Design of Membrane Structure as a Temporary Roofing System

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Abstract. *This contribution is focused on the design analysis of membrane structure and finding an optimal shape of such structure due to the surrounding possibilities with using numerical modeling. The membrane structure is designed for roofing of the experimental stand, which is in the campus of Faculty of Civil Engineering, VSB – Technical University of Ostrava and is currently not protected against unfavorable weather conditions. Design of membrane structures as temporary or permanent roofing has recently become very popular because of its shape variability, very low weight, and possibility of large spans. However, in addition to aesthetic requirements, structural and dispositional requirements are also necessary to consider on the same level during the design. The aim of this paper is to give an overview of the design of the temporary membrane structure starting from the architectural visualization and continuing to deal with structural and dispositional parts of the design using the RFEM software which has special add - on module for nonlinear analysis of membrane structures, RF Form - Finding.*

Keywords

Membrane structures, tensile structures, lightweight structures, roofing system, form finding, numerical modelling, nonlinear analysis, RFEM software, Rhino software.

1. Introduction

Membrane structures combine surface material and supporting elements, mostly made of steel. When designing such a structure, the first step is to find the optimal shape [1]. This process is called Form – Finding. Form – finding process deals with finding the optimal deflection and visual shape based on the given boundary conditions. It is also important to find an optimal shape with respect to the pre-specified stress field [2, 3]. It is necessary to apply pre-stressing into the structure which prevents inversion of the curvature and after that, the structure can be loaded. The initial shape of membrane structure must be designed in such a way that only the tensile forces can occur in the structure [4, 5]. This paper is focused on design and analysis of membrane structure for roofing of the experimental stand in the campus of Faculty of Civil Engineering, VSB – Technical University of Ostrava [13] which can be seen in Figure 1.

Fig. 1: Experimental stand in the campus of Faculty of Civil Engineering, VSB – Technical University of Ostrava

This equipment has been designed for static load test according to CSN 736190 and other experiments for investigation into the stress/strain relations for soil/structure interaction and was built in 2010 [13].

Department of Structural Mechanics of the Faculty of Civil Engineering, VSB – Technical University of Ostrava started to be more interested in detailed research in task of membrane structures since 2018. After studies in field of numerical models of basic shapes of membrane structures and biaxial testing of textile materials used for these types of structures, here comes the first experience in the field of realization.

2. Form Finding approaches

Finding the optimal shape of the structures is closely related to determining the minimum area. There are two options of approaches to form finding process – physical approaches and numerical approaches [2, 3, 16, 17]. Physical approaches methods were used from the start of designing membrane structures many years ago when there was not such an option in computer field.

2.1. Physical approaches

For physical approaches, there are many ways which can be used for finding the optimal shape. These approaches are used mainly for communication between the members of the design team and as a verification of computational numerical models [6].

Textile models can be great option for finding the shape of membrane structure, verify stability and, also to see an aesthetic aspect (see Figure 2).

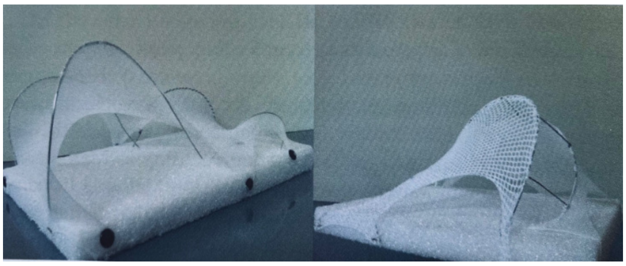

Fig. 2: Example of textile model [2]

Another way for physical approaches in form finding process Can be done by using reverse hanging models or soap film models (see Figure 3 and Figure 4).

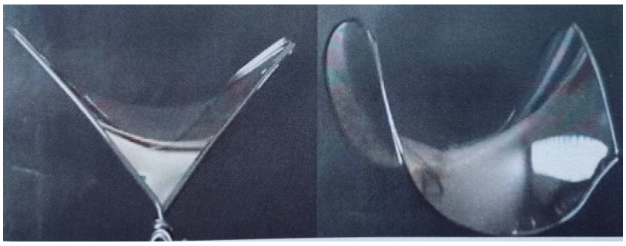

Fig. 3: Example of soap film model [2]

