A new hybrid: elastic gridshells braced by membranes

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Abstract

Deployable elastic gridshells are cost-effective lightweight structures making use of a rapid construction process, in which the geometry of the gridshell is obtained by bending an initially flat grid. This particular shaping process saves time during the erection of the structure, as the grid rods must not be bent individually but the grid can be shaped as a whole. Moreover, the assembly of the connections between the superposed rod layers of the grid can be done on the ground on a flat geometry, which is easier than connecting single elements in the air. Nevertheless, in order to introduce shear stiffness to the initially unstable grid lattice, an additional layer of beam elements or diagonal cables must be added. The assembling of this bracing layer is usually time-consuming and requires additional supplies such as cherry-pickers or movable scaffolds. In this manner one of the great advantages – the rapid deployability of elastic gridshells – is clearly reduced.

In order to accelerate the construction process of deployable elastic gridshells, we propose to use covering textile membranes as stiffening and at the same time cladding surfaces. In this paper, we study the structural behaviour of an elastic hemispheric gridshell braced with a membrane layer. Different connection configurations between membrane and grid have been analysed and the results have been compared with traditional bracing systems.

Keywords: elastic gridshells, bracing membrane, hybrid structure, active-bending, finite element modelling.

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1 Introduction

Developable elastic gridshells are cost-effective lightweight structures making use of a rapid construction process, in which the geometry of the gridshell is obtained by bending an initially flat grid. This particular erection process saves time and costs, as the grid profiles must not be individually bent but the grid can be shaped as a whole. Moreover, the connections between superposed grid profiles can be assembled on the ground in the initially flat geometry, which is easier than joining them in the air [1–4].

Nevertheless, after the bending process, the grid must be additionally braced in order to provide the structure with in-plane stiffness. Usually the bracing members consist of a third outer layer of diagonal profiles, tensile cables or rigid panels. The assembling of this bracing layer is generally more time-consuming than that of the grid, as the multiple bracing elements must be individually handled, connected in the air to the grid nodes and, in case of using diagonal profiles, bent into the gridshell geometry. In this manner one of the great advantages of elastic gridshells – its rapid construction through developable grids – is clearly reduced.

In order to optimise the construction process of developable elastic gridshells, we propose to employ a unique membrane surface to cover and at the same time to restrain the grid, by connecting the membrane to the grid nodes. Thus, fewer elements must be handled on site, less time is needed for the construction process and material savings are achieved.

The use of tensile membranes as restraining element has been already investigated in hybrid arch structures with stress-free curved and elastically-bent chords in [5–7]. Tensile restraining membranes can efficiently reduce deformations by hybrid structures. Their influence on the global bearing behaviour of the structures strongly depends on the material and sectional properties of the structural elements and stiffness, pre-stress and orientation of the membrane.

In this paper, the potential and limitations of using tensile membranes to restrain elastically-bent gridshells are investigated. The influence of the membrane and grid properties has been analysed first numerically on a 4-field grid and then numerically and experimentally on a hemispheric gridshell of 5 m diameter.

2 Structural effect of restraining membrane on a 4-field grid

The restraining effect of tensile membranes and the influence of the membrane properties on it have first been studied on a 2 m x 2 m 4-field grid. The shear stiffness of the 4-field grid, restrained with different elements and membranes with different properties, has been analysed by means of finite element modelling using the FEA-software Sofistik. The 4-field grids have been punctually loaded by applying horizontal forces on their upper corner and the corresponding deformations have been compared.

2.1 Description of the structure

The 2 m x 2 m 4-field grid is composed of two superposed crosswise layers of three continuous profiles each. The intersections between the layers take place every 1 m. The material of the profiles corresponds to GFRP (E-Modulus = 25.10^3 N/mm^2), their section is tubular with a diameter of 20 mm and a thickness of 3 mm. The connections between superposed profiles allow scissoring – variation of the angle between profiles – of the grid fields.

The restraining effect of the tensile membrane has been compared with that of plywood panels, diagonal steel cables and glass fibre reinforced plastics (GFRP) profiles (Figure 1). All the restraining and bracing elements are connected punctually to the grid intersection points. The membrane and plywood panels have been modelled as plane elements, while the cables and profiles as tensile (they cannot carry any compression) and continuous beam elements, respectively. In the case of the membrane and plywood panels, contact between the grid profiles and the sides of the panels has been modelled using spring elements.

