# Study on the Influence of Protruding Elevated Rib Beams on the Wind Load of Large-Span Cantilever Roofs (Postprint)

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## Abstract

For a large-span cantilevered roof equipped with protruding overhead rib beams, the RANS method is employed to simulate the wind pressure distribution. Based on varying wind directions, an interference factor IF for wind pressure is defined to investigate the influence characteristics of the protruding rib beams on the roof wind loads. The results show that the roof is generally subjected to negative pressure, and under the combined effects of flow separation and conical vortices, the wind pressure at the windward eave edge and its corners is relatively high. For wind directions in the ranges of 0°–165° and 180°–345°, the wind pressure variation on the upper surface of the roof exhibits symmetry, whereas on the lower surface different regions display non-synchronous variation of wind pressure with wind direction. Comparing conditions with and without protruding rib beams, the flow-field structures differ only slightly at a wind direction of 0°, but the rib beams prevent the formation of a vorticity amplification region in their wake. At a wind direction of 270°, the interference induced by the protruding rib beams is pronounced: the wind speed above the roof differs significantly between the two cases, vortices in the wake impinge back onto the roof, and, in the absence of rib beams, the velocity gradient is large and the vorticity distribution is more concentrated. Overall, the rib beams exert a shielding and reduction effect on the roof wind pressures, with a more pronounced influence on the top region of the roof, and the reduction effect is most significant at 270°. In wind-direction ranges where the angle between the rib beams and the incoming flow is small, the roof IF values are highly sensitive to changes in wind direction, with peak values reaching -3.8 and 3.7, leading to increased local wind pressures and alternating positive and negative pressures; this effect is particularly evident at a wind direction of 0°.

# Full Text

## Abstract

This study investigates the wind load effects on a large-span cantilever roof with protruding overhead rib beams using CFD simulation. By defining a wind pressure interference factor (IF), the influence characteristics of the protruding ribs on roof wind loads are examined across varying wind directions. The results demonstrate that the roof generally experiences negative pressure due to the combined effects of airflow separation and conical vortices, with particularly high wind pressures observed at the windward eaves and corners. The upper surface pressure distribution exhibits symmetrical variation for wind directions between 0° and 165°, while different regions of the lower surface show distinct pressure variation patterns. For wind directions from 180° to 345°, the flow structure differences are relatively small, but the rib beams effectively prevent the formation of vortex enhancement zones downstream. Significant differences in wind speed above the roof are evident between the two configurations, with vortices in the wake region impinging back onto the roof surface. In the absence of rib beams, the wind speed gradient is steep and vorticity distribution becomes concentrated. Overall, the rib beams provide a shielding effect that reduces roof wind pressure, with the most pronounced reduction occurring at specific wind directions. However, when the angle between the rib beams and incoming flow is small, local wind pressure increases and alternates between positive and negative values, an effect that becomes particularly significant under certain conditions.

**Keywords:** large-span roof; protruding rib beam; numerical simulation; roof wind pressure; interference factor

## Introduction

Large-span roof structures, characterized by their extensive spans and diverse geometries, are widely employed in large-space multifunctional venues. Given their sensitivity to wind loads, high-velocity winds can induce excessive structural responses that affect normal building operation or even cause local collapse. The primary cause of wind-induced damage is the formation of concentrated negative pressure on roof surfaces due to flow separation and conical vortices at roof edges. For complex roof geometries with protruding components, flow collision and recirculation phenomena intensify compared to smooth roof surfaces, resulting in more severe wind loading effects.

Previous research on large-span roofs has primarily focused on smooth surfaces or small-scale protruding elements. Studies have simulated wind load characteristics for both closed and retractable large-span roofs, revealing that roof geometry significantly influences pressure distribution patterns. Large eddy simulations of low-rise buildings with eaves have shown that while eaves cause premature flow separation at the windward edge, their impact on roof pressure distribution is minimal. Investigations into rib elements have examined drag reduction mechanisms for various rib configurations and wind tunnel tests on low-rise double-slope models with different roof protrusion designs have demonstrated that hollow roof ridges provide the best wind shielding effect. However, research on large-span roofs with multiple protruding rib beams, particularly large-span overhead arc-shaped protruding members, remains insufficient. The hollow configuration at the bottom of rib beams substantially alters airflow patterns, necessitating project-specific investigations.

This study examines a fan-shaped large-span cantilever roof of a science and technology museum, considering the interference of staggered protruding rib beams on airflow. Using the Reynolds-Averaged Navier-Stokes (RANS) method to simulate the wind field around the building, the study analyzes roof pressure distribution characteristics and obtains the variation patterns of wind load shape coefficients with wind direction. By comparing with a smooth roof without protruding rib beams, the influence of rib beam components on roof wind pressure characteristics is analyzed to provide effective references for wind-resistant design of complex roofs.

# 1 CFD Simulation Method

## 1.1 Turbulence Model

The Realizable $k$-$\varepsilon$ turbulence model introduces a new eddy viscosity formulation and modifies the transport equation for turbulence dissipation rate $\varepsilon$ to avoid stagnation point anomalies and wake region divergence. This model satisfies mathematical constraints on Reynolds stresses and can accurately capture near-wall turbulence effects, making it suitable for building wind field simulations with high precision. The model effectively simulates flow separation and can capture reattachment and recirculation phenomena.

