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SUSTAINABLE INNOVATION IN MINIMAL MASS STRUCTURES AND LIGHTWEIGHT ARCHITECTURES

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Pressure coefficient distributions for the design of hypar membrane roof and canopy structures

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Abstract

Membrane structures are used in the built environment as roof or canopy and must therefore be designed to resist the external conditions. Nonetheless, the topologies of membrane structures are not covered by existing wind load standards and relevant wind load distributions for the basic shapes of these structures are almost not available. To have a realistic analysis of the wind loading, wind tunnel tests can be performed for each design. However, due to the lack of resources or time, for many projects the wind analysis will be based on rough approximations by relying on conventional shapes in the Eurocodes, with applying very high safety factors or designing unsafe structures as risk. Therefore, this paper presents a study of the orientation and curvature dependency of the wind load distributions over hypar roof and canopy structures. This study is performed with a numerical wind tunnel, using CFD with Reynolds averaged Navier Stokes equations. The outcomes are summarised in pressure coefficient distribution plots for most important wind orientations for hypar roofs and canopies with different curvature. The presented pressure coefficient distributions can be used in line with the Eurocode to derive more relevant wind load estimations for hypar membrane structures. These wind load estimations will give the engineer information about the average response of these structures under wind loading and will facilitate more reliable wind design of membrane structures.

Keywords: CFD, Cp-distribution, Eurocode, Hypar, Tensile surface structures, Wind loading.

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1. Introduction

Membrane structures are mainly used in the built environment as a canopy structure or as part of a building roof. Therefore, they are subject to the elements and must be designed to resist them. In addition, due to the small self-weight, these lightweight pretensioned structures tend to be vulnerable to wind loading. However, standards for wind design of membrane structures do not exist. The basic anticlastic double curved geometries of membrane structures are not covered by the conventional building standards such as EN 1991-1-4:2005 (CEN, 2005) and even in literature very little studies are available.

1.1. Problem Statement

Membrane structures are used in different applications within the built environment and exist in a wide variety of double curved shapes and dimensions. These double curved shapes are not covered by the existing wind load standards, and the structural engineer has to perform dedicated wind tunnel tests or has to deal with approximations while considering the existing standards. Dedicated wind tunnel testing allows to obtain accurate wind loading, but is very expensive and time consuming. Due to lack of resources or time, wind tunnel testing is only conducted for large projects that have enough time and budget to conduct these tests. Consequently, for most projects the engineer has to make simplifying assumptions and approximations based on the wind load distributions for other shapes that are present in the existing standards. These assumptions will lead to over-dimensioned structures by applying conservative approaches and high safety factors or in some cases under-dimensioned structures that can jeopardise the safety of the users.

The need for general rules in wind design and for accurate wind load determinations over membrane structures has been stipulated in the past (Forster and Mollaert, 2004) (Gorlin, 2009) (Mollaert et al. 2016). The design of membrane structures will benefit from more accurate wind load estimations. Hereby, relevant wind pressure data is essential to conduct the analysis and design process in a reliable manner. Accurate wind load determinations over the 'typical' membrane shapes (hypars, cones, arch forms, and wave types) will allow the structural engineer to perform a more precise wind analysis and to design more efficient and safe membrane structures.

1.2. Outline

The paper starts with a brief introduction of the Eurocode procedure for determining the wind loads over conventional building structures, followed by an overview of the current state in wind design of membrane structures. The main part of the paper discusses the results of the numerical studies towards pressure coefficient (Cp) distributions over hypar roofs and canopies for different wind directions and for different curvatures. This study focusses on hypars with two high and two low corners because this shape can be considered the most basic shape of anticlastic double curved surfaces. The setup of CFD simulations is presented and the obtained wind loads are visualised by Cp-distribution maps. The paper concludes with a comment on the use of the presented Cp-distributions and identifies the additionally required studies in order to draft simplified Cp-distributions over hypar roofs and canopies in line with the Eurocode procedure for wind design of buildings.

2. Wind loading according to EC1 -part 1.4

EN 1991 Eurocode 1: *'Actions on structures'* and more particular, Part 1-4: General actions - Wind actions (CEN, 2005) gives a step by step calculation method to define wind loads over constructions with a height up to 200 m.

