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CFD analysis of double-curvature roof using RANS and SAS

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SUMMARY:
The significant flexibility and light weight of double-curvature cable roofs make them highly sensitive to wind loads. The accurate evaluation of wind pressure distribution on these roofs is essential for understanding their aeroelastic behavior. This study presents computational fluid dynamics (CFD) simulations of the wind pressure distribution on a double-curvature roof. The evaluation is based on steady Reynolds-Averaged Navier-Strokes (RANS) and the Scale-Adaptive Simulation (SAS) approaches, validated with wind-tunnel data of a hyperbolic-paraboloid roof. The results show that both models can accurately predict mean wind-induced static pressures on the roof with an average deviation of 4.7 and 10.7%, respectively. In addition, the superior performance of SAS is highlighted in predicting the peak pressure coefficient.

Keywords: double-curvature, Scale-Adaptive Simulation (SAS), turbulence models

1. INTRODUCTION

In addition to their aesthetic appearance, double-curvature cable roofs have better stability and rigidity than the corresponding positive-curvature roofs. Examples of these roofs are hyperbolic-paraboloid cable nets and double-curvature cable domes. However, the significant flexibility and light weight make these structures highly sensitive to wind loads. Therefore, the accurate evaluation of the pressure distribution is essential for understanding the aeroelastic behavior of double-curvature roofs, especially with the lack of clear regulations in the current design codes for tensile structures in general and this form in particular. Several wind-tunnel experiments were performed to investigate the aeroelastic behavior of double-curvature roofs (Davenport and Surry, 1984; Rizzo et al., 2021). However, to the best of the authors' knowledge, the performance of CFD has not yet been systematically investigated for double-curvature roofs. Therefore, the objective of this study is to evaluate the performance of steady RANS and SAS in reproducing the wind pressure distribution for double-curvature roofs. The study is based on validation with wind-tunnel data of a hyperbolic-paraboloid roof by Davenport and Surry (1984).

1. WIND-TUNNEL EXPERIMENT

Davenport and Surry (1984) measured the wind pressure distribution on a hyperbolic-paraboloid (HP) roof, nearly circular in plan, in the Boundary Layer Wind Tunnel of the University of Western Ontario. As shown in Figure 1, the model dimensions are 0.349 m along the major axis and 0.333 m along the minor axis, with the rise and sag values equal to 0.0195 m and 0.0326 m, respectively. The exterior wall is defined by a circumscribing sphere of radius 0.1745 m, and a base radius of 0.1563 m. The mid-height of the roof H equals 0.095 m. The scale ratio of the reduced-scale model is 1:384. The reference mean wind speed at height H above the ground is 3.57 m/s, model scale. Roughness elements were placed upstream of the model to generate the turbulent boundary layer flow on "suburban" terrain. The aerodynamic roughness length $z_0 = 0.00135\ m$, model scale. The total statistical sampling time is 1 min (1 h in full scale).

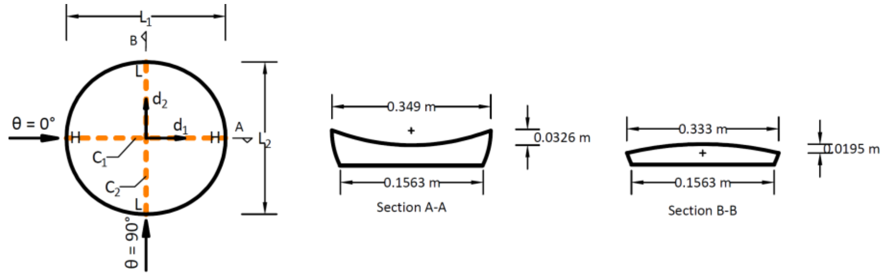

Figure 1. Layout, dimensions, and wind directions of the CFD model.