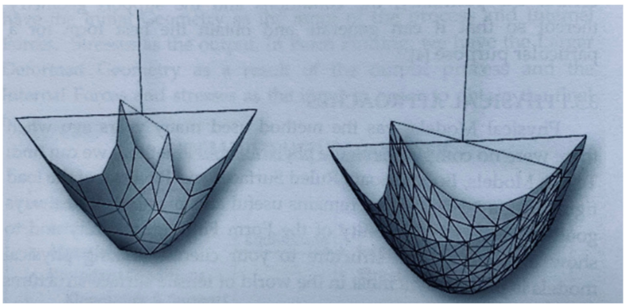

Fig. 4: Example of hanging model [2]

2.2. Numerical approaches

With the gradual development of computer technology, the computational methods were invented. Nowadays, thanks to these methods, it is allowed to design more complicated and larger structures. For numerical modelling, following methods can be used:

- Grid method [7],
- Dynamic relaxation method [6, 15],
- Force density method [8],
- Surface stress density method [9],
- Updated reference strategy (URS) [10].

For numerical analysis of the membrane structure for roofing the experimental stand, the structural analysis and design Software RFEM software was chosen because of its special add - on module, RF Form – Finding, which can find the optimal shape of the structure using URS method by K. U. Bletzinger and E. Ramma.

1) **Updated reference strategy (URS)**

The equilibrium state of the membrane is defined by the principle of virtual work. It is assumed that the sum of the virtual work performed by the required prestress, σ, and the external load, p (e. g. overpressure, the weight of the structure itself), must be equal zero. The governing equation is the principle of virtual work:

$$\delta w = t\int_a \sigma : \frac{\partial(\delta u)}{\partial x} da = t\int_a \sigma : \delta u_x da = 0. \qquad (1)$$

Where σ is the prescribed Cauchy stress tensor, which is applied to the surface in equilibrium; $\delta u_{,x}$ is the variation of the virtual displacement with respect to the geometry of the current surface; and t is the thickness of the membrane, which is relatively thin and assumed to be constant during deformation; the Poisson's coefficient of the thickness is neglected.

Equation (1) expresses that the virtual work of the given stress field is zero at equilibrium. The whole mathematical description of Updated reference strategy method can be found in [10].

3. Design of membrane roofing

In order to prepare a satisfactory and effective design, the surrounding context was determined around the existing experimental equipment. It was necessary to consider the type of surrounding buildings, obstacles, and the slope of the terrain and orientation with respect to the world sides.

The membrane structure was not designed for research purposes only, but it should provide shadow in the summer during experimental measurements and complete the overall surroundings of the campus of Faculty of Civil Engineering.

As a basic input data, a situation drawing (see Figure 5) was provided to obtain information about the location of individual buildings, walkways and green areas. Also, a rough geodetic survey from the ČÚZK server was used to determine the morphology of the terrain. Another more detailed survey of the objects and especially the experimental stand took place on site using a hand-held laser which was also for verification all provided data.

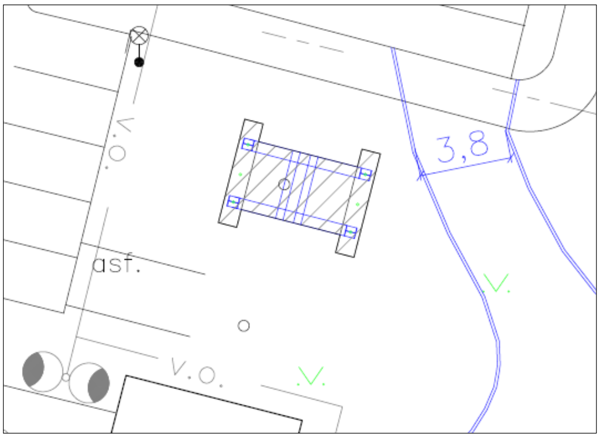

Fig. 5: Situation drawing of the experimental stand

3.1. Architectural visualization

Based on the design aspects described above, several architectural visualizations were created based on current floor plan options depended on the situation of the experimental stand. The Archicad software was used to prepare a virtual model of the surroundings and the stand.

As first, the shape of the needed to be determined. Basic shapes of membrane structures can be divided into three categories – hyperbolic paraboloid (see Figure 6), cone (see Figure. 7), and saddle (see Figure 8).

