August 27-31, 2023
FLORENCE - ITALY
ICWE 16
16th International Conference on Wind Engineering

Aerodynamic studies for standardized pressure maps on double-curved freestanding membrane roof canopies

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SUMMARY:

The fast construction and material efficiency of lightweight textile structures makes them an ideal solution for a wide range of situations, from building roofs to provisional or permanent structures in public spaces. However, their lightness also makes them vulnerable to wind loads. Despite the increasing usage of such structures, there is still a lack of standardized wind loading to consider for their design, being necessary to assess specific geometries case by case. This study investigates five representative shapes (hypar, tent, barrel, upward umbrella, and inverted umbrella), in an effort towards a standardized guide to design membrane roof canopies subjected to wind actions. Our project makes use of an extensive numerical campaign employing a formulation of the flow based on the finite element method, implying a large eddy simulation approach for modelling turbulence. The respective shapes are assumed to be completely rigid and are tested as freestanding structures. Additionally, an atmospheric boundary layer wind condition for an open-type terrain is assumed. We provide mean pressure and standard deviation maps of the pressure coefficient for the baselines shapes, as well as highlight deviations due to changes in aspect ratio or configuration.

Keywords: lightweight structures, CFD, LES

1. INTRODUCTION

Our work presents recent aerodynamic studies by means of computational wind engineering in order to standardize pressure maps on double-curved membrane roofs. The project aims at freestanding constructions, which are a typical use case when covering public spaces or leisure venues. Most norms and standards only marginally address the load assessment for such geometries. Typical shapes can be observed in case of cable net structures as well as membrane canopies, with the geometry being mechanically defined by the level of prestress. For high levels of such forces, the structures can be considered rigid, which is the assumption for the current investigation as well.

Multiple famous examples of freestanding canopies inspire this investigation. Works – such as the Tanzbrunnen in Köln (1957, membrane), the Olympic Stadium Roof in Munich (1972, cable net) or the inverted umbrellas in the Haram Plaza in Medina (2010, deployable membranes), as seen in Fig. 1 – have motivated numerous engineering advances, including the research activities at our institute. Particularly, our group has contributed with various numerical methods on formfinding, analyzing the nonlinear behavior of structures, and computational approaches to wind engineering (Péntek et al, 2022).

Figure 1. Iconic double-curved freestanding canopies: Tanzbrunnen in Köln (1957, upper-left, SL-Rasch), Olympic Stadium Roof in Munich (1972, lower-center, SBP), Haram Plaza in Medina (2010, upper-right, SL-Rasch).

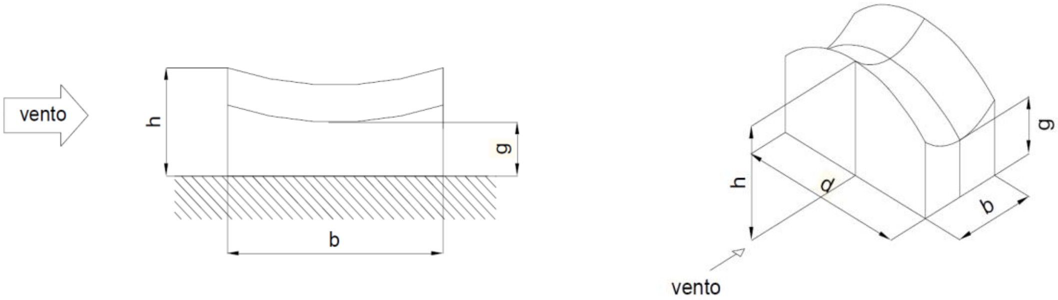

Figure 2. Excerpt from the *Instructions for the evaluation of wind actions and effects on constructions*, provisions related to external pressure on hyperbolic paraboloids, here with a rectangular plane shape.

Urban planning favors simpler variations of the structures and shapes above, which substantiate the need for standardizing design, including the effects of wind. As such constructions are often used in public spaces or events hosting many people (inner courtyards of schools, logistic hubs, leisure resorts, exhibition venues), a resource-efficient yet safe design needs to be supported. Recent efforts include multiple contributions by Rizzo since 2009 (Rizzo et al, 2009-2022), which resulted in specific content included in the *Instructions for the evaluation of wind actions and* *effects on constructions* (Consiglio Nazionale delle Richerche, 2019), a regional document amending the Eurocodes in Italy, with an exemplary snippet as seen in Fig. 2. The insight is non-exhaustive, as recommendations are mostly related to external pressure on enclosed spaces covered by hyperbolic paraboloids. Various other works address selected aspects, but there is still a clear lack of a systematic study and respective guides for planning.

2. METHODOLOGY

Our study covers five generic shapes – hypar, tent, barrel, upward umbrella, inverted umbrella, as seen in Fig. 3 (Goldbach, 2021) – which are deemed representative by the TensiNet work group, and specifically mentioned in the Round Robin 3 (RR3) call from 2015 (TensiNet, 2015) and its outcome (Colliers et al, 2016). We particularly focus on producing high resolution pressure maps, by providing the mean and standard deviation of the respective coefficient, so practicing engineers and scientists can make use of them for similar design scenarios.