2.1. Wind interaction

The wind interacts with any structure that disturbs the free wind flow. During this interaction energy is transferred from the wind flow to the structure. The magnitude of the wind loads depends on amount of energy that is transferred during this interaction and thus the kinetic energy in the wind flow and the aerodynamic parameters of the structure relative to the wind direction. The kinetic energy of the flow is represented by the peak velocity pressure and the aerodynamic parameters are accounted for by pressure coefficients or Cp-values. The Eurocode prescribes a step by step calculation method to calculate the peak velocity pressure at the height of the eave of the roof and gives simplified Cp-distributions for the common building topologies, including flat and pitched roofs and canopies. The wind loads can then be easily computed by multiplying the peak velocity pressure with the Cp-distribution.

2.2. Cp-distributions

The Cp-distributions in EN 1991-1-4 are based on wind tunnel studies in a free flow field. The distributions are given for rectangular ground plans and are subdivided in zones based on geometrical proportions. For each zone, Cp-values are listed in tables, with different Cp-values given for different pitch inclinations in the case of pitched roofs and canopies.

For building roofs, the wind interacts only directly with the external face of the roof and indirectly with the internal face. The loads on these roofs have to be calculated by the summation of the pressure over the external and internal faces. The external pressure is computed by multiplying the external Cp-distribution with the peak velocity pressure at the height of the eave of the roof, while the internal pressure can be defined depending on the building permeability relative to the wind direction. The Eurocode presents external Cp-distributions for the most important wind orientations.

For open canopies, the Eurocode presents only net Cp-distributions, because the upper and lower face of open canopies are directly loaded by the wind. Therefore, these structures can be calculated by multiplying the net Cp-distribution with the peak velocity pressure at the height of the eave of the canopy. Mark that only one net Cp-distribution represents the maximal local values for all wind directions and that six load cases have to be considered. Two cases with the entire roof loaded and four cases with only one pitch of the roof loaded, respectively for net down acting and net uplifting pressure, are defined to cover all possible wind load distributions for canopies.

In addition, in the case of unconventional structures, the Eurocode prescribes that sufficiently safe assumptions have to be made while using pressure coefficients based on the provided data in the norm, or otherwise additional wind investigation is required.

3. Wind loading on membrane structures

The European Design Guide for Tensile Surface Structures (Forster and Mollaert, 2004) could be seen as a first step in the direction of a European Normative document for designing tensile surface structures. This guide emphasizes the need for accurate wind load distributions over the basic shapes of membrane structures as one of the main research priorities.

The current standards point out wind tunnel testing and CFD to study the aerodynamics and to obtain accurate wind load distributions over complex surfaces that are not covered by the current standards. Up to now few studies are performed towards wind load distributions over double curved membrane structures. In (Colliers et al., 2016) the available but fragmented Cp-distributions for these double curved membrane shapes are explored and summarized. This study identified a shortage in available data of wind load distributions over the basic membrane shapes. Due to the high costs of these specialised studies they are almost solely performed for very specific case studies and large-scale projects (Balz and Fildhuth, 2004) (Cook, 2011) (El-ashkar and Novak, 2004) (Irwin and Wardlaw, 1979) (Xuany et al, 2013). For the basic membrane shapes, studies are limited to some conicals (Hincz and Gamboa-Maruffo, 2016) (Nagai et al., 2012), umbrellas (Mall, 2014) (Michalski, 2009) and hypars with high and low points (Colliers, 2014) (Luo and Han, 2009) (Otto, 1954) (Sun et al., 2008) (Takeda et al. 2014) or with arched edges (Rizzo et al., 2012). In addition, recent numerical studies focus on fluid structure interaction frameworks (Kupzok, 2009) (Michalski, 2009) (Wüchner et al., 2006).

Currently, CEN TC 250 WG5 Membrane structures is preparing a technical document about the design and analysis of tensile membrane structures as the next step in the process for developing a Eurocode for membrane structures. In this context, there is need for relevant wind load distributions over the basic shapes of membrane structures in order to draft general recommendations in line with the current standards, which has already been stressed in the science and policy report - Prospect for European Guidance for the structural design of tensile membrane structures (Mollaert et al. 2016).

4. Cp-distributions for hyperbolic paraboloids

In this work, the aerodynamics of hypar roofs and canopies with different orientations and curvatures are studied in a virtual WT using CFD with Ansys Fluent.