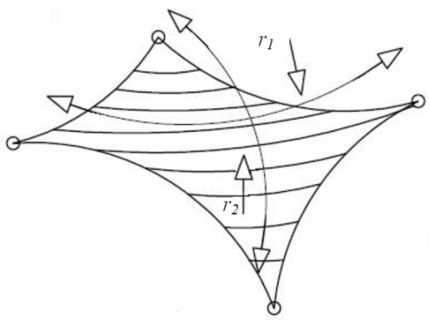

Fig. 6: Hyperbolic paraboloid shape [11]

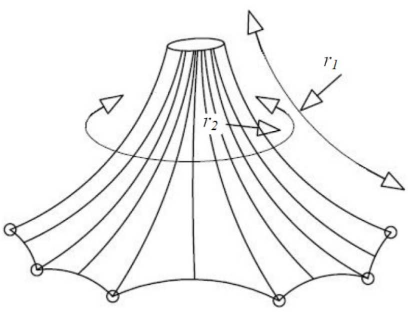

Fig. 7: Cone shape [11]

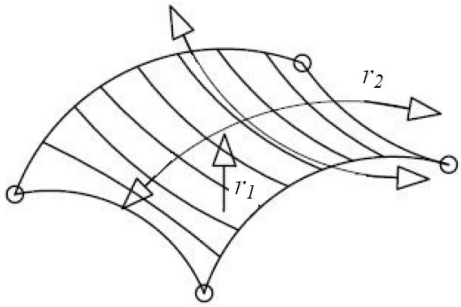

Fig. 8: Saddle shape [11]

For the membrane roofing of the experimental stand, the membrane structure in shape of hyperbolic paraboloid was chosen. The double curvature of membrane structure in shape of the hyperbolic paraboloid is achieved by clamping the membrane material between four (or more) points which are not in one plane. In two perpendicular cuts, one curvature is concave and, the other one is convex. In order to achieve the most favourable stress results, the effort was to keep the slope of the anchor columns in the range of 0 – 15 ° [12].

The Rhino software with the Grasshopper add - on module which is suitable for parametric designing was used to create the membrane surface. The coordinates of the anchor points of the designed membrane structure were inserted into the Rhino software. Subsequently, a script was created which could generate the assumed shape of the prestressed membrane structures. The algorithm of the script can be seen in the Figure 9 and Figure 10.

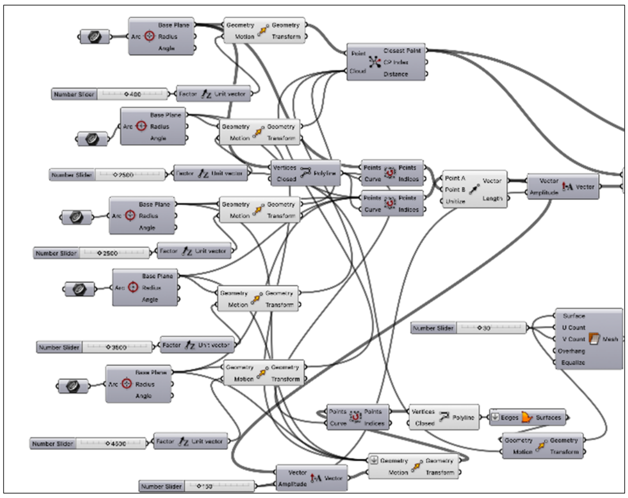

Fig. 9: Preview of the script in the Grasshopper software – part 1

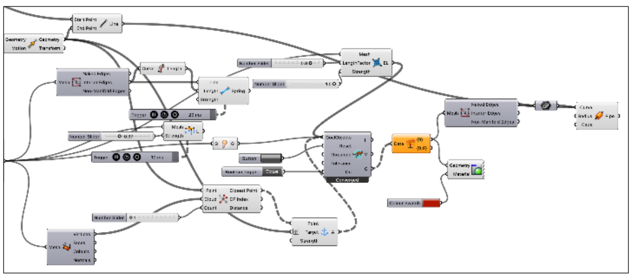

Fig. 10: Preview of the script in the Grasshopper software – part 2

Because it is a parametric software, it was possible to make changes of the position of the anchor points without recreating the complex model and gradually optimize the desired shape of the required shape of membrane structure.

