CWE-8
June 7-11, 2026
London, ON, Canada

Aerodynamic Characterisation of Tensile Membrane Canopies: CFD-Based Reference Pressure Coefficients

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Summary

Tensile membrane structures exhibit wind responses that depend strongly on their geometry, yet design standards offer limited guidance for such forms. This study uses numerical modelling validated with existing wind tunnel data to examine wind pressure distributions on several representative membrane geometries, including hypar, ridge–valley, arch-supported, cone, umbrella and cone array canopies. Scaled wind tunnel experiments provide detailed pressure fields that are used to validate a numerical wind tunnel developed through CFD. Once validated, the model will be applied to idealised geometries and extended to selected Fluid–Structure Interaction (FSI) simulations to assess the influence of membrane deformation. The aim of this work is to produce comparable pressure coefficient maps and displacement fields that illustrate the aerodynamic sensitivity of each geometry and support future improvements in structural design guidance for lightweight membrane roofs.

Keywords: *tensile membrane structures; wind tunnel testing; computational fluid dynamics (CFD); lightweight structures*

1 INTRODUCTION

Tensile membrane structures are increasingly used in public spaces, sports facilities, temporary installations and lightweight roofing applications. Their appeal lies in the combination of architectural freedom, efficient use of material and relatively simple construction processes. At the same time, their behaviour under wind loading is strongly determined by their geometry. Although standards such as Eurocode EN 1991-1-4 European Committee for Standardization (2005) offer a general framework for wind loading, their guidance for membrane structures remains limited. Designers often have to rely on simplified shape categories or adopt conservative assumptions, which highlights the need for more detailed and shape-specific information on wind pressure coefficients. In this context, initiatives such as the "Round Robin Exercise 3" proposed by the TensiNet Working Group Specifications, which aims to collect reliability indexes for basic tensioned structures TensiNet (2015), further illustrate the need for coordinated efforts and shared datasets. Studies such as Colliers et al. (2016) have shown that doubly curved membrane shapes exhibit specific wind-pressure patterns, indicating that standardized pressure fields for these geometries must adequately reflect their characteristic behaviour.

This work contributes to this broader effort by examining several commonly used membrane geometries—hypar, ridge–valley, arch-supported, cone, umbrella and cone arrays canopies (Figure 1)—through both experimental and numerical approaches.

As part of the experimental campaign carried out under the ERIES WENSS project, wind tunnel tests were performed on seven rigid 1:25-scale models equipped with surface pressure taps embedded within hollow bases and supported by legs used to accommodate the pressure tubing and stabilise the structures during testing. Measurements were taken for wind directions between 0° and 180° in 10° increments, with additional tests at 45° and 135°, and pressure coefficients were derived from static and dynamic pressure readings. These datasets (Bletzinger et al. (2024))

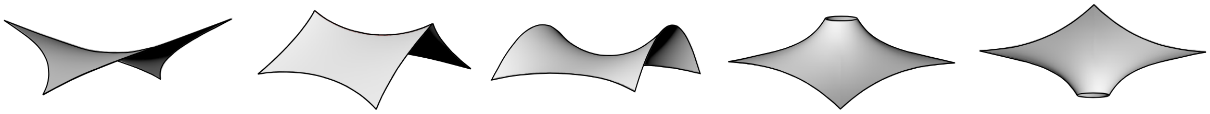


Figure 1: From left to right: Hypar, ridge-valley, arch-supported, cone and umbrella.

provide the foundation for validating the numerical models in the next phase of the study.

Pressure coefficients were calculated as in Eq.1:

$$Cp = \frac{p - p_{inf}}{\frac{1}{2}\rho U} \tag{1}$$

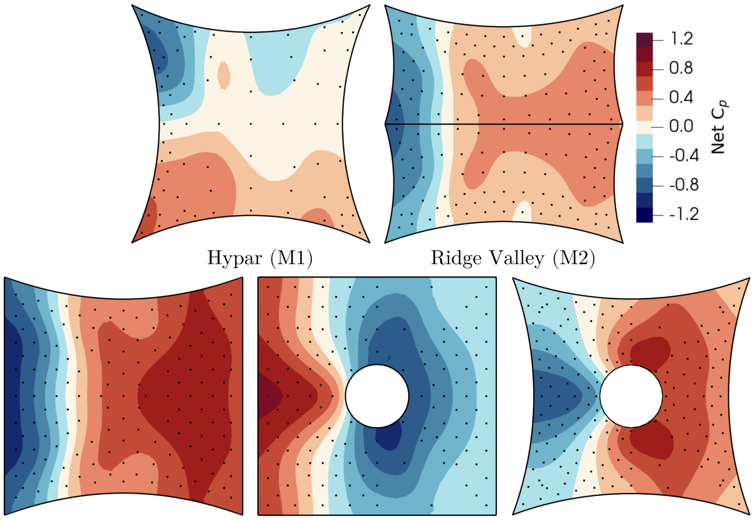
where p is the measured surface pressure, p_{inf} is the reference static pressure, and $\frac{1}{2}\rho U$ the dynamic pressure associated with the reference velocity U.