The hypars are considered with a square ground plan and with different curvatures in line with the representation of Cp-distributions in the Eurocode. Hypars with a Shape Parameter (SP, sag divided by half the span) (Colliers, 2016) of 0.09, 0.18, 0.27 and 0.35 (Figure 1) are considered, as they directly correspond to pitch inclinations of 5°, 10°, 15° and 20° for the pitched roofs and canopies that are considered in the Eurocode.

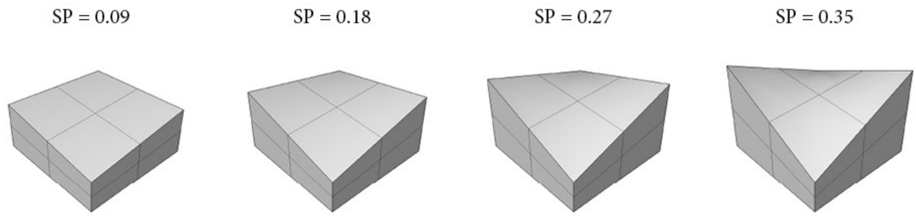

Figure 1: Hypars with an SP of 0.09, 0.18, 0.27 and 0.35 are considered to study the SP dependency of the Cp-distribution over hypar roofs and canopies.

The simulations continue on the numerical validation of previous experimental WT testing at a scale of 1/25. The hypar is considered to have a ground plan of 0,4m by 0,4m and the low corner at 0,13m high, what refers to 10m by 10m and the low corner at 3,25m high in reality.

The Navier Stokes equations are combined with the standard kε turbulence model. The fluid domain is modelled as a box of 2 m wide by 1 m high by 2 m long, with a velocity inlet, a pressure outlet, a no-slip floor, with symmetry top and symmetry side conditions. A uniform inflow over the height of 15 m/s, with a turbulence intensity of 1% is defined at the inlet. The floor has a 0-sand grain roughness. The grid is fully hexahedral and more refined close to the roof or canopy structure. Grid convergence is achieved with the smallest cells of approximately 5mm (Figure 2). Results are less qualitative by double cell sizes (10 mm) and do almost not improve by half the cell sizes (2.5 mm).

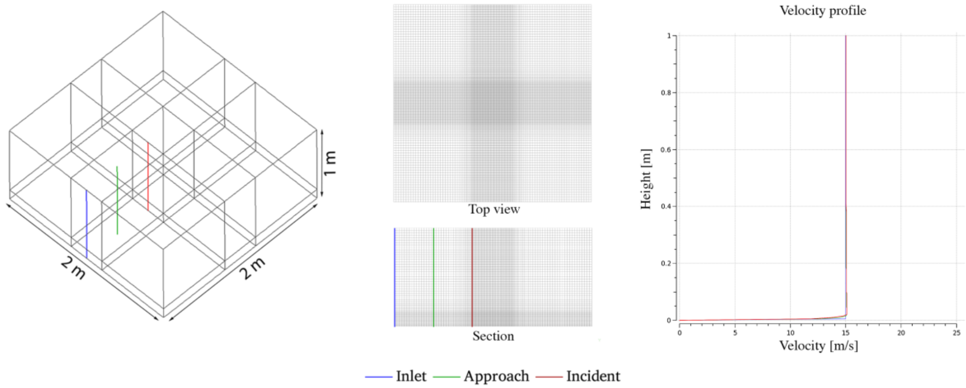

Figure 2: Mesh of the virtual wind tunnel in Ansys Fluent CFD and the velocity profile in the fluid domain.

The size of the fluid domain in these CFD simulations is rather small, because it results from the size of the test section of the WT that has been used in preliminar tests for the validation of the results. To confirm the accuracy of the results, the numerical studies are also performed at scale 1/1 and for a larger fluid domain in line with the best practice guidelines for CFD simulations of flows in the urban environment (Franke et al., 2007), and this for hypars with the lowest and the highest SP. Furthermore, the simulations are also run at lower wind speeds to verify the Reynolds independence. All simulations yield identical results, what indicates that hypars can be considered as bluff bodies and that the smaller fluid domain can be used to reduce computation time without jeopardising the accuracy of the results for the intermediate SP.