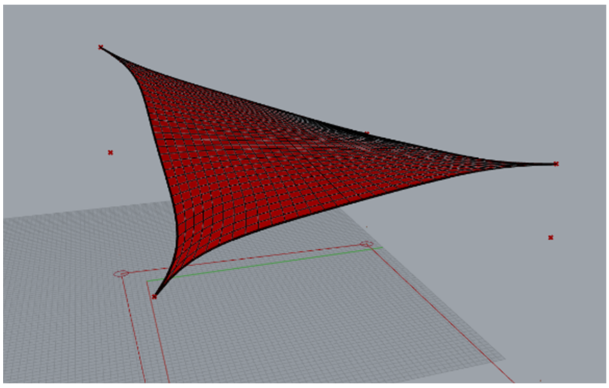

Fig. 11: The resulting membrane shape in Rhino software

With gradual adjustment of the height and the angles of the columns was achieved the required shape of membrane structure in shape of hyperbolic paraboloid. It was also considered the study of sun exposure and rainwater run - off. Final architectural visualizations can be seen in the Figures 12, 13, 14.

Fig. 12: Visualization of the membrane structure 1 - view from the north

Fig. 13: Visualization of the membrane structure 2 - view from the east

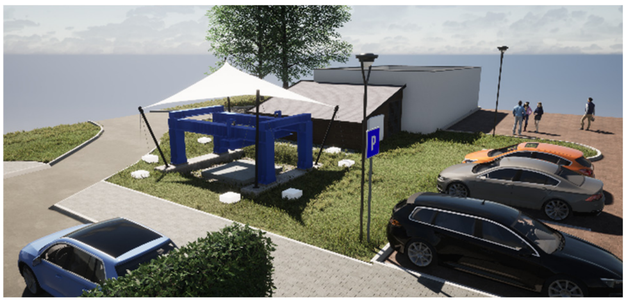

Fig. 14: Visualization of the membrane structure 3 - view from the north

Final floor plan dimensions are approximately 6,4 x 6,2 m. This virtual model of the membrane structure subsequently served as input data for the numerical model in the RFEM software and its add – on module, RF Form – Finding. The RF Form – Finding add – on module is very useful in searching for the shapes of member and surface models subjected to tension or compression.

3.2. Numerical analysis of membrane structure

As mentioned above, software RFEM by Czech company Dlubal was chosen for numerical analysis. The next step in solving the roofing was to determine boundary conditions. Due to limited anchoring possibilities, existing foundation of the experimental stand was used for location the columns which are pin supported. There are also inserted two cables for every column for pre - stressing the membrane fabric. Pre – stressed cables are also inserted along the entire membrane fabric where the value of relative slack of the cable is set as 8%.

As a textile material, Flexlight Advanced 902 S2 by Serge Ferrari group was chosen. Serge Ferrari company designs, manufactures, and distributes innovative, flexible composite materials over the world. Materials by this company are renowned for its lightweight, durable, and recyclable possibilities. The material is long - lasting lifetime (over 20 years) and easy maintenance, high dimensional stability due to Precóinraint technology.

Based on technical sheets by manufacturer, the material characteristics (see Table 1) were inserted into the RFEM software, and it was determined the material model as orthotropic – elastic 2D, since there is no more accurate material model suitable for membrane structures. The initial pre – stress was set as 1 kN/m in both directions.

Table 1. Mechanical characteristics of Flexlight Advanced 902 S2 by Serge Ferrari group [15].

Material characteristic	Value
Tensile strength warp [daN/5cm]	420
Tensile strength weft [daN/5cm]	400
Warp modulus of elasticity E_w [kN/m]	708
Weft modulus of elasticity E_f [kN/m]	774
Poisson's ratio warp-fill v_{w-f} [-]	0.32
Poisson's ratio fill-warp v_{f-w} [-]	0.49

These material characteristics are obtained from biaxial testing and all manufacturers of textile membrane materials provide the biaxial tests for determining material characteristics and their results. One of the initial models with boundary conditions before the form finding calculation and optimizing the structure can be seen in Figure 15.

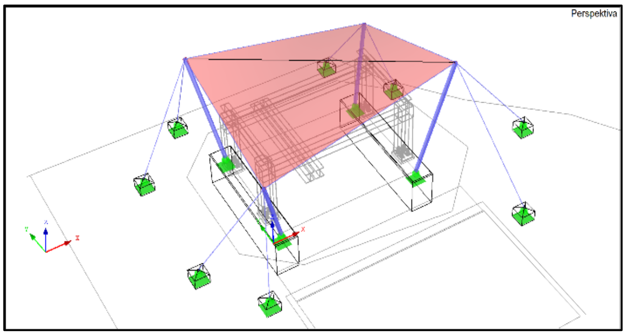

Fig. 15: Initial model and boundary conditions before form finding calculation

After determining all the needed boundary conditions, a suitable shape of hyperbolic paraboloid of the membrane structure was solved using RFEM add - on module, RF Form - Finding.

