Dependance of Membrane Stress on the Supports Geometry of the Barrel-Vault Shaped Tensile Membrane Structures

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This research aims to find out how geometry of the supports affects the membrane stress in barrel-vault shaped membranes. A numerical experiment is conducted and the parameters of the support geometry are varied in order to understand their influence on the maximal membrane stress under load.

Tensile membrane structures are among the most attractive lightweight structures. The combination of structural and esthetic qualities makes them the top choice for designers, and favorite among users. In the past decade, an opportunity to connect green energy solutions with the tensile membrane structures arose. As the most prominent, the integration of photovoltaics onto membranes, has been researched [1, 2]. This paper is a part of a larger research [3] examining the possibilities of this integration. The aim of this paper is to deepen the understanding of membrane stress under loads. This is done in order to assess the feasibility of the integration of contemporary PV solutions on the membranes.

The membrane used as the main structural material has very distinct properties. Both architectural [4] and engineering aspects [5, 6] of designing membranes need to be analyzed. Mechanical properties of membranes have been researched in the past. Physical testing of the membranes has been conducted and analyzed in several researches, for example [7, 8]. Membranes have been tested under monotonous and cyclic loading [9]. More recently, saturation of stress-strain behavior has been researched [10]. Biaxial tensile behavior [11] and load-dependent mechanical behavior [12] have been analyzed. PTFE coated membranes are subject to several researches, such as [13, 14]. Shear behavior of architectural fabrics is also examined [15]. The dependence of membrane stress has already been researched with respect to a few influencing parameters [16].

In the research presented in this paper, numerical models of barrel-vault shaped tensile membrane structures are analyzed. The goal of the paper is to determine how different support geometries influence the membrane stress under external loads. For this purpose, several different geometries were defined. As the two basic parameters of the geometry of the barrel-vault shape, the size of the base and the height of the arch, are varied. To reach general conclusions, the situations where the height of one arch is different from the height of the other arch are not analyzed, therefore the heights of the arches are changed simultaneously. The base is square shaped, although it is not uncommon to use rectangular bases for this type of membrane structures. The results of the research will be used in the next phases of evaluating the PV-membrane integration and selecting the most suitable tensile membrane structures for this hybrid system.