The equations for turbulent kinetic energy $k$ and dissipation rate $\varepsilon$ are:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon$$
$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}$$

where $u_i$ $(i = 1, 2, 3)$ represents the velocity components in the $i$ direction, $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$ is the eddy viscosity coefficient, $\mu$ is the kinematic viscosity, $G_k$ is the turbulent kinetic energy generated by mean velocity gradients, and $\sigma_k$ and $\sigma_\varepsilon$ are the turbulent Prandtl numbers for $k$ and $\varepsilon$, respectively, with $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.2$.

## 1.2 Wind Field Boundary Conditions

The velocity inlet boundary condition is selected based on terrain category B from the Chinese Load Code for Building Structures (GB 50009-2012). The wind speed profile follows a power law:

$$U_z = U_{10} \left( \frac{z}{10} \right)^{\alpha}$$

where $U_z$ is the mean wind speed at height $z$, $U_{10}$ is the basic wind speed at the reference height of 10 m (taken as 27.1 m/s), and $\alpha$ is the ground roughness exponent (0.15 for terrain category B). The gradient wind height is 350 m.

The turbulence profile follows Japanese loading specifications. The turbulent kinetic energy $k$ and dissipation rate $\varepsilon$ are calculated considering streamwise turbulence:

$$k = \frac{3}{2}(U_z I_z)^2$$

$$\varepsilon = C_{\mu}^{3/4} \frac{k^{3/2}}{L}$$

where $I_z$ is the turbulence intensity at height $z$, $L$ is the turbulence characteristic length scale ($L = 100(z/10)^{0.5}$), and the empirical constant $C_{\mu}$ is taken as 0.09.

The outlet boundary employs a free outflow condition, while the sides and top surfaces use symmetric boundaries. All other wall surfaces are set as no-slip walls.

## 2 Model Establishment and Method Validation

### 2.1 Project Overview

The study focuses on a science and technology museum with a fan-shaped large-span cantilever roof. The building consists of main and auxiliary halls connected by a central bridge. The roof is closed in the middle section with cantilevered edges, and the overall geometry features a longitudinal profile that is higher in the middle and lower at both sides, with a transverse height decreasing from the main hall to the auxiliary hall.

[Figure 1: see original paper] Science and Technology Museum

### 2.2 Computational Model and Method Validation

A full-scale detailed model of the museum is constructed, retaining fine details that affect airflow such as the main hall platform and the connecting bridge. The computational domain dimensions are determined as $L_x = 8D$, $L_y = 12D$, and $L_z = 5H$, where $D = 220$ m is the building length and $H = 30$ m is the building height. The maximum blockage ratio of the cross-section is less than 3%, with the museum positioned near the center in the $x$ direction.

[Figure 2: see original paper] Physical model of Science and Technology Museum

The roof load is transferred through 18 large-span arc-shaped beams forming rib beams. Main rib beams converge at the building center, while secondary rib beams are arranged at the edges of the auxiliary hall.

[Figure 3: see original paper] Computation domain

### 2.3 Mesh Generation and Solution Parameters

Due to the complex building geometry with undulating surfaces, tetrahedral meshing would introduce significant iteration errors. Therefore, a Poly-Hexcore meshing approach is adopted, generating polyhedral prism layers at walls and near-wall regions while filling the remaining domain with hexahedral elements. The first layer height is 0.01 m with a growth rate of 1.1, ensuring wall $y^+$ values exceed 30 to meet Scalable Wall Function requirements. The region within 200 m of the building is refined to accurately capture airflow characteristics.

A double-precision segregated solver is employed with second-order upwind discretization for convective terms and SIMPLEC algorithm for pressure-velocity coupling. Convergence is achieved when all equation residuals fall below $10^{-4}$ and monitored roof surface pressures stabilize.

[Figure 4: see original paper] Schematic diagram of mesh generation

### 2.4 Mesh Independence Analysis

Three mesh densities are tested for independence: a baseline mesh (Model A) and refined meshes with growth rates of 1.15 (Model B) and 1.05 (Model C) and minimum size of 0.5 m. Mesh counts are 2.8 million, 4.2 million, and 6.1 million cells respectively. Wind speeds at points 1-3 and pressures at points 3-5 are compared. Models B and C show close agreement with deviations less than 5% for wind speed and 10% for pressure, while Model A shows larger deviations. Therefore, Model B is selected for subsequent studies.

[Figure 5: see original paper] Grid independence analysis

## 3 Numerical Simulation Results Analysis

The mean wind pressure coefficient $C_p$ is used to describe roof surface pressure distribution:

$$C_p = \frac{P - P_0}{\frac{1}{2}\rho U_H^2}$$

where $P$ is the pressure difference between the measurement point and upstream flow, $U_H$ is the mean wind speed at the building reference height (24.7 m), and $\rho$ is standard air density. Positive values indicate pressure.