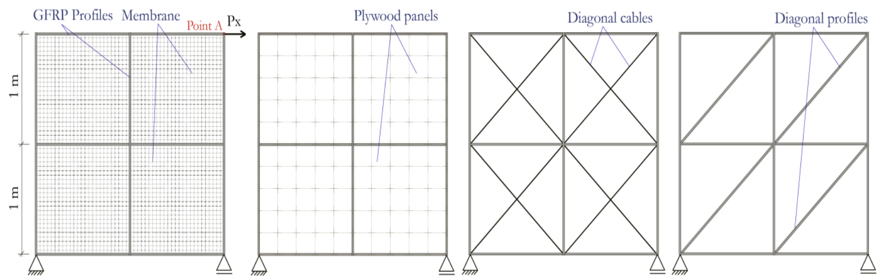

Figure 1: Structural system of the 4-field grid with different restraining elements.

In the following paragraphs the studied parameters and properties of the restraining elements are summarised:

1. <u>Membrane orientation</u>

Tensile membranes are usually strongly elastically anisotropic; their mechanical properties are different depending on the yarns' orientation. The influence of the membrane orientation has been analysed by comparing the shear stiffness of two grids, restrained with membranes whose warp and weft yarns are oriented diagonally and longitudinally.

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Restraining element	Material	Warp/weft orientation
1.a Membrane	*Polyester cloth, PVC/PVDF coating Typ III, thickness = 1.02 mm Pre-stress warp/weft = 0.1 kN/m E-Modulus warp/weft = 1000 N/mm²*	*Diagonal*
1.b Membrane	*(1020 kN/m) Shear modulus G = 30 N/mm² (30 kN/m) Poisson's ratio v = 0.25*	*Longitudinal*

2. Stiffness of restraining element

Membranes dispose of lower axial stiffness than diagonal cables, bars or rigid panels and can only carry in-plane forces so that using them as restraining elements only the shear stiffness of the grid can be improved. The mechanical properties of tensile membranes strongly vary depending on the nature of their components (yarn and coating). In order to investigate the influence of the membrane's stiffness on the shear stiffness of the 4-field grid, membranes with varying stiffness values have been modelled and their restraining effect has been compared with that of bracing diagonal cables, beams and rigid plane elements.

Restraining element	Material	Stiffness
2.a Membrane	*Polyester cloth, PVC/PVDF coating*	*E-Modulus warp/weft = 500 N/mm² (510kN/m)*
2.b Membrane	*Typ III, thickness = 1.02 mm Pre-stress warp/weft = 0.1*	*E-Modulus warp/weft = 1000 N/mm² (1020kN/m)*
2.c Membrane	*kN/m Shear modulus G = 30 N/mm²*	*E-Modulus warp/weft = 1500 N/mm² (1530kN/m)*
2.d Membrane	*(30 kN/m) Poisson's ratio v = 0.25*	*E-Modulus warp/weft = 2000 N/mm² (2040kN/m)*
2.e Diagonal Cables	*Stainless steel, d = 6 mm*	*E-Modulus = 130.10³ N/mm²*
2.f Diagonal Profiles	*GFRP, d = 20mm, t = 3 mm*	*E-Modulus = 25.10³ N/mm²*
2.g Panel	*Plywood F40/40 E60/40, t = 4mm*	*E‖ = 4400 N/mm², E⊥ = 4700 N/mm²*

3. Membrane pre-stress

Membrane surfaces represent light structural elements as they are supposed to carry only tensile forces. Loss of stress, and with it folding of the membrane due to compression forces, should be avoided, which is achieved by inducing tensile pre-stress on the membrane surfaces. With the tensile stresses, compression forces can be removed and the stiffness of the structure incremented. In the case of the 4-field grid, four models with different pre-stress levels of the membrane have been defined and the distribution of the principal membrane forces as well as the shear stiffness of the grid have been noticed.

