Literature review

State-of-the-Art

Wind Loading on Tensile Surface Structures
Research Questions

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1. Problem Statement

During the last decades, the use of tensile surface structures has increased significantly. Since the design and the application of these structures developed fairly recently, a lot of expertise and research still has to be performed. Especially in the field of wind analysis accurate wind load determination has to be examined. Compared to conventional building typologies, these structures tend to be extremely vulnerable to wind because of the low self-weight-to-load-ratio. In addition, the structural engineer has to deal with uncertainties in wind load estimations for these organically shaped flexible structures, which implies the need for expensive wind tunnel tests or for simplifying assumptions and approximations during the calculation of membrane structures under wind loading. In general, conventional codes on wind design give upper bound values for the majority of structures, but the level of uncertainties increases as the building configuration deviates from the codified norms.

The structural analysis of membrane structures can only benefit from improved and more accurate wind load estimations and analysis methods. Currently wind loading on tensioned surface structures is often based on rough approximations referring to flat or spherical shapes of EN 1991-1-4, which does not account for the special nature of the textile covers. Extrapolation from the Standard is acceptable for conventional static structures, but for organically shaped flexible membrane structures additional wind investigation has to be performed. The European standards (EN 1991-1-4 and EN 13782 which refers to EN 1991-1-4 for wind loading) are insufficient for tensile surface structures, dynamic actions, flexible deformations etc. The need for accurate wind-load standards on these types of structures has already been stressed in several publications (Forster & Mollaert, 2004; Gorlin 2009a/b), stating the lack of the current standards in governing the wind-resisting strength for these structures and the need for an industry-wide set of standards. Appropriate wind pressure data is essential to provide confidence in the analysis and design process, and to ensure the development of the Eurocode that will facilitate the safe and efficient design of membrane structures.
2. Research questions in literature

The structural typologies of membrane architecture are ignored by the existing building regulations, even no information is provided about preliminary design or about wind loads (Rizzo et al., 2011). The design wind pressure coefficients depend on the geometry and the orientation relative to the wind’s angle of attack, which stipulates the need for more detailed investigations on the complex aerodynamic behaviour of double curved structures (Rizzo et al., 2012). Furthermore, the pressure coefficients are influenced by several parameters, such as type supporting system, load conditions, load paths, membrane stiffness pre-stress, and the deformations of structure (Nagai et al., 2010; Takeda et al., 2014).

When analysing the structural response of these structures, the gust effect factor which is function of the shape and the applied pre-stress in membrane should be taken into account (Nagai et al., 2012) together with the effect of aerodynamic mass and damping of the structure (Xuanyi et al., 2013; Sun et al., 2008). The wind induced response of a membrane structure as a result of the wind-structure interaction cannot be accounted by conventional static analysis methods (Sun et al., 2008). The dynamic properties of a three-dimensional spatial structure are very complicated. Extensive experimental and numerical studies are required to provide absolute conclusions on the wind-structure interactions of membrane constructions (Qingshan et al., 2010; Luo and Han, 2009).

Research questions as stated in Literature

- The structural typology of membrane architecture is ignored by building regulations, even no information is provided about preliminary design or about wind loads. (Rizzo et al., 2011)

- When defining wind loads, the buildings plan and height do play an important role (AOA). The measured pressure coefficients depend on the geometric shape, what stipulates the need for more detailed experimental investigations. (Rizzo et al., 2012)

- The design wind force coefficients are influenced by the supporting system, the load conditions, the load paths, the roof stiffness, the shape and the deformations of membrane structures. (Nagai et al., 2010) (Takeda et al., 2014)

- Wind-structure interaction is very complicated, extensive theoretical and numerical studies are required, and the number of experimental wind tunnel tests should be increased to provide absolute conclusions. (Qingshan et al., 2010)
• Dynamic properties of a 3D spatial structure are very complicated, more experiments and measurements are required. (Luo and Han, 2009)

• Wind tunnel tests on hyperbolic paraboloid roof structures have shown that double curved structures cause a complex aerodynamic behavior and three-dimensional vortex shedding should be considered. (Rizzo et al., 2011)

