A STUDY ON THE ARCH-SUPPORTED MEMBRANE STRUCTURES RESISTANCE TO PONDING EFFECT

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Abstract

This study deals with the ability of arch-supported membrane structures to withstand water accumulation. A previously developed specialized software tool may help prevent the occurrence of the ponding effect already in the design process. The influence of dimensions, surface prestress level and membrane material was investigated. The initial support layout and topology's influence on the occurrence of the ponding effect was proved. The study outcomes may serve as the basis for the initial dimensions design of arch-supported membrane structures.

Keywords

Arch, membrane structures, ponding effect, prestress, snow load

1 INTRODUCTION

Tensile surface structures represent lightweight, aesthetic and economical solutions for large space roofing. Airport halls, courtyards or even squares may be covered due to the variety of shapes. Different materials may protect against weather conditions or just shield against sunshine. Permanent structures as well as temporary structures may serve well for a long time if maintained properly. All these benefits prove that membrane structures may be a good choice for roofing.

However, there are also disadvantages of tensile surface structures. Great deformability may result in a large deviation from the original shape. The construction process may be complicated due to large prestressing forces, and defects may especially threaten the whole structure.

Based on the location, membrane structures must withstand the loading that may occur in the area. Permanent structures must carry the load during the winter. The membrane surface could undergo large deformations from snow load and melted snow. In case of insufficient design, the membrane surface may deform, leading to the accumulation of load in the area. This unfavourable phenomenon is called the ponding effect and a closer description is provided in [1]. The causes and consequences of load accumulation on membrane surfaces are summarized in [2]. The authors described real examples of collapsed and damaged membrane roofs and concluded that the load was not properly assumed.

Tensile surface structures are not included in Czech standards yet, so publications such as [1] or [3] provide guidelines for design and construction. However, most assumptions and load applications rely on the expertise of engineers. Research [4] contributes to a better understanding of tensile structure loading by snow and point loads. The outcome of the research indicates the importance of standards for proper load assumptions.

Shape and material properties were studied in [5]. The parametric study of typical shapes such as conical, hyperbolic paraboloid and barrel vault showed that in the case of the barrel vault shape, highly curved surfaces may be designed with lower prescribed prestress. Lower curvature leads to higher stresses and deflections.

The study contributes to general knowledge about the loading of tensile surface structures. The subject of interest was the deflection of loaded membrane surfaces and their ability to accumulate additional load. The aim is to facilitate the design process of arch-supported membrane structures and to explore the design limits of the shape.

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2 METHODOLOGY

The calculation was performed using the algorithm developed by the authors in the current research. It is a part of a finite element solver by FEM consulting, s.r.o., implemented in RFEM 6 [6] by Dlubal Software GmbH.

Shape

A parametrically defined shape of arch-supported tensile membrane structure was studied. The dimensions of the studied structure are shown in Fig. 1. The span of the arch *S* was 5.0 m. The length *L* changed from 3.0 m to 8.0 m with a step size of 1.0 m. The rise of the arch *R* ranged from 0.5 m to 2.0 m with a step size of 0.25 m. The arch was modelled as a rigid member to eliminate the influence of member stiffness.

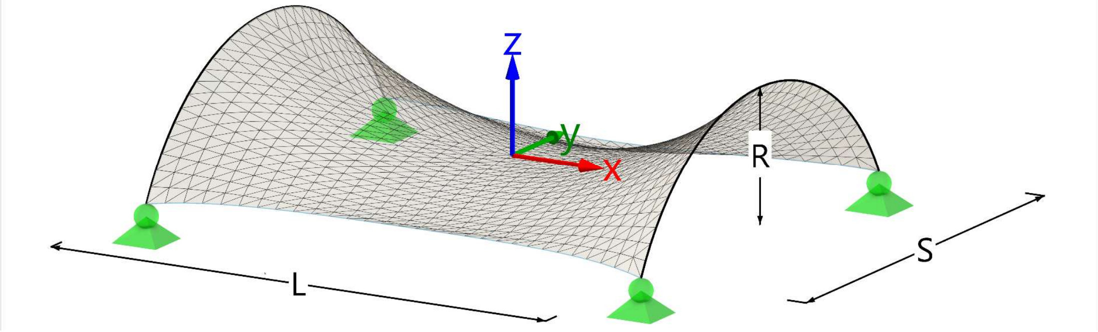

Fig. 1 Dimensions of arch-supported membrane structure.