Restraining element	Material	Prestress
3.a Membrane	*Polyester cloth, PVC/PVDF coating* *Typ III, thickness = 1.02 mm* *Pre-stress warp/weft = 0.1 kN/m* *E-Modulus warp/weft = 1000 N/mm² (1020 kN/m)* *Shear modulus G = 30 N/mm² (30 kN/m)* *Poisson's ratio ν = 0.25*	$v_{warp} = 0.1$ *kN/m,* $v_{weft} = 0.1$ *kN/m*
3.b Membrane		$v_{warp} = 1.0$ *kN/m,* $v_{weft} = 1.0$ *kN/m*
3.c Membrane		$v_{warp} = 1.5$ *kN/m,* $v_{weft} = 1.5$ *kN/m*
3.d Membrane		$v_{warp} = 2.0$ *kN/m,* $v_{weft} = 2.0$ *kN/m*

2.2 Results

2.2.1 Influence of membrane's orientation

The following graphic shows the nodal displacement at Point A (Figure 1) as a function of the applied horizontal point load on the 4-field grid, restrained with membranes with varying orientation of the warp and weft yarns. One can observe the much higher shear stiffness of the grid by orientating warp and weft in the diagonal restraining direction: by a horizontal load of 0.55 kN the nodal displacement at Point A results on 175 mm with a longitudinal orientation and 18 mm with a diagonal orientation of the fibres. Figure 3 illustrates the distribution of the principal membrane forces for both warp/weft orientations and shows the higher efficiency and performance of the diagonal orientation.

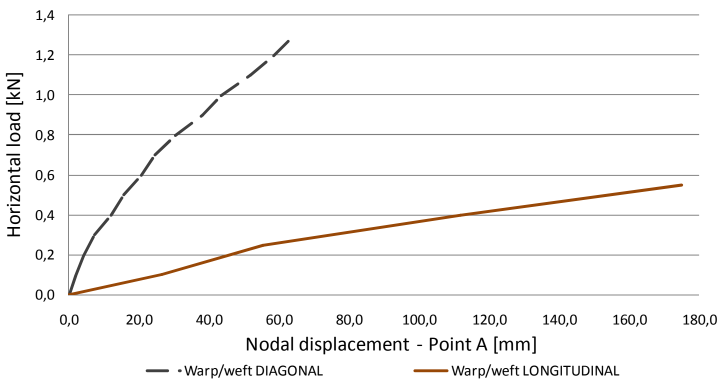

Figure 2: Nodal displacement at Point A by increasing horizontal point load in grids restrained with membranes with diagonal (blue) and longitudinal (red) orientation of the warp/weft yarns.

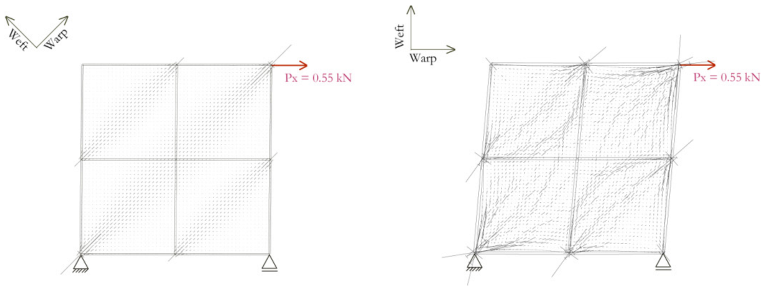

Figure 3: Distribution of principal membrane forces and deformation under horizontal load of 0.55 kN at Point A of the 4-field grid restrained with membranes with a diagonal (left) and longitudinal (right) orientation of the warp/weft yarns.

2.2.2 Influence of membrane's stiffness

In the following graphic, the influence of the membrane's stiffness ($E_{warp/weft}$ = 500–2000 kN/m^2) on the shear stiffness of the 4-field grid under a horizontal point load is illustrated and compared to that of the diagonal cables (d = 6 mm), diagonal GFRP-tubes (d = 20 mm, t = 3 mm) and F40/40-plywood panels (t = 4 mm). One can observe that with a higher membranes' stiffness, the restraining action of the membrane can be strongly increased. By a horizontal load of 1.15 kN, the nodal displacement at Point A corresponds to 113 mm, 55 mm, 39 mm and 28 mm for the membranes with elasticity moduli of 500 N/mm^2, 1000 N/mm^2, 1500 N/mm^2 and 2000 N/mm^2, respectively. Nevertheless, the restraining effect of the tensile membrane remains significantly lower than that of the diagonal cables, bars and rigid panels.