4.1. Orientation dependency

The orientation dependency of the Cp-distribution has been identified for a hypar roof and canopy with an SP of 0.09. The external Cp-distributions over the hypar roof are presented for different wind orientations, in steps of 15° ranging between the 45° with the high corner under attack and the 135° orientation with low corner under attack (Figure 3). For all orientations the hypar roof is entirely subject to suction, with highest suction near the upwind edges and corners. Mark that the asymmetric solution is the stable variant when the corner is under attack.

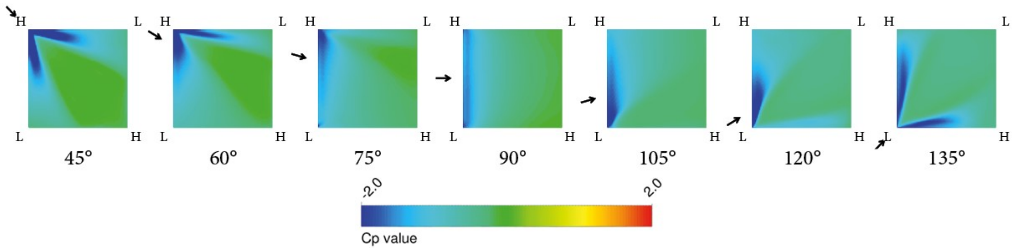

Figure 3: The orientation dependency of the Cp-distributions over a hypar roof with a SP of 0.09 with increments of 15 degrees in wind orientation.

The same sequence is shown for the hypar canopy, with Cp-distributions over the upper and over the lower face of the canopy separately (Figure 4). The Cp-values for hypar canopies have reduced significantly compared to the Cp-values for hypar roofs. Hypar canopies are not only subject to suction such as hypar roofs, but they are loaded by differential pressure and suction, depending on the local inclination of the roof relative to the wind flow.

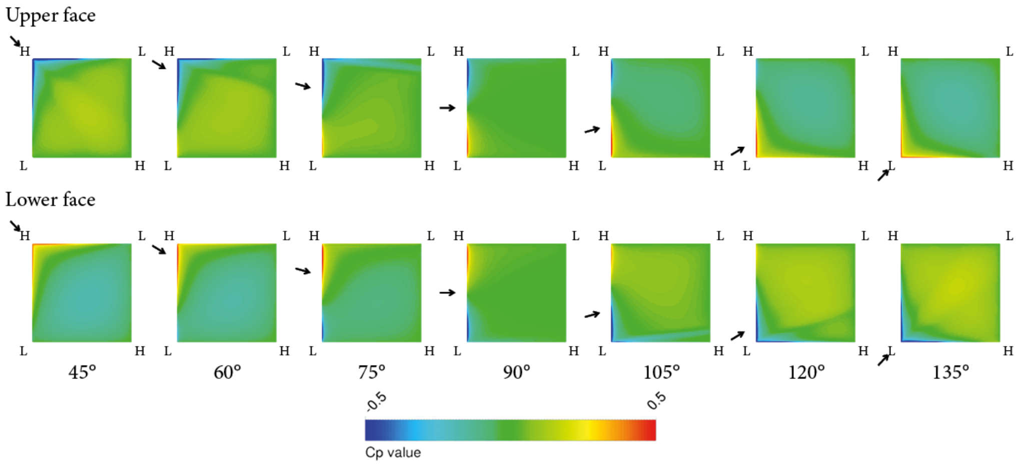

Figure 4: The orientation dependency of the Cp-distributions over the upper and lower face of a hypar canopy with a SP of 0.09 with increments of 15 degrees in wind orientation.

Three important wind orientations are identified for the hypar roof and canopy, respectively with the high corner under attack, the low corner under attack and with the leading edge perpendicular to the flow. Two of these orientations, respectively with the high and the low corner under attack were already proposed in the Design Guide (Forster and Mollaert, 2004) based on wind tunnel tests over a hypar roof with an SP of 0.18, done by Otto Frei in (Otto, 1954). Both orientations yield strongly different Cp-distributions with the highest absolute values near the upwind corners. The third orientation, with the leading edge perpendicular to the flow, should also be considered due to the highest total lift in the case of a roof, and the almost uniform net loading in the case of a canopy.