Two variants of the structure shown in Fig. 2 were studied. Firstly, the sides along the length *L* of the structure were supported, keeping the edges straight. Secondly, prestressed cables were modelled on the edges of the structure.

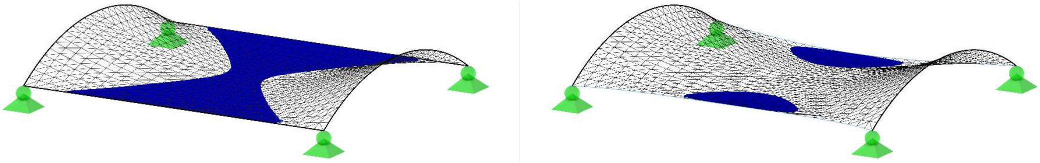

Fig. 2 Arch-supported structure with straight edges (left) and cables (right).

Membrane material

To study and compare the influence of material properties, the tensile surface was made of PVC-coated fabric types I and III. The main material properties of the tensile membrane used in the study are presented in Tab. 1. The elastic modulus *E* and tensile strength *f* are specified in the *x* and *y* directions, corresponding to the warp and the weft, respectively. The local coordinate system of the surface is shown in Fig. 1.

Tab. 1 Material properties of PVC-coated fabric.

Type	E_x **(kN/m)**	E_y **(kN/m)**	f_x **(kN/m)**	f_y **(kN/m)**
I	*720.0*	*590.0*	*60.0*	*60.0*
III	*1220.0*	*810.0*	*115.0*	*102.0*

Prestress level

To determine the equilibrium shape for the prescribed prestress level in the tensile membrane, a form-finding process was carried out. Two levels of surface prestress, 0.5 kN/m and 2.0 kN/m, were studied. In the second

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variant, the cables were prestressed to 5.0 kN and 20.0 kN. The same multiplier ensured that the obtained shape was consistent while adjusting the prestress level.

Snow load

The shape of the arch-supported structure naturally facilitates water drainage. However, snow load may accumulate on a deformed surface. To initialize deformation, a uniform load of 2.0 kN/m^2 was applied.

Ponding effect determination

An algorithm for detecting the ponding effect was developed to assess the possibility of load accumulation and determine its magnitude. The algorithm was presented at the 20th International Conference of Numerical Analysis and Applied Mathematics in Heraklion, Crete [7].

The algorithm was used to detect catchment areas on a deformed tensile membrane under snow load. The volume of accumulated water was calculated and the surface was loaded accordingly. This process was repeated in each iteration until equilibrium was reached.

3 RESULTS

Firstly, the variant with straight edges was studied. Subsequently, the second variant with prestressed cables was examined. The total amount of water accumulated on the membrane surface was recorded, and the results are summarized in the following graphs. The horizontal axis represents the arch height-to-span ratio, while the vertical axis represents the total amount of water in kN.

Straight supported edges

The surface prestress level was prescribed the same in both directions. The amount of water accumulated on the arch-supported structure with straight supported edges is depicted in Fig. 3. The picture on the left in Fig. 2 captures the water depth on the surface with a length equal to 6 m and a prestress level of 0.5 kN/m.

The water volume on the membrane surface made of PVC-coated fabric type I is maximal in the case of the largest length. The amount decreases with an increasing ratio but remains non-zero for the highest curvature. Only for lengths shorter than the span of the arch, the accumulated water amount was zero, even for a ratio of 0.2.