The calculation takes into account the interaction between the form - found elements and the supporting structure. The final shape of membrane structure stabilized in the position of the minimum area. The final shape can be seen in the Figure 16 and the final floor plan can be seen in the Figure 17.

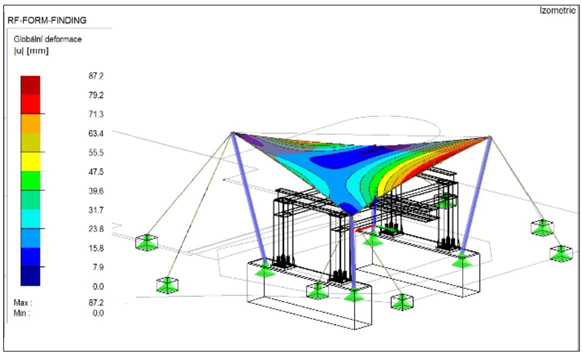

Fig. 16: Final shape of membrane structure

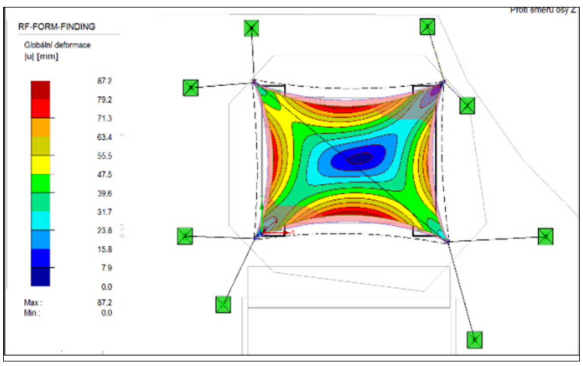

Fig. 17: Floor plan of the final shape of membrane structure

In the Figure 18, the final normal forces which occurred after form – finding calculation in all steel members of the supporting system of membrane structure can be seen. During the gradual optimization of the location of the anchor ropes, the effort was to obtain the most symmetrical values of normal forces in the anchor ropes for each pair at the individual columns.

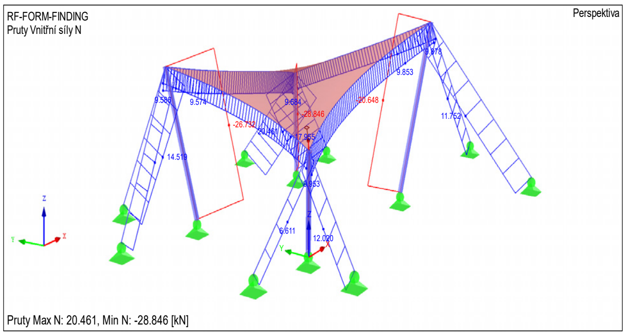

Fig. 18: Internal normal forces in final shape of membrane structure

The new presented prestressed shape of the membrane structure is afterwards used as the initial state for the structural analysis. Every next load situation (e. g. snow and wind loading) is then applied on the shape after form finding calculation. For this type of temporary roofing system, the wind loading will be the most important to consider.

The final shape of the membrane structure after the form finding calculation is also needed because of determining the cutting patterns of the membrane textile material [14].

4. Conclusion

The aim of this paper was to give an overview of the design of the temporary membrane structure starting from the architectural visualization and continuing to deal structural and dispositional parts of the design.

It was presented the considerations which were needed to be taken into account in the architectonic point of view, as the type of surrounding buildings, obstacles, and the slope of the terrain.

After the architectonic part of work was done, the final shape of membrane structure for roofing the experimental stand in the campus of Faculty of Civil Engineering, VSB – Technical University of Ostrava were determined by using RFEM software and its add – on module RF Form - Finding.

As the next step of the task of the design of the membrane structure, the structural analysis needs to be done. The membrane structure should be designed only as a temporary type of roofing and should be taken – of for the winter season, that is why the most important loading state will be the loading by wind. Then, cutting pattern of the textile material needs to be determined. These parts of the design will be presented in the next contribution.

Acknowledgements

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