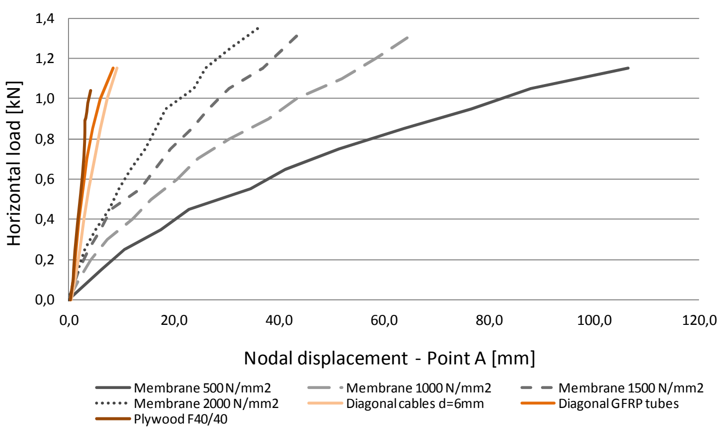

Figure 4: Comparison of restraining effect of tensile membranes of different stiffness, diagonal cables, diagonal GFRP tubes and plywood panels on the deformation of the 4-field grid under increasing horizontal point load in A.

The final choice of the membrane's stiffness should however consider its constructive consequences. The higher the stiffness is, the more complex the confection and handling on site of the membrane will be. Figure 5 illustrates the deformation – exaggerated of a factor of 2 by the membrane E = 500 N/mm^2 (left) and E = 2000 N/mm^2 (right) and 5 by the diagonal cables, bars and plywood panels – of the 4-field grid under a horizontal point load in A of 1.15kN.

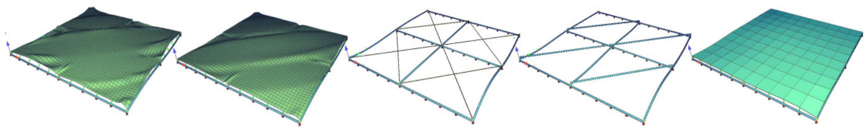

Figure 5: Deformation of 4-field grid, exaggerated by a factor of 2 by the membranes E = 500 N/mm2 (left) and E = 2000 N/mm2 (right) and 5 by the diagonal cables, bars and plywood panels under a horizontal point load of 1.15 kN in A.

2.2.3 Influence of membrane's pre-stress

The following figure illustrates the bearing capacity of the 4-field grid restrained with membranes with varying level of pre-stress ($v_{warp/weft}$ = 0.1, 1.0, 1.5 and 2.0 kN/m). For the pre-stress levels of 1.0, 1.5 and 2.0 kN/m, one can observe a kink in the nodal displacement curves at horizontal loads of 0.5, 0.7 and 0.9 kN, respectively, corresponding to the loss of tensile stress on the diagonal receiving compression forces. The deviation at point A by inducing higher pre-stress on the membrane could be reduced, for example under a horizontal load of 1.3 kN, from 58 mm with v = 2.0 kN/m to 40 mm with v = 0.1 kN/m.

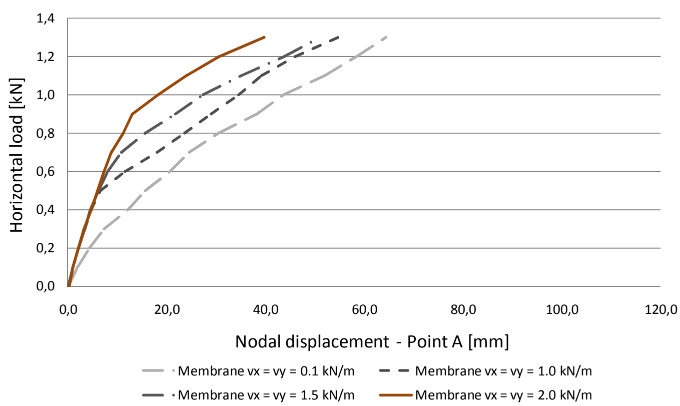

Figure 6: Nodal displacement at Point A by increasing horizontal point load in grids restrained with membranes with pre-stress levels in warp and weft of 0.1, 1.0, 1.5 and 2.0 kN/m.