4.2. Curvature dependency

The SP-dependency of the Cp-distribution has been studied for hypar roofs and canopies for the most important wind orientations. Hypars with a SP of 0.09, 0.18, 0.27 and 0.35 are considered for this study, all with the same height of the low corner to span ratio in order to study only the influence of surface curvature on the Cp-distributions. Simulations are performed for the three important wind orientations that have been identified during the orientation dependency, respectively with the high corner under attack, with the low corner under attack and with the leading edge perpendicular to the flow.

The Cp-distributions for hypar roofs are more different with increasing SP (Figure 5). With the high corner under attack pressure develops near the downwind corner, while the suction zone spreads near the upwind corner. Only for the highest SP of 0.35, a significant reduction of suction near the upwind corner is observed, due to the local separation of the flow. With the low corner under attack, pressure develops at the upwind corner, while the highest suction zones move more downwind over the leading edges and suction increases in the middle of the roof.

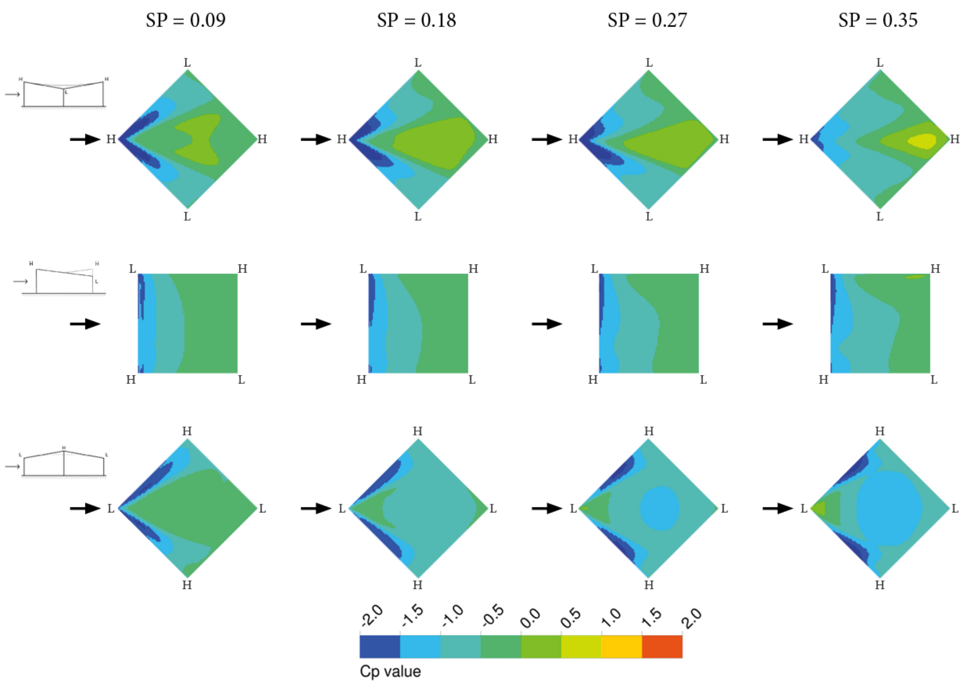

Figure 5: The SP-dependency of the Cp-distributions over hypar roofs with different SP for the three most important wind orientations.

For canopies, the Cp-distributions are also more pronounced with increasing SP (Figure 6). In general, rather similar changes take place as for hypar roofs, but for canopies the flow does not separate for high SP.