2. CFD SIMULATION

CFD simulations are performed at the model scale. The computational domain (CD) lengths upstream and downstream of the model are $5H$ and $15H$, respectively. The domain height is $6H$, while the lateral extension of the domain is $10H$ from both sides to maintain the blockage ratio below 3% as recommended by Franke et al. (2007). The computational grid is created by extruding the surfaces with a stretching ratio of 1.1 as shown in Figure 2a-c. The first cell height adjacent to the walls is 0.006 m. The turbulent kinetic energy k is calculated based on the measured data shown in Figure 3a, and the results at inlet and incident are shown in Figure 3b. The sand grain roughness height k_s and the roughness constant C_s are determined according to Eq. (1) derived by Blocken et al. (2007). For the ground surface, $k_s = 0.00265\ m$ and $C_s = 5$, while the building surface is smooth with $k_s = 0$ ($C_s = 0.5$). RANS simulations are performed considering four turbulence models: standard k-ε (Sk-ε), realizable k-ε (Rk-ε), renormalization Group k-ε (RNG k-ε), and Reynold Stress Model (RSM). For the RSM model, the Reynolds stress components are obtained from k assuming isotropy of turbulence (see Eq. (2)). For SAS, the vortex method is adopted to impose a time-dependent velocity profile at the inlet with the number of vortices equal to 2850. The time step is set at 0.0002 s. SAS simulations are initialized with RNG k-ε RANS simulation for 6 s, then statistical sampling is conducted for 60 s.

$$k_s = \frac{9.793 Z_0}{C_s} \quad (1)$$

$$\overline{u_i'^2} = \frac{2}{3}k\ , \overline{u_i' u_j'} = 0.0\ (i, j = 1,2,3) \quad (2)$$

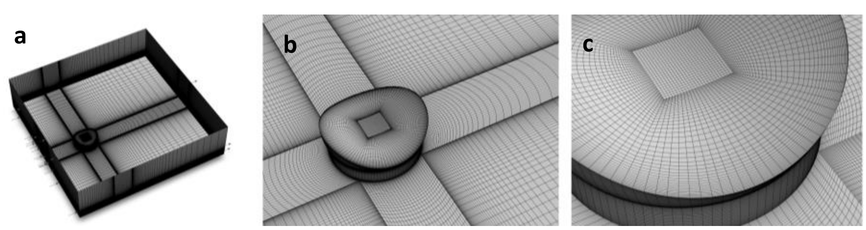

Figure 2. Computational grid (a) at bottom and side faces of CD, (b) at building surfaces, and (c) near edges.

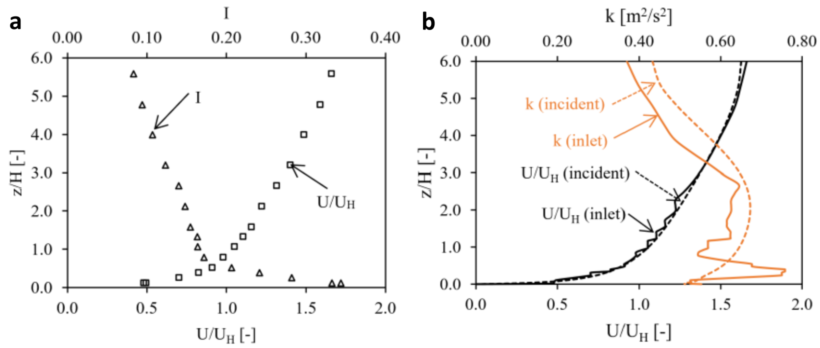

Figure 3. (a) Measured profiles of normalized mean wind speed U/U_H and turbulence intensity I (Davenport & Surry, 1984). (b) Inlet and incident vertical profiles of U/U_H and turbulent kinetic energy k using RNG k-ε for 0˚.

3. RESULTS AND DISCUSSION

Figure 4a-d compares the wind-tunnel data with the RANS result of wind pressure coefficient along curves C_1 and C_2. As shown in Fig. 1, C_1 is the concave curve between the highest points on the roof and C_2 is the convex curve between the lowest points. The comparison is performed for two wind directions: 0˚ (parallel to C_1) and 90˚ (parallel to C_2) based on the validation metrics recommended by Schatzmann et al. (2010). The sensitivity of the RANS turbulence models is more pronounced along C1, where the flow detaches at the highest edge of the roof. The realizable and standard k-ε models overestimate the suction at the detached region, while the RSM overestimates the pressure at the middle of the roof. The results of RNG k-ε are generally very close to the wind-tunnel data with a maximum average absolute deviation of 0.047. Fig. 5a compares the results of the RNG k-ε model with SAS at 0˚ wind direction along C_1. It can be seen that both RANS and SAS can predict the mean pressure variation on the roof with an average absolute deviation of 0.047 and 0.107, respectively. A fairly good agreement can also be seen for the peak pressures predicted by SAS and wind tunnel (see Figure 5b).