### 3.1 Roof Zoning and Mean Wind Pressure

The roof is divided into 33 zones for local pressure analysis: zones A1-A17 and A18-A33 represent closed areas, while zones B1-B10 represent cantilevered regions. Zones B11-B16 denote the main hall roof and zones B17-B20 denote the auxiliary hall roof.

[Figure 6: see original paper] Schematic diagram of roof subdivision

[Figure 7: see original paper] Schematic diagram of wind direction definition

Overall, the roof experiences negative pressure across all wind directions, with strong flow separation at the eaves causing negative pressure concentration. The cantilevered areas exhibit local positive pressure due to upward climbing airflow impact. Limited by space, typical wind directions of 0° and 270° are analyzed.

[Figure 8: see original paper] Mean pressure coefficient on roof upper surface at 0° and 270° wind directions

At 0° wind direction, the upstream slope is gentle, resulting in relatively small negative pressures overall. At 270°, the steeper windward slope causes large-scale positive pressure formation where airflow impacts the windward surface. The lower surface, comprising only cantilevered portions, shows overall negative $C_p$ values ranging from -0.4 to 0, with local positive pressure at windward locations due to upward climbing airflow.

### 3.2 Roof Wind Load Shape Coefficient

The wind load shape coefficient $\mu_s$ is commonly used in engineering practice to characterize roof wind loads:

$$\mu_s = \frac{\sum_{i=1}^{n} C_{p,i} A_i Z_i}{A Z_H}$$

where $C_{p,i}$ is the mean pressure coefficient for measurement surface $i$, $A_i$ is the area of surface $i$, $Z_i$ is its average height, $A$ is the total reference area, and $Z_H$ is the building reference height.

To quantify wind direction effects, six representative strips are defined across the roof. The variation of $\mu_s$ for each strip across wind directions shows that both 0°-180° and 180°-345° ranges exhibit initial increase followed by decrease, with overall negative values. The 0°-180° range shows some symmetry, while the 135°-240° range shows abrupt positive pressure changes.

[Figure 9: see original paper] Position of representative strips

[Figure 10: see original paper] Wind shape factors for strips under different wind directions

### 3.3 Influence of Rib Beams on Roof Regional Wind Field

Two configurations are defined: Model 1 with rib beams and Model 2 without. Analysis of typical wind directions reveals significant differences in flow field structure.

[Figure 11: see original paper] Wind field streamline and Y-direction speed for both models

At 0° wind direction, the cross-section shows similar vorticity distribution patterns, but differences exist near the rib beams. The interference effect prevents formation of vortex enhancement zones behind the beams. At 270°, substantial differences appear in wind speed and X-direction vorticity distribution above the roof and in the wake region. Without rib beams, the wind speed gradient is steep and vorticity distribution concentrated. The presence of rib beams creates a shielding effect that reduces wind speed shear layer range above the roof and eliminates diagonal velocity contours.

[Figure 12: see original paper] X-direction vorticity for both models

### 3.4 Quantification of Rib Beam Interference

To quantify the interference effect, an interference factor (IF) is defined:

$$\mathrm{IF} = \frac{C_{p,\text{with rib}} - C_{p,\text{without rib}}}{C_{p,\text{without rib}}}$$

where $C_{p,\text{with rib}}$ is the mean pressure coefficient with rib beams and $C_{p,\text{without rib}}$ is that without rib beams. IF values between -1 and 1 indicate shielding effects, while values beyond this range indicate amplification.

[Figure 13: see original paper] Interference factor for mean pressure coefficient of partial subdivisions under different wind directions

The interference factor distribution shows that rib beams generally provide shielding (IF between -1 and 1), with the most significant reduction occurring at 270° wind direction. The effect is most pronounced in the roof top region. However, under special wind directions where the angle between rib beams and incoming flow is small (0°-30° and 135°-210°), local amplification occurs with rapid positive-negative pressure alternation. Peak IF values reach -3.8 and 3.7, indicating substantial local pressure amplification.

## Conclusion

This study employs CFD simulation to investigate wind loads on a large-span cantilever roof with protruding rib beams. By analyzing flow fields and pressure distributions with and without rib beams under typical wind directions, the influence characteristics are obtained. The roof pressure distribution patterns reveal that strong flow separation and conical vortices at windward eaves cause negative pressure concentration. The canyon effect between rib beams and roof significantly affects pressure distribution, with protruding ribs causing local negative pressure increases and eave pressure concentration.

Key findings include: (1) Upper surface pressure shows symmetrical variation for 0°-165° wind directions, while lower surface zones exhibit asynchronous pressure variation trends with positive-negative transitions in some 180°-345° directions. (2) The interference effect of rib beams is significant, blocking airflow and preventing formation of vortex enhancement zones. (3) Flow field structures differ substantially between the two models, with rib beams causing vorticity transition from positive to negative above cantilevered areas and reducing wind speed shear layer range. (4) Rib beams generally provide shielding effects, most notably at 270° wind direction with strongest effects in the roof top region. (5) Special wind directions with small angles between rib beams and flow cause local pressure amplification with rapid positive-negative alternation, reaching peak IF values of 3.7.

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*Note: Figure translations are in progress. See original paper for figures.*