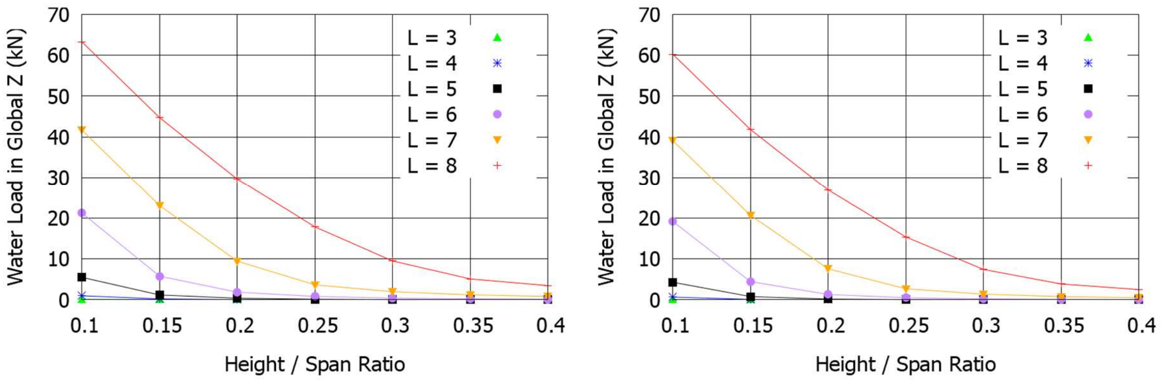

Fig. 3 PVC type I a) $n_x = n_y = 0.5$ kN/m (left), b) $n_x = n_y = 2.0$ kN/m (right).

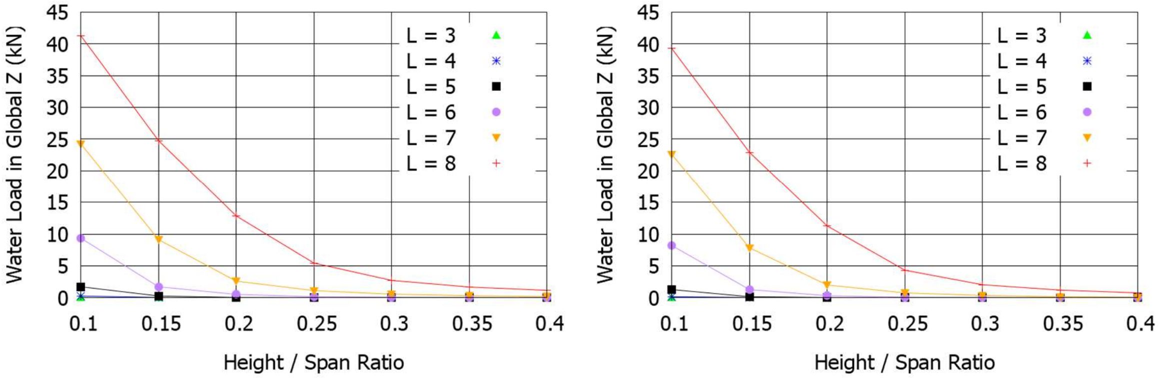

Fig. 4 PVC type III a) $n_x = n_y = 0.5$ kN/m (left), b) $n_x = n_y = 2.0$ kN/m (right).

The results recorded in the graphs in Fig. 4 represent the amount of water accumulated on the membrane surface made of PVC-coated fabric type III. The overall load was reduced by more than 50% in the case of a length equal to 5.0 m. Additionally, the structure with the stronger material prevents the ponding effect, even for a ratio of 0.15. The ponding effect on the longest structure was prevented even with the highest curvature (ratio of 0.4).

Prestressed cables on edges

To reduce the amount of accumulated water, the study focused on finding a more economical shape of the structure. Thus, the membrane surface material was made of PVC-coated fabric type I and the edges along the length were reinforced with prestressed cables. The level of prestress P in the cables was 5 kN and 20 kN for a less and more prestressed membrane surface, respectively. The results were recorded in the graphs in Fig. 5.

The amount of accumulated water was considerably reduced by more than 70% compared to the structure with straight edges. Additionally, the risk of the ponding effect occurrence was eliminated for the majority of the dimensions. Moreover, the longest structure is safe to build with a ratio of 0.4. Compared to previous results, it is possible to design a structure with the same prestress level, but more economically.