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Figure 7 shows the principal membrane forces of the restraining membranes with pre-stresses of 0.1 and 2.0 kN/m for horizontal loads of 0.2, 0.8 and 1.3 kN. While for the first pre-stress level, the restraining effect of the membrane only acts on the diagonal carrying tensile forces, with the higher pre-stress level, the membrane is able to stiffen the diagonal subjected to compression forces until the tensile stress is consumed.

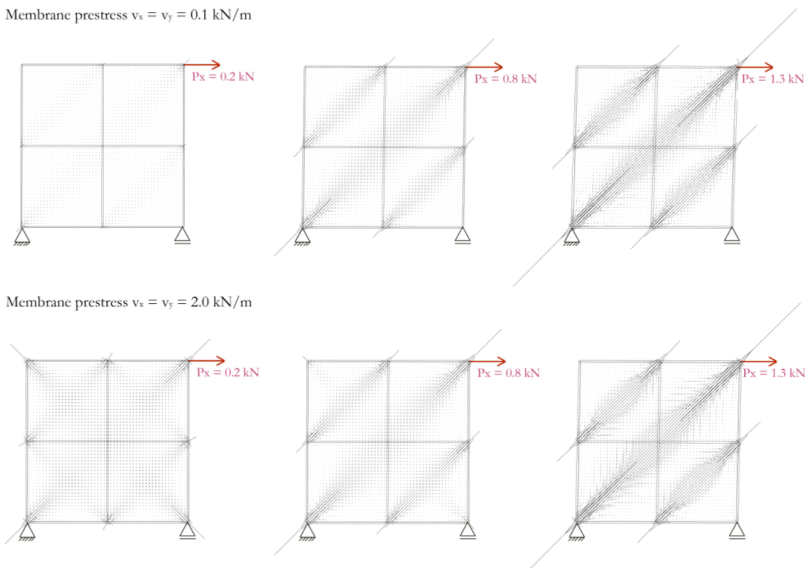

Figure 7: Principal membrane forces of restraining membranes with pre-stress of 0.1 and 2.0 kN/m for horizontal loads of 0.2, 0.8 and 1.3 kN.

3 Structural effect of a double-curved hemispheric elastic gridshell

The aim of this chapter is to investigate the restraining effect of tensile membranes on doubly-curved elastic gridshells. A hemispheric regular gridshell of 5 m diameter and 0.74 m mesh size has been considered as example. The analyses focus on the influence of the connection conditions between grid and membrane. Two cases corresponding to the covering membrane with and without joining at the grid nodes have been studied. The structural analysis has been performed using three-dimensional non-linear finite element models defined with the FEM-package of SOFISTIK.

3.1 Description of FEM-Model

Grid profiles have been modelled as beam elements and the membrane as plane elements. The grid profiles are made of glass fibre reinforced plastic (E = 25000 N/mm^2, d = 20 mm, t = 3 mm), the membrane corresponds to a Ferrari

Précontraint 1302 S2 with polyester cloth and PVC/PVDF coating (E = 1500/1200 N/mm^2, t = 1.02 mm). The connections between superposed layers have been modelled as hinged couplings.

Spring elements have been used for the connection between grid and membrane. Two types of spring elements have been defined to consider the different connection conditions. The first type corresponds to axial springs modelling the contact of the membrane over the grid. They are defined along all the beam elements, their direction is approximately perpendicular to the membrane surface, their axial spring coefficient is 10 kN/m and they can only carry compression forces. The second type corresponds to the connection of the membrane at the grid nodes. They are defined only at the intersection of the grid layers and their direction is also approximately perpendicular to the membrane surface. They have axial and lateral stiffness with coefficients of 10^3 kN/m. Fixed supports have been defined for the profiles' ends. The edge support of the membrane is also modelled using spring elements with axial and transversal coefficients of 1 kN/m. The spring coefficients of the connections have been defined after benchmarking the FE-model with the prototype described in section 4.

The FEM consists of two parts. Firstly, the bending process of the grid has been modelled. The bending of the beam elements has been generated applying virtual elements, inducing the deformation of the profiles. The form-finding methodology for active-bending structures suggested by Lienhard *et al.* in 2011 [8] has been used. This methodology consists on defining virtual cable elements with reduced elastic stiffness between the start and target positions of the profiles and pre-stressing them to generate the bending of the beam elements. Once the bent geometry of the grid has been simulated, the membrane can be activated and the loading of the structure can be modelled.

