. Existing load standards are typically designed for enclosed structures. Therefore, this paper studies the characteristics of local average wind pressure variations on circular arc roofs with different wall opening rates by comparing multiple wind tunnel tests on circular arc stadiums. The findings aim to provide a basis and reference for future design standards of such roofs.

2 Wind Tunnel Test

In this study, four stadiums were selected for wind tunnel tests, all of which are ring-arch cantilever structures with partial openings. The selected stadiums are Ma'anshan Stadium, Taizhou Stadium, Maoming Stadium, and an Indonesian Stadium. The rigid body model wind tunnel tests for these stadiums were conducted in the TJ-3 atmospheric boundary layer wind tunnel at the State Key Laboratory of Disaster Prevention in Civil Engineering at Tongji University. This wind tunnel is a closed-circuit vertical low-speed wind tunnel with a test section width of 15 meters, height of 2 meters, and length of 14 meters. The models were constructed with sufficient strength and stiffness to prevent deformation and significant vibrations at a test wind speed of 15 m/s. In the wind tunnel tests, the geometric scale ratio for the Maoming Stadium model was 1:150, for the Taizhou Stadium and Indonesian Stadium models it was 1:200, and for the Ma'anshan Stadium model it was 1:280. For the Maoming Stadium, wind pressure measurements were taken every 10° for a total of 36 wind directions, while for the other stadiums, measurements were taken every 15° for a total of 24 wind directions. The wind profile used in all tests adhered to the "Category B" terrain profile defined by the Chinese load standard. Measurement points were distributed on both the upper and lower surfaces of the stadiums, and the wind tunnel test models for each stadium are shown in Table 1.

Wind pressure data were obtained using rigid model wind tunnel tests, and the shape coefficient for the ith measurement point on the roof surface was calculated using the following formula:

$$\mu_{si} = \frac{P_{iu} - P_{id}}{0.5\rho V^2}(Z_R / Z_i)^{2\alpha} \tag{1}$$

In the equation: P_{iu} and P_{id} is the pressure on the outer and inner surfaces of the measurement point I; V is the wind speed at the reference height; Z_R is the height of the selected reference point for wind pressure analysis; Z_{i} is the height of the ith measurement point; α is the roughness index of the landform where it is located, such as B class landforms take 0.16; μ_{si} is the wind load shape factor for roof surface measurement point.

Table 1. Wind tunnel test models for each stadium

		
Ma'anshan Stadium	Taizhou Stadium	Maoming Stadium
		
Indonesia Stadium (Wall openings)	Indonesia Stadium (Wall closure)	

3 Characteristics of Changes in Localized Shape Factor of Roofs under Different Opening Rates

Each stadium selected specific roof measurement points at wall openings or apertures to compare and analyze the variation of shape coefficients of local roof sections under different wall opening rates. This study aims to clarify the variation patterns of shape coefficients for local wind loads on ring-arch roofs under different wall opening rates. The strip positions of measurement points used are shown in Table 2, representing the measurement columns and the corresponding wall opening rates at the walls as listed in Table 3.

Table 2. Selection of measurement point areas for each stadium

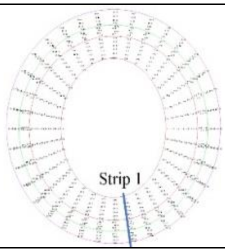	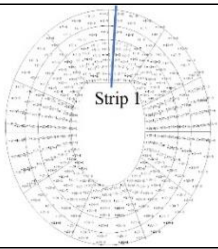	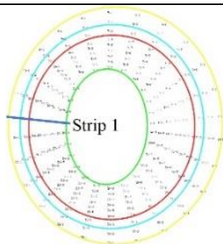	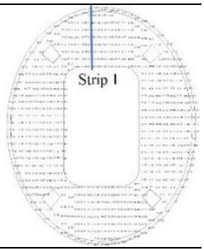
Maoming Stadium	Ma'anshan Stadium	Taizhou Stadium	Indonesia Stadium

Table 3. Representative site columns and open rates

stadiums	survey point series	Openness of the wall under the measurement point	note
Indonesia Stadium	Strip 1	0%	confined
Maoming Stadium	Strip 1	12%	open hole
Ma'anshan Stadium	Strip 1	74%	wide open

Taizhou Stadium	Strip 1	82%	wide open
Indonesia Stadium	Strip 1	100%	wide open

Note: The open hole ratio for open hole stadiums is the area of open holes divided by the area of the façade; the opening ratio for open stadiums is the height of openings divided by the height of the façade.