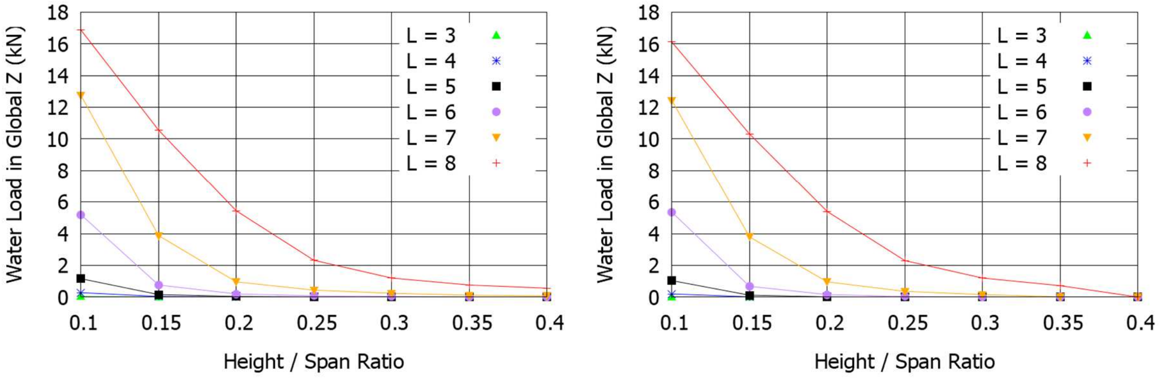

Fig. 5 PVC type I a) $n_x = n_y = 0.5$ kN/m, $P = 5$ kN (left), b) $n_x = n_y = 2.0$ kN/m, $P = 20$ kN (right).

4 DISCUSSION

A comparison of accumulated water amounts on surfaces made of different materials in Fig. 3 and Fig. 4 shows that the overall load was significantly reduced for the majority of cases.

However, PVC-coated fabric type III requires a higher minimal prestress level than type I. Hence, a higher prestress level of the surface may affect the overall design of the structure and both directly and indirectly increase financial costs. This requirement was intentionally violated for study purposes. The overall benefit of using more expensive material to reduce the ponding effect occurrence on the membrane surface does not seem to be significant.

Although the previous solution is not generally applicable, basic recommendations may follow from the study. The most important outcome is low dependence on the prestress level. The amounts of accumulated load on the surface are almost the same for both stress conditions in all variations. Hence, the prestress level does not significantly affect the ponding effect occurrence risk.

Material properties may be crucial for load transfer ability. However, the risk of the ponding effect and the amount of accumulated load on a membrane surface were not significantly affected.

The study shows that an essential parameter for ponding effect prevention and reduction was the initial shape of the membrane structure. The length of the structure is not only limited by the rise of the arc but also by the edge conditions. If the edges are straight and supported, the risk of ponding is increased as the load accumulates close to the edge, as can be seen in Fig. 2 on the left. This behaviour may be prevented if a cable on the edge is designed as it adapts to the load better and the shape is not disturbed.

5 CONCLUSION

The study focused on the arch-supported tensile surface structure and its ability to prevent load accumulation. The outcomes of the study may facilitate the design process of tensile membranes as the official standards for membrane structures are still being prepared.

As supposed, the initial shape of an arch-supported membrane structure is crucial for ponding effect resistance ability. Also, the amount of accumulated water was reduced by more than 70 % just by a little shape adjustment. Hence, a proper initial design may help reduce the final costs both directly and indirectly.

Modifying the prestress level of the membrane surface turned out to be less effective than expected. The influence was low compared to the amount of accumulated load. Also, the effect of using stronger material for the membrane surface may be noticeable but negligible considering the additional costs for a support structure.

The results listed may be used as the minimum basic dimensions of an arch-supported membrane structure with a small curvature, hence facilitating the workflow and helping eliminate insufficiently designed structures.

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