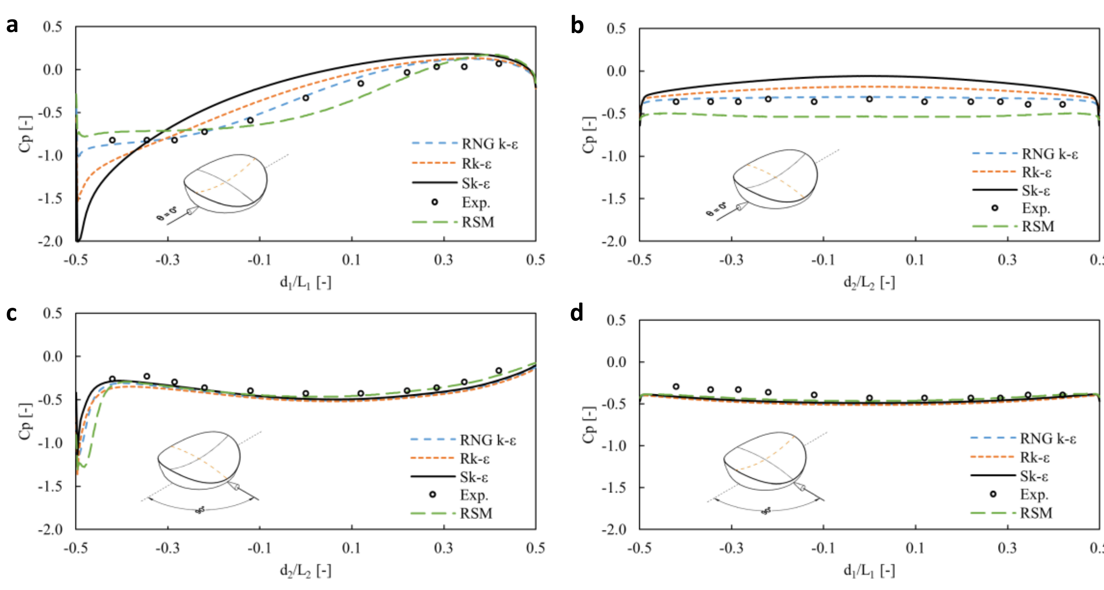

Figure 4. Impact of turbulence model on CFD simulation results of pressure coefficient (C_P), along (a) curve C_1 and (b) curve C_2 at $\theta = 0°$, and along (c) curve C_2 and (d) curve C1 at $\theta = 90°$.

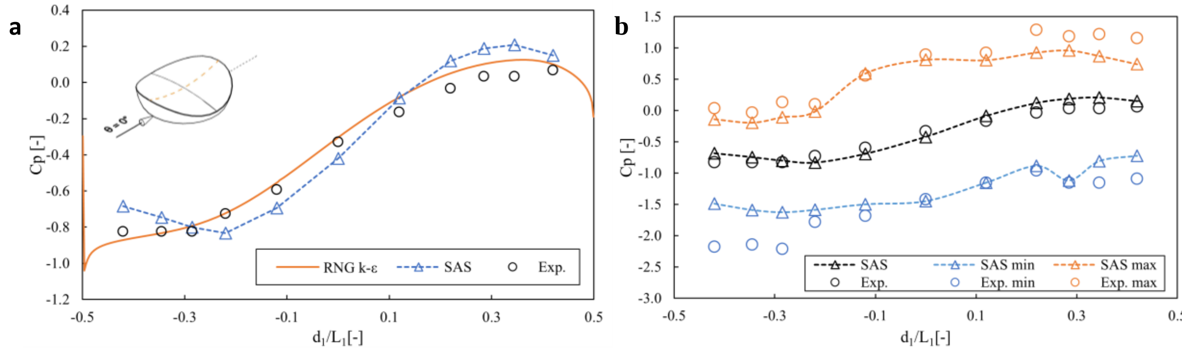

Figure 5. (a) Mean and (b) peak C_P along C_1 at $\theta = 0°$. Comparison between RANS, SAS, and experiment results.

5. CONCLUSIONS

This study evaluates the performance of steady RANS and SAS in predicting the wind pressure distribution on large span double-curvature roofs. The evaluation is based on a sensitivity analysis for the turbulence model and on validation with wind-tunnel measurements of a hyperbolic-paraboloid cable roof. The simulations are performed for two approaching wind directions. The results show that both models can accurately predict mean wind-induced static pressures on the roof with an average deviation of 4.7 and 10.7%, respectively. In addition, the superior performance of SAS is highlighted in predicting the peak pressure coefficient.

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