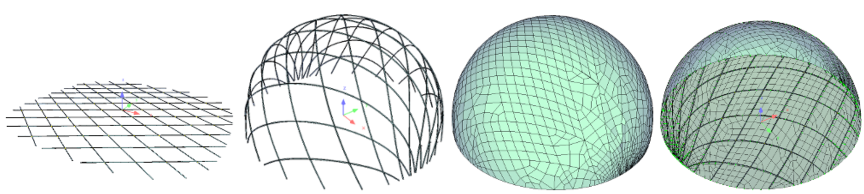

Figure 8: FEM-Model of hybrid elastic gridshell; (from left to right) planar grid's geometry, bent grid's geometry; hybrid gridshell from the outside and from the inside.

3.2 Study of the influence of connection between grid and membrane

The connection of the membrane to the grid has important consequences on the construction process of the gridshell. Therefore, it is important to be able to previously estimate its structural effects. In this chapter, the influence of the restraining membrane on the geometry resulting from the bending process and on the deformations under an asymmetric load case has been calculated and compared for three systems: grid without membrane, grid with membrane without connections to the grid and grid with membrane with connections to the grid at the intersections of the grid layers.

3.2.1 Influence on geometry resulting from bending process

Once the grid has been bent in a specific geometry, if the applied shaping forces are removed, the grid adopts a new equilibrium and a new geometry. Figure 9 illustrates the nodal displacement of the grid when the external forces are removed for the three configurations. One can see that using the membrane as restraining elements reduces the maximum nodal displacements from 50 mm to 24 mm and 19 mm, without and with joining between membrane and grid, respectively.

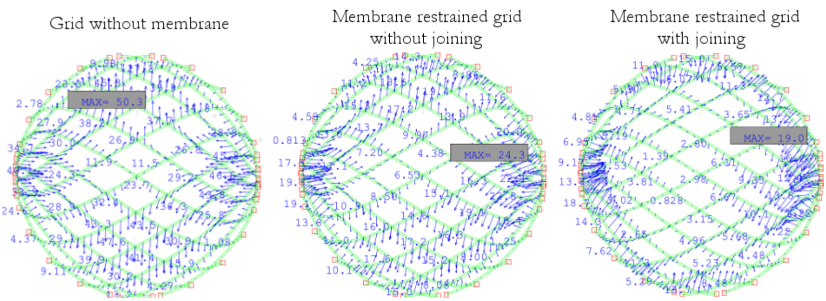

Figure 9: Nodal displacements of the grid by removing external shaping forces.

3.2.2 Influence on bearing behaviour

The restraining effect of the membrane is more evident under the action of external forces. As external load case, half of the grid has been loaded with vertical nodal loads of 0.2 kN in 47 intersection points (Total load = 9.4 kN, projected area = 9.8 m^2). Figure 10 shows the respective grid deformations. The membrane achieves to reduce the maximum nodal displacements of the grid from 189 mm to 90 and 30 mm, without and with joining between membrane and grid, respectively.

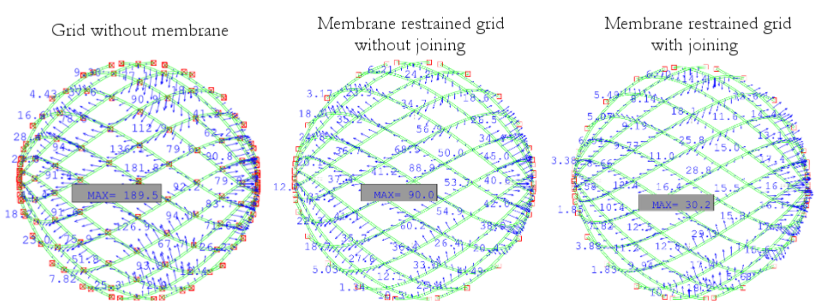

Figure 10: Nodal displacements of the grid under asymmetric load.

4 Construction of a prototype: hemisphere of 5 m diameter

The purpose of the prototype is to benchmark the FEM simulation and to detect and understand constructive difficulties by the construction of membrane restrained elastic gridshells.