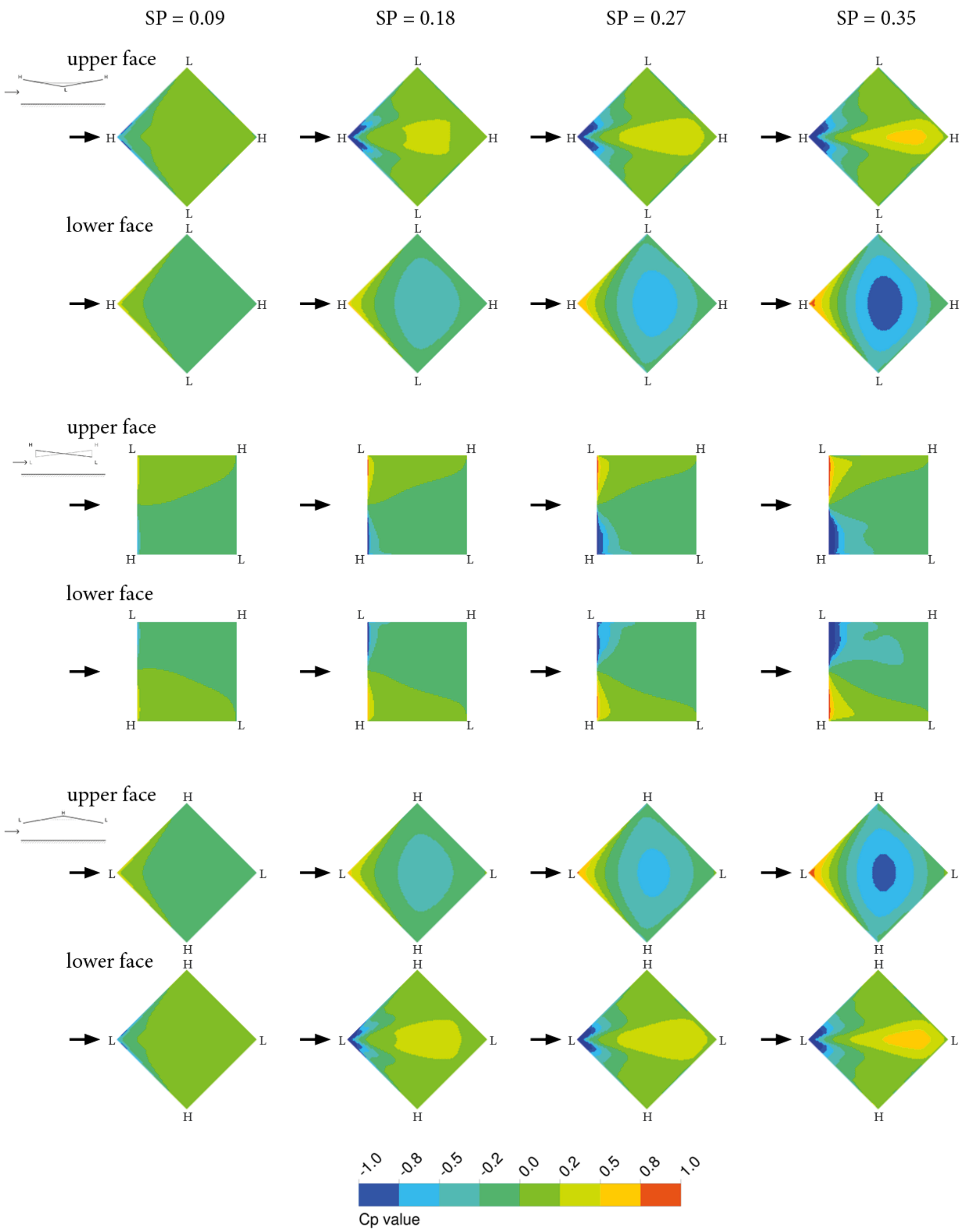

Figure 6: The SP-dependency of the Cp-distributions over the upper and lower face of hypar canopies with different SP for the three most important wind orientations.

5. On the use of Cp-distributions in line with the Eurocode

More studies are required in order to define simplified Cp-distributions that fully cover the wind load distributions over hypar roof and canopies in the same way as done for pitched roofs and canopies in the Eurocode. For example, different height of the low corner to span ratio will cause different displacements of the air flow and thus different Cp, especially when considering the atmospheric boundary layer.

With precautions the average results of these RANS simulations can be used for the design of hypar membrane structures with similar height of the low corner to span ratio. Furthermore, the presented Cp-distributions should be used in combination with the peak velocity pressure to account for the effects of wind gusts as established by the Eurocode for quasi static responses. Nonetheless, the accuracy of these gust loads and the influence of turbulence should be verified for aeroelastic responses of these structures, using extreme value analysis of real scale measurements, specialised WT tests or LES simulations.

6. Conclusion

This paper presents a clear overview of the orientation and curvature dependency of the Cp-distribution for hypar roofs and canopies under wind loading and could form a basis for further research on wind loading over the basic shapes of tensioned membrane structures within the scope of a prospect Eurocode on membrane structures.

The presented Cp-distributions can be used in line with EN 1991-1-4 to have information about the average response under wind loading of hypar membrane structures with similar height of the low corner to span ratio, but the influence of turbulence fluctuations on the Cp-values should be verified with extreme value analysis in further research.

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