• The wind induced response of a membrane structure as a result of the wind-structure interaction cannot be accounted by conventional analysis methods. Importance of aerodynamic damping and added mass should be further investigated. (Sun et al., 2008)

• Take into account the effect of aerodynamic mass and damping when analyzing the structural response. (Xuanyi et al., 2013)

• The gust effect factor should take into account the initial pre-stress of membrane structure. The gust effect factor is function of the form and the applied pre-stress. (Nagai et al., 2012)

• In a physical experiment only point wise or integral quantities can be measured, whereas numerical simulation gives a very detailed spatial solution of the quantities of interest. Numerical experiments are much faster and less expensive and more easy for aero-elastic models. Need for accurate wind-structure interaction. (Rank et al., 2005)

• Full scale building monitoring could also lend valuable information to structural engineers in developing structural models. (Irwin, 2011)
3. State-of-the-Art

The European Design Guide for Tensile Surface Structures (Forster et al., 2004) could be seen as a state-of-the-art report and a first step in the direction of a European Normative document. This guide stipulates the determination of accurate wind loadings on lightweight tensile membrane structures as one of the research priorities, because Standards for the calculation and dimensioning of lightweight structures subjected to wind loading do not exist currently and in addition the exact structural behaviour of membrane structures under wind loading is not well known. Nowadays structural engineers have to deal with uncertainties in wind load estimations for these organically shaped flexible structures, which imply the need for expensive wind tunnel tests or rough approximations of the conventional Standards. However, for many projects (due to the lack of resources or time) the calculation of membrane structures under wind loading, will be based on simplifying assumptions and rough approximations of the conventional shapes in the existing building Codes. Therefore, being able to correctly estimate wind pressures will allow designing and analysing more accurately lightweight membrane structures.

Figure 1: \( C_p \) distribution for the wind directions 0°, 45°, 90° on a stadium roof (Forster et al., 2004).

Notwithstanding some studies have already been performed, there is still need for additional accurate and representative research on the wind loading of membrane structures. Up to now the wind analysis for membrane structures is rather limited, to external pressure coefficient distributions for conical or horn shaped membrane roofs (Burton and Gosling, 2003; Elnokaly et al., 2004; Nagai et al., 2012, 2011, 2010) and hypar roofs (Otto, 1954; Rizzo et al., 2011; Rizzo et al., 2012) both part of an enclosed building envelope, and some specific case studies (Baglin, 2002; Balz et al., 2004; Carradine, 1998; Cook and Buro Happold Engineers Ltd., 1981; Michalski et al., 2004) whether or not in combination with Computational Fluid Dynamics (CFD) or other numerical simulations.
On the other hand, the deformability and flexibility of the membrane structure should be considered incontestable in structures that deform significantly under external wind loading. Therefore, wind-structure interactions of aero-elastic models should be used for more detailed analysis of the sensitivity to the dynamics and side effects of wind loading on membrane structures. The interaction between the wind loading and the structural behaviour of the lightweight membrane constructions is a complex problem, causing the need for an integrated approach. In this field, experimental wind tunnel testing and/or computational fluid dynamics is often combined with structural finite element analysis to study the influence of wind loading on the structural behaviour of lightweight membrane structures. Wind tunnel testing and computational fluid dynamics are used to determine and analyse pressure coefficient distributions (Cp-values) on the surface of these double curved membrane structures, where after structural finite element calculations are used to monitor and analyse the interaction between the obtained wind pressure coefficients and the deformations of these pretensioned membrane structures.

**Wind Tunnel Testing**

There are three main approaches for experimental wind analysis of tensile surface structures (Figure 2), i.e. (a) direct pressure measurements during wind tunnel testing on rigid models, (b) direct measurements of the overall reaction forces by load cells during wind tunnel testing on rigid or aero-elastic models, or (c) a combination of optical measurements during wind tunnel testing on aero-elastic models and numerical fluid-structure analyses.