Fig. 1 gives a comparison of the changes in the roof shape factor under windward winds for strip 1 of the column of measurement points selected for each stadium, with the measurement point numbers for each strip ordered from the upper roof from the inside to the outside. (Define the windward leading edge of a circular roof as the outer gable and the inner gable away from the windward leading edge)

From Fig. 1 the stadium shape factor changes can be seen: in the windy down near the ring-arch roof eaves position, the roof curvature changes dramatically, due to the impact of air flow separation leads to increased negative pressure, are shown as a stronger wind suction; roof eaves wind pressure is more stable, for the micro-negative pressure or micro-positive pressure (wind pressure).

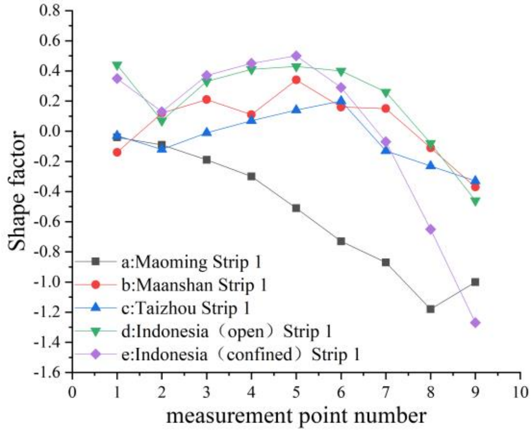

Fig. 1. Variation of local roof shape factor under different opening rate

In Fig. 1 a is the wall opening hole, b, c and d is the wall opening and e is the wall closure, the comparison reveals significant differences in wind pressure on the outer edge of the roof at different opening rates. Fig. 2 shows the variation in shape coefficients of the outer edge of the roof at different opening rates, for example, the shape coefficient of the outer eaves of the roof in the Indonesian Stadium (enclosed) is around -1.3, while the Maoming Stadium, with a wall opening rate of 12%, has a shape coefficient of around -1.2. In contrast, the wall opening rates of Ma'anshan Stadium, Taizhou Stadium, and the Indonesian Stadium (open) are all greater than or equal to 74%, with the shape coefficients of the outer eaves of the roof ranging from -0.4 to -0.5. As the opening rate increases, wind pressure on the outer edge of the roof gradually decreases, with a maximum shape factor difference of around 0.7. When the opening rate is 74% or more, the size of the wall opening rate has little impact on the wind pressure of the roof's outer edge. The reasons may include enclosed wall surfaces obstructing airflow, resulting in stronger flow separation, thereby increasing wind suction on the eaves of the roof. As the openness ratio of the walls increases, more wind can enter through openings, gradually reducing wind suction on the roof eaves.

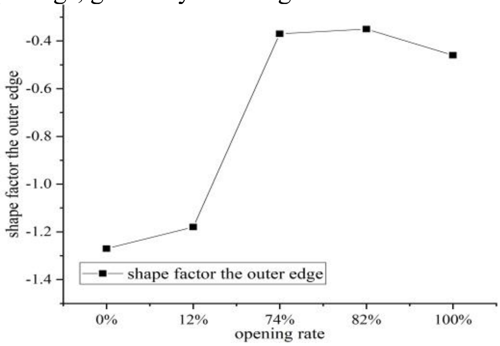

Fig. 2. Variation of shape factor at different opening rates of the outer edge

It can be observed from the comparison between Stadium "a" and Stadiums "b", "c", "d", and "e" in Fig. 1 that when the wall opening rate of 12%, which is relatively small compared to the opening rate of b, c, d, the wind pressure on the eave of the ring-arched roof cover has a small impact on the shape factor of the minimum in -1.3 or so; but near the position of the wall openings in the eave of the roof cover of the negative pressure decreases, the shape factor of the - 0.9 or so, therefore, in close proximity to the eave of the ring-arch roof cover opening can be appropriately reduced near the openings Therefore, the negative pressure at the eaves of the ring-arch roof can be appropriately reduced near the openings, and the high negative pressure area at the eaves of the ring-arch roof can be reduced.