The investigation proceeds through three components:

1. CFD simulations calibrated against the experimental measurements
2. extended CFD simulations with additional angles of attack and aspect ratios of the initial structures
3. Fluid–Structure Interaction (FSI) analyses to examine how deformation affects the aerodynamic response.

The overarching goal is to produce pressure and displacement fields that illustrate the aerodynamic sensitivity of different geometries.

Figure 2 shows the pressure coefficient maps obtained from the Wind Tunnel results.



Hypar (M1) Ridge Valley (M2)

Arch Supported (M3) Cone (M4) Umbrella (M5)

Figure 2: Pressure coefficient maps for the different structures studied in the wind tunnel.

2 NUMERICAL METHODOLOGY

A Computational Fluid Dynamics study was performed, reproducing the inlet conditions and turbulence characteristics used in the physical tests. The first phase of the numerical work focuses on validation.

For this validation phase, the models in the simulation are identical to the ones in the wind tunnel to ensure that the numerical geometry aligns with the experimental setup. After the validation stage, simulations will be extended to the same geometries but without the supports that they need in order to be tested in the wind tunnel, allowing the aerodynamic behaviour of the idealised membrane forms to be examined without interference from support components—conditions that are not achievable in the physical wind tunnel.

The numerical wind tunnel is implemented using Kratos Multiphysics, Ferrándiz et al. (2024), an open-source finite element framework. The simulations employ a Variational Multiscale (VMS) formulation. No-slip boundary conditions are applied on the membrane surface and on the wind-tunnel floor, while a turbulent inlet velocity profile and appropriate outlet conditions reproduce the physical test environment. The pressure coefficient is derived from the net surface pressure, computed as the combination of the top and bottom faces of the geometry.

A mesh independence study was performed to ensure that the spatial discretisation is adequate for capturing the relevant aerodynamic features. Different mesh resolutions were tested, and the resulting forces acting on the structure were compared across refinements. The selected mesh therefore represents a compromise between accuracy and computational efficiency.

3 RESULTS AND DISCUSSION (PLANNED WORK)

The first part of the planned work concerns the validation of the numerical model. This process is currently underway, and will involve detailed comparisons between CFD predictions and wind tunnel measurements from Kodakkal et al. (2025), including surface pressure distributions and sectional plots for selected regions (see Figure 3).

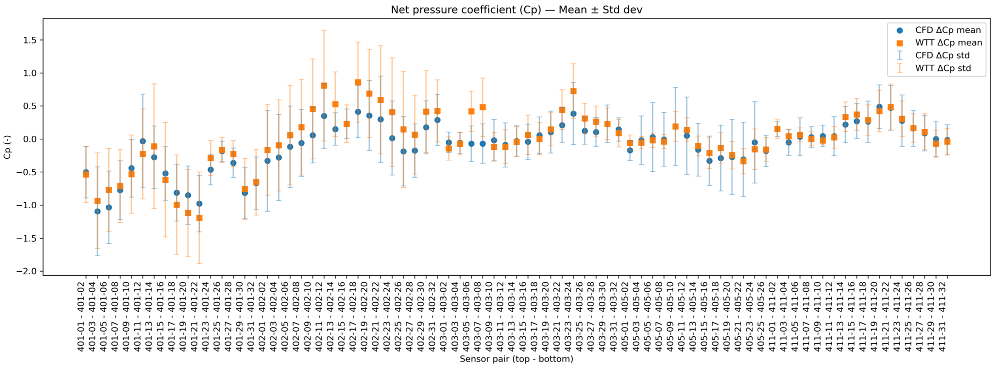


Figure 3: Comparison of mean net pressure coefficient (ΔCp) and std. deviation between CFD and WTT.

The mean values show the same trend and similar with the standard deviation values. The observed standard deviations reflect the high inflow turbulence intensity (20%), which enhances pressure fluctuations; lower values are typically reported in studies performed under smooth inflow conditions with negligible turbulence intensity.

A second component of the study focuses on the influence of geometry. Once the validation phase is complete, the full set of membrane configurations will be analysed numerically. Particular attention will be given to identifying shape-dependent pressure patterns, characteristic suction zones and flow features that may be relevant for the development of design guidelines.

4 CONCLUSIONS AND OUTLOOK

This study combines wind tunnel data and CFD modelling to investigate the wind response of tensile membrane structures. The numerical wind tunnel has been implemented and the validation process is ongoing, with preliminary comparisons showing consistent agreement with the experimental measurements.

The next steps will extend the numerical campaign beyond the validation stage. First, the CFD framework will be applied to idealised geometries without the support elements required in the wind tunnel. The simulations will also be expanded to include additional angles of attack, aspect ratios and geometric variations.

Finally, the study will incorporate fluid–structure interaction. Selected geometries will be analysed using two-way FSI to evaluate how membrane deformation influences the aerodynamic response. Comparisons between rigid and deformable configurations will be performed using pressure coefficients, displacement fields and associated aerodynamic metrics.

The expected outcomes include geometry-specific pressure coefficient maps, a comparative assessment of aerodynamic behaviour across forms, insights into the role of structural flexibility, and data that may support future refinements of standards such as Eurocode EN 1991-1-4.

ACKNOWLEDGEMENTS

This work was carried out within the framework of the European project ERIES (Engineering Research Infrastructures for European Synergies), funded by the European Union.

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