Direct pressure measurements on rigid wind tunnel models (a) generally performed when the membrane structure could be considered to deform very little under external wind loading which would not cause significant variation of the wind pressure coefficients. These direct pressure measurements are usually performed using pressure tubes that are placed inside the model. For open shell-like structures the tubes affect the flow field and hence other techniques should be used. The common procedure to measure the...
reaction forces (b) of a wind tunnel model is to use strain gauges. The application of these sensors is tedious and calibration issues are important. For the deformation of flexible (aero-elastic) wind tunnel models (c), the photogrammetry technique is mainly used (Chang, 2007). In addition, two other state-of-the-art measurement techniques (digital image correlation and scanning laser Doppler vibrometry) allow obtaining an accurate full field displacement measurement of the flexible structure.

In (Nagai et al., 2012, 2011, 2010) the wind load on basic horn-shaped membrane roof structures is investigated. Wind tunnel testing is performed on single and multi-bay models to study the influence on the pressure coefficient distribution of configurations of units linked one to another. Rigid models are used to measure the mean, maximum and minimum wind pressure by turbulence intensities of 16% and 25% with pressure transducers. The single and multi-bay models are tested in open and enclosed configuration, with the multi-bay models organised in configurations of 3 by 5 and 5 by 5 units. Pressure coefficients are presented for each configuration with shape parameters of 1,25; 2,5 and 5,0 for an angle of attack of 0° and 45°. The pressure coefficient distributions of the cone with a shape parameter of 2,5 are specified in Round Robin exercise 3 (Colliers, under preparation), in open and enclosed configuration for an angle of attack of 0°.

In (Rizzo et al., 2014, 2012, 2011) the aerodynamics of hyperbolic paraboloid (barrel vault) membrane roof structures is investigated. Rigid models are used to measure the mean, maximum and minimum wind pressure with pressure transducers. Pressure coefficient distributions are presented for a low-rise and a medium-rise model with various shapes of floorplan (circular, square and rectangular) and shape parameters (8,5 and 14,1 for the models with a circular and square ground plan; 6,7 and 11,2 for the models with the rectangular ground plan), for an angle of attack of 0°, 45° and 90°. The pressure coefficient distributions of the barrel vault with a shape parameter of 6,7 are specified in Round Robin exercise 3 (Colliers, under preparation), in enclosed configuration for an angle of attack of 0° and 90°.

In (Takeda et al., 2014, 2012, 2009) the wind force coefficients for hyperbolic paraboloid membrane roof structures are investigated. Rigid models are used to define the overall wind force coefficients. The force coefficients are calculated from the reactions measured with a force balance. Overall pressure coefficients are derived for three models (shape parameters
2,825; 4,25 and 8,5), for an angle of attack of 0°, 15°, 30°, 45°, 60°, 75° and 90°. The structural response of the hyperbolic paraboloid roof with a shape parameter of 2,825 is evaluated analytically for three different supporting systems (stiff frame of perimeter girders and binding beams, stiff frame of perimeter girders without binding beams and suspension model with perimeter cables) by accounting the overall pressure coefficients for an angle of attack of 0° and 90° in Finite Element Analysis.

In (Sun et al., 2008) the aeroelastic behaviour of pretensioned saddle-shaped suspended roofs is investigated. Wind tunnel testing is performed on a rigid and a flexible model. The mean and fluctuating (RMS-values) wind pressure is measured for both models with pressure transducers, while for the flexible model also the vibration characteristics are measured by touch acceleration sensors. Pressure coefficient distributions and the amplitudes are presented for models of a membrane structure with a shape parameter of 3,0 for an angle of attack of 0°, 45° and 90°.

In (Qingshan et al., 2010) the static and dynamic interaction between membrane structures and the wind environment is investigated. The added mass and the aerodynamic damping are studied separately by presenting a method to isolate them from the coupled mass and coupled damping of the structure, which includes its structural mass and structural damping. Wind tunnel testing is performed on four hyperbolic paraboloid roof structures, being two cable-net and two membrane models with a shape parameter of 4,0 and 6,0. The displacements are recorded with acceleration sensors and non-contacting laser displacement sensors. Damping ratios of the first three vibration modes of both models are presented in relation to the wind velocity, for an angle of attack of 0°, 45° and 90°.