4.1 Construction

The elements of the prototype correspond to those of the FE-model defined in Chapter 3: grid composed of glass fibre-reinforced plastic profiles of 20 mm diameter and 3 mm wall thickness and covering membrane Ferrari Précontraint 1302 S2 with polyester cloth and PVC/PVDF coating. Double swivelling clamps with inner rubber walls have been used to connect both grid layers. The prototype has been tested with and without connection between membrane and grid. On the first case, this connection was provided by threaded pins screwed on nuts welded on the upper clamps of the grid nodes and clamping washers. For it, the membrane was perforated with eyelets and reinforced at the 85 grid intersection nodes. The grid was fixed on a ring made of OSB-plates using single clamps, also the membrane by cording its edge on a PVC-tube.

The construction of the hybrid gridshell started with the assembling and bending of the initially plane grid by pushing it upwards and connecting the profiles' ends to the ring. Afterwards, the membrane was progressively spread over the grid and finally tensed and fixed to the ring. The hybrid gridshell was loaded with point loads of 10.3–18.9 kg applied on one half of its surface (asymmetric load). The deformations were registered using 3D-scanning.

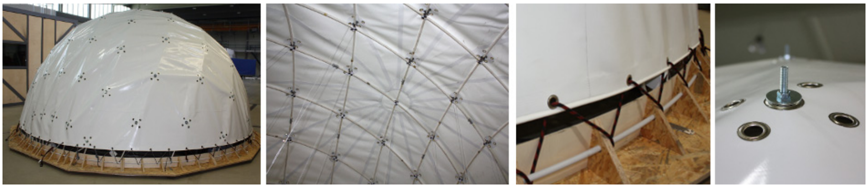

Figure 11: Prototype of the hybrid hemispheric elastic gridshell of 5 m diameter: outer and inner view, details at edge ring and grid nodes.

4.2 Results

For the finite element simulation of the bearing capacity of the prototype it is important to consider the real stiffness of the grid nodes' double clamps with inner rubber wall instead of using hinged couplings. Therefore, spring elements with respective axial and lateral coefficients of 10 and 1 kN/m have been introduced in the model. Only the case without connection between grid and membrane is considered here.

Figure 12 compares the nodal displacements of the prototype and the finite element model resulting from the asymmetric load case at 74 grid nodes. One can observe similar distributions; nevertheless, the values of the prototype are to some extent higher than those of the FE-model. Moreover, differences between both systems are lower on the middle profiles (e.g. number 5–7) than on the profiles at the sides (e.g. 1 and 11).

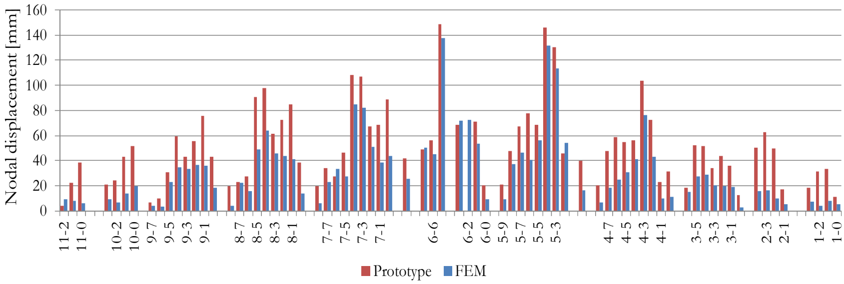

Figure 12: Comparison between prototype (red) and finite element model (blue) of nodal displacements at 74 grid nodes under asymmetric loading.

5 Summary

This paper has the aim to investigate the potential of tensile membranes as restraining element for elastic gridshells. Firstly, the influence of the membrane on the shear stiffness of a 4-field grid and, secondly, its effect on the bent geometry and bearing capacity under asymmetric loading of a hemispheric gridshell have been analysed by means of finite element modelling. An important increment of the grid's stiffness has been observed by membrane restrained systems.

To benchmark the finite element model, a prototype of the hemispheric gridshell with 5 m diameter has been built and loaded. On the one hand, constructive effects and limitations of the hybrid system were identified. On the other hand, the structural comparison of the prototype with the FE-model allowed determining the influence of certain parameters, such as the stiffness of the grid nodes or the pre-stress level of the membrane, on the bearing behaviour of the hybrid structure.

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