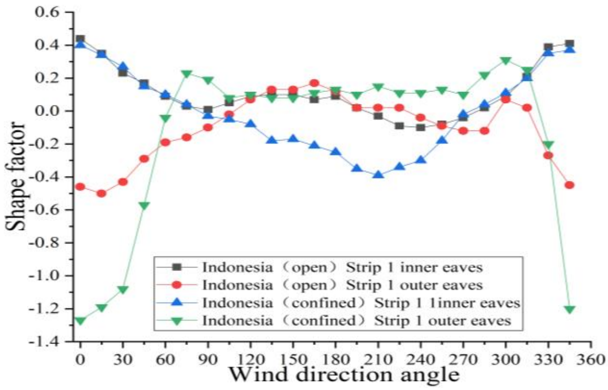

Fig. 3. Variation of shape factor for representative measurement points in the Indonesian Stadium with wind direction angle

It can be observed from Fig. 3, comparing the variation of shape factor for representative measurement points on the inner and outer eaves under open and enclosed conditions in the Indonesian Stadium, that when the walls are open, the trend of wind pressure variation on the outer eaves of the local roof is minimally affected by changes in wind direction angle, whereas the wind pressure variation on the inner eaves is significantly impacted by changes in wind direction angle.

4 Conclusions

The preliminary conclusions obtained from comparing the characteristics of local wind pressure variations on ring-arch roofs under different wall opening rates in multiple ring-arch stadiums are as follows:

- As the opening rate increases, wind pressure on the outer edge of the roof gradually decreases. When the opening rate is 74% or more, the size of the opening rate has minimal impact on the wind pressure of the outer edge. The maximum difference in shape factor between closed and open states is around 0.7.
- When the wall opening rate is low, such as 12%, the impact on the wind pressure of the outer edge of the circular arc roof is minimal. The minimum wind pressure on the outer edge of the ring-arch roof is similar to that when the wall is closed. However, openings near the outer edge of the ring-arch roof can slightly reduce the negative pressure in these areas, thereby decreasing the high negative pressure zones on the outer edge of the ring-arch roof.
- When the walls are open, wind pressure on the outer eaves is barely affected by wind direction changes, while the inner eaves are more influenced.

References

1. Qu ,W., Zhang,M., Wang,R.Q. (2020) Analysis of Wind Loads Before and After Opening on a Large Span Curved Roof. Engineering Construction,52:6–10+29. DOI:10.13402/j.gcjs.2020.09.002
2. Hu,W.S.(Southeast University), 2021. Research on Wind Loads of Large Span Open-type Canopy Structure. DOI:10.27014/d.cnki.gdnau.2021.002712
3. Kang,J.X. (2024) Numerical Simulation Study on Wind Load and Wind Field Characteristics of Special-shaped Open Roofs. Journal of Henan University of Urban Construction, 33(01): 79-85. DOI:10.14140/j.cnki.hncjxb.2024.01.011
4. Zhang,C.H. (Chongqing University), 2011. Research on Wind Load Characteristics of Large-span Annular Cantilever Roof Structure.
5. Pan,D.(Guilin University of Technology), 2021. Wind Load Characteristics and Wind-induced Response Analysis of Open Semi-circular Arched Large-span Roofs. DOI:10.27050/d.cnki.gglgc.2021.000418
6. Killen,G., Letchford,C.(2001) A Parametric Study of Wind Loads on Grandstand Roofs. Engineering Structures, 23(6): 725-735.
7. Kim,Y.C., Yoon,S.W., Cheon,D.J., et al. (2019) Characteristics of Wind Pressures on Retractable Dome Roofs and External Peak Pressure Coefficients for Cladding Design. Journal of Wind Engineering and Industrial Aerodynamics, 188: 294-307.