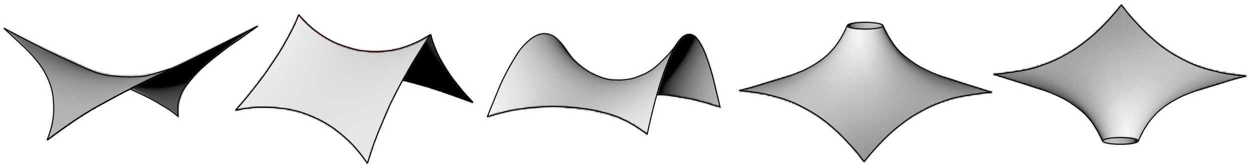

Figure 3. Representative shapes as the focus of the current study (based on RR3): hypar, tent, barrel, upward umbrella, inverted umbrella (from left to right).

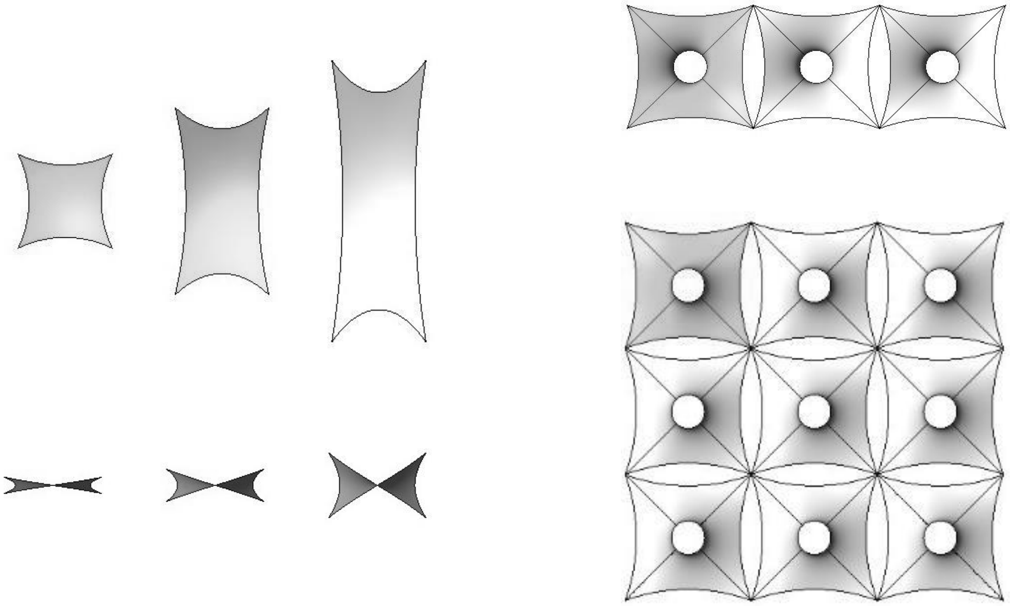

Figure 4. Planned scenarios and configurations as part of numerical simulations on rigid roof canopies, exemplary shown on the hypar and upward umbrella: changes in horizontal shape ratios (upper-left), changes in vertical shape ratios (lower-left), grouped configurations row-like (upper-right), grouped configurations square-like (lower-right).

We employ a large eddy simulation-type approach, numerically investigating these shapes at their real geometric scale. Wind scenarios include smooth flow as well as natural turbulence present in the atmospheric boundary layer. Apart from the baseline dimensions, we investigate variations in local loading occurring due to changes in the aspect ratios. Our project also explores potential effects of grouped configurations, as seen in Fig. 4. The observed changes in loading are intended to be summarized in form of deviations from the baseline setting, defined as standalone, in open terrain, with the original proportions. The multitude of numerical simulations is supported by recent advances in simulation technology, with our contributions to the Kratos Multiphysics open-source project. SuperMUC-NG by LRZ supports the high performance computing resources needed for the vast simulation campaign.

3. OUTLOOK

We are carrying out a transient computational fluid dynamics simulation campaign to analyze wind loads on some of the most typical shapes for freestanding roof canopies. The objective is to layout pressure coefficient maps to assist with the planning and design of these structures, contributing with an additional step towards standardization. Several configurations and aspect ratios are tested to ensure that the results are not case dependent.

These results should serve as solid basis for further investigations. Proceeding developments will aim at investigating aeroelastic models, particularly their structural behavior and possible changes in loading patterns as a function of the prestress levels of such roof canopies. We are looking into options to further substantiate computational results with experimental wind tunnel tests.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Gauss Centre for Supercomputing e.V. (www.gauss-centre.eu) for funding this project by providing computing time on the GCS Supercomputer SuperMUC-NG at Leibniz Supercomputing Centre (www.lrz.de).

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