In (Kawamura and Kiuchi, 1986) the wind resistant design of pneumatic membrane structures is investigated. Wind tunnel testing is performed on rigid and flexible pneumatic structures. Rigid models are used to measure the mean and fluctuating wind pressure with pressure transducers, while flexible models are used to evaluate the damping characteristics and the behaviour (deformations) of the membrane under fluctuating wind pressure with an eddy current type non-contacting measurement system and optical measurements. Pressure coefficient distributions, static displacements and amplitudes are presented for a low-rise and a high-rise model, respectively with a shape parameter of 0.15 and 0.75, for an angle of attack of 0°.
Computational Fluid Dynamics

Numerical simulations could give a very detailed spatial solution of the quantities of interest, whereas in a physical experiment only point wise or integral quantities can be measured. Furthermore, numerical experiments are less expensive and moreover feasible for aero-elastic models (Rank et al., 2005). The numerical simulation of two way fluid-structure interaction (steady or unsteady) based on finite volume Computational Fluid Dynamics in combination with Finite Element Analysis, or Smoothed Particle Hydrodynamics in combination with Dynamic Relaxation, has been studied by many authors (Hart et al., 2010; Degroote et al., 2012; Andre et al., 2015). Two way coupling is required for detailed analysis of membrane structures that deform significantly under wind loading, causing modifications in the flow regime (Wüchner et al., 2006). However, few research groups are using numerical fluid-structure interaction simulations taking into account the deformation of the membrane structure. One example is a case study with a 29m high umbrella (Michalski et al., 2011, Takeda et al., 2014) by confronting the numerical outcome with wind tunnel tests and real scale measurements.

Special care has to be taken into account for the description of the atmospheric boundary layer flow (e.g. Blocken, 2007). In most cases the natural wind flow is simulated by Reynolds Averages Navier-Stokes equations extended with Large Eddy Simulations turbulence. In addition, a finite number of sinusoidal perturbations of the considered thin structures could be superposed on incompressible fluid flows to analyse their fluid-structure interaction explicitly (Andre et al., 2015).

R. Wuchner developed a methodology that combines structural and fluid calculations for organically shaped membrane structures. In (Wüchner, 2006), the focus is on flexible software environment for numerical simulations of membrane structures, and more specific on the underlying computational dynamics of the fluid-structure interactions for these structures. In his methodology he approaches the fluid-structure interactions by flexible modular software environment. The partitioned approach considers the multi-field problem of formfinding, structural analysis and fluid-structure interaction as a relation between formfinding and fluid-structure interactions as well as the influence of flexibility on this relationship. He developed an algorithm that allows coupling between Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) through a Mesh-based parallel Code Coupling Interface (MpCCI). The geometry and the behaviour of the structure are linked by nonlinear analysis with a reference updating strategy for the formfinding of the mechanically determined equilibrium shape. Therefore, the wind flow is modelled as incompressible Reynolds Averaged Navier Stokes (RANS) equations with Large Eddy Simulations (LES) in the CFD module and the structural behaviour is calculated with geometrically nonlinear elastodynamics in the CSD module. The algorithmic coupling is
discretised in time. The mechanically determined equilibrium shape of the CSD is used as input for the CFD calculations, the output of the CFD is translated into external net-loads representing the wind loading, the net-loads are applied in the CSD in order to define the new equilibrium shape under this load case, and the process is repeated. For highly flexible membrane structures the process has to be iterated several times because the large deformations of these membranes influence the flow field significantly, which leads to a new surface wind load that results in a change of the structural response. The proposed partitioned coupling model, which describes the fluid-structure interactions for membrane structures accounting for geometry and structural behaviour, establishes a fundamental basis for solving structural and fluid procedures within the coupled differential problems of membrane structures. A continuous integrated approach would give better solutions for parametric designs and analysis of coupling strategies concerning stability, accuracy and robustness. However, the partitioned approach allows focussing and controlling both individual modules, while the computing power remains manageable.

In (Kupzok, 2009) the methodology of R. Wuchner is further developed and applied in a case study of the ARIES canopy. A. Kupzok developed a new central coupling tool CoMA that performs the data transfer between the CSD and CFD software. The central coupling field allows single-field solvers to be used in multi-field simulations. This coupling field contains all information about the degrees of freedom on the fluid structure interaction interface and organises for each time-step update the discretised data exchange between the single field solvers. Furthermore, CoMA allows the exchange of mesh-based data between non-matching discretisation CSD and CFD, with parallelisation of single field solvers to
reduce computation time by partitioning the solution in smaller parts. Pressure coefficient distributions, velocity vectors and deformations are presented for the two main wind orientations of the ARIES canopy, being an angle of attack of 0° and 180°.

**Figure 4: Data exchange in central coupling scheme CoMA (Kupzok, 2009).**

In (Luo and Han, 2009) a wind-induced time-history response analysis is conducted for a hyperbolic paraboloid cable-membrane structure. The stochastic 3D coupling wind field model is derived by the spectral representation theory, considering the correlations of the three orthogonal turbulent components. The time-history analysis shows that the wind load response is 10% to 25% larger for this correlated turbulence model compared to the uncorrelated models, but that the modified wind pressure does not change significantly. Therefore, the modified wind pressure can be omitted, while the turbulence components should be considered for wind-induced vibration analysis. In this paper, pressure coefficient distributions are presented for hyperbolic paraboloid canopy with a shape parameter of 12.1 for an angle of attack of 0°, 15°, 45°, 60°, 75° and 90°.

In (Takeda et al., 2014, 2012, 2009), in addition to wind tunnel testing on rigid models, the wind force coefficients for hyperbolic paraboloid membrane roof structures are also investigated for flexible models to study the effect of roof deformation due to wind loads by numerical analysis. CFD is used to determine the mean wind force coefficients, which
on their turn are applied in the structural analysis to calculate the deformed membrane roof, where after the process is retaken till convergence is achieved. Overall pressure coefficients, derived for three models (shape parameters 2,825; 4,25 and 8,5), for an angle of attack of 0°, 15°, 30°, 45°, 60°, 75° and 90°, showed good correspondence to the wind tunnel data. Pressure coefficient distributions are presented for the first and the second iteration of the three models for an angle of attack of 0°.

In (Sun et al., 2012) a numerical approach on the time-dependent fluid-structure interaction for tension structures with large displacements is proposed, based on a partitioned solution approach of CFD and CSD. The structural response of a membrane structure under wind loads is analysed by three components: the static response as change of geometry under mean wind pressure, the steady response as motion of large scale eddies and the transient response as dynamic magnification of the fluctuating wind. For the static and steady interactions the wind pressure change due to structural deformation is evaluated by CFD simulations, while for the transient interaction the resonant response is evaluated by nonlinear random vibration analysis. The maximum displacements are presented for a flat, a single-curved convex, a single-curved concave and a hyperbolic paraboloid membrane roof structure (with a shape parameter of 10,0 for the single-curved roofs and 8,0 for the hyperbolic paraboloid roof).

**Current state**

Two substantial problems we are dealing with nowadays are: (i) how accurate is wind design while applying wind load estimations based on rough approximations referring to conventional building typologies from the existing codes, and (ii) to which extent are we designing safe structures by relying on the conservative static approach and ignoring the fluid-structure interaction due to the flexibility of the structure. Additional qualitative and quantitative analysis is required towards the form and pretension dependence of the fluid-structure interaction, and more specific the influence of curvature and flexibility on the pressure coefficient distribution for doubly curved membrane structures. Therefore membrane structures should be investigated on several influencing parameters to fully cover these flexible structures and their behaviour under wind loading. Parameters such as: open/enclosed, rigid/flexible, pretension, curvature et cetera could be investigated by experimental wind tunnel testing and/or Computational Fluid Dynamics both coupled to computational structural dynamic analyses.
4. Bibliographical References

Codes and Guides
Colliers, J., Mollaert, M., (under preparation). Round Robin exercise 3 - Collating wind data for the basic shapes of tensioned surface structures.

Wind Tunnel Testing

Computational Fluid Dynamics

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