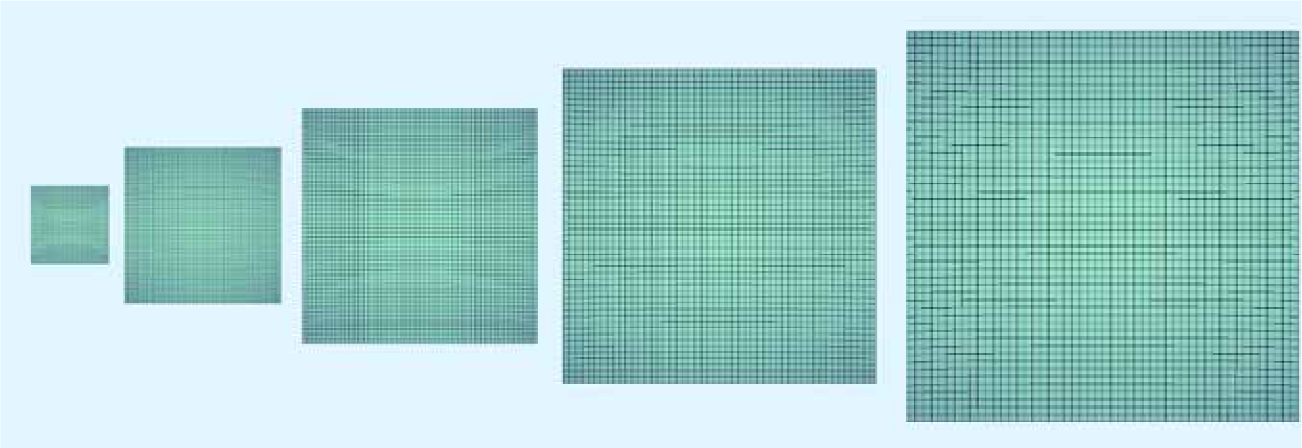

Fig. 1. Analyzed base sizes: a=2 m, a=4 m, a=6 m, a=8 m and a=10 m

Methodology

In the part of the research presented in this paper, membrane stresses are analyzed under different loads. This is a preparatory step towards selecting the appropriate tensile membrane structure for the PV integration. Therefore, the PV integration is still not analyzed in this part. The research focuses on the dependence of the membrane stress on the geometry of the supports in barrel-vault membrane shapes. It is conducted as a numerical experiment in software Sofistik. This type of research produces different results compared to physical testing due to simplifications, such as material linearity for the membrane material [17]. However, the results are intended to help in understanding the trends and influence that support geometry has on the maximal membrane stress.

The structure of the numerical model is defined according to the following parameters. The supports are fixed and their geometry is defined using variable parameters. The membrane material is linear elastic with elastic modulus of 600 kN/m in both directions, shear modulus of 30 kN/m and Poisson's coefficient of 0.4, according to [18]. The warp direction of the membrane is perpendicular to the straight support edges, and weft direction is parallel to them. The intensity of membrane prestress is equal in warp and weft directions and is set to 3 kN/m.

As the first variable parameter, the size of the base of the supports is taken. The base represents the horizontal plan of the supports. The shape of the base is defined as square and the length of the side is varied. Selected values for the side length are 2, 4, 6, 8 and 10 m. This represents typical spans for barrel-vault shaped membranes. The size of the mesh of the finite elements was scaled according to the size of the base. The height of the support arches is selected as the second variable parameter. This parameter determines the curvature of the structure. Since the size of the base is varied, the height of the arch had to be defined in relation to it. Flat membranes are not considered, as they exhibit problems with ponding. As the highest supporting arch, a semicircle is selected. Five parameter values are therefore considered, 0.1a, 0.2a, 0.3a, 0.4a and 0.5a, "a" being the length of the side of the base. The height of the supporting arches, being simultaneously also the height of the structure, is marked as "h". Figure 1. shows different base sizes of models, while fig. 2. shows different heights of supporting arches for one size of the base. A total of 25 models were analyzed in the research.

Three different load types were applied to the models. Each load was applied separately. These loads are concentrated load, snow load and wind load. The concentrated load has a total intensity of 1 kN, vertical downward direction [19], and a 0.1×0.1 m application area. It acts in the middle of the membrane. The snow load has a 0.6 kN/m^2 intensity across the whole membrane, and a vertical downward direction. The wind load has a 1 kN/m^2 intensity and is applied upwards, perpendicular to the membrane surface, according to [20]. All loads are applied as static.

Results

Each of the 25 models was loaded with all 3 loads separately. The resulting data on the maximal and minimal membrane stresses in warp and weft directions were recorded. Here, only the maximal stresses under each load are presented, as this information is more significant. Figure 3. presents the maximal stress data. On the left side of fig. 3. the relation between the size of the base and the maximal stress is presented. The right side of fig. 3. shows the relation between the height of the structure and the maximal stress. Each of the 5 charts presented on the left side of fig. 3. shows results for 5 models and for each of these models 6 values for stresses are provided. These are the maximal stress in warp and in weft directions for concentrated, snow and wind load. The right side of the figure presents the same data, but arranged in a different way in order to better depict the relation between the second parameter and the membrane stresses. Maximal stresses in warp direction are marked with continuous lines, while maximal stresses in weft direction are marked with dashed lines. Results for concentrated load are given in blue, for snow load in orange and for wind load in green color.

The position of the maximal stresses was not presented here graphically, due to the space limitations. For the concentrated load, the position of the maximal stresses is always the same as the position of the load action, both for the warp and weft directions. Under snow load, the position of the maximal stresses in warp and weft fibers is close to the

Fig. 2. Analyzed model heights: h=0.1a, h=0.2a, h=0.3a, h=0.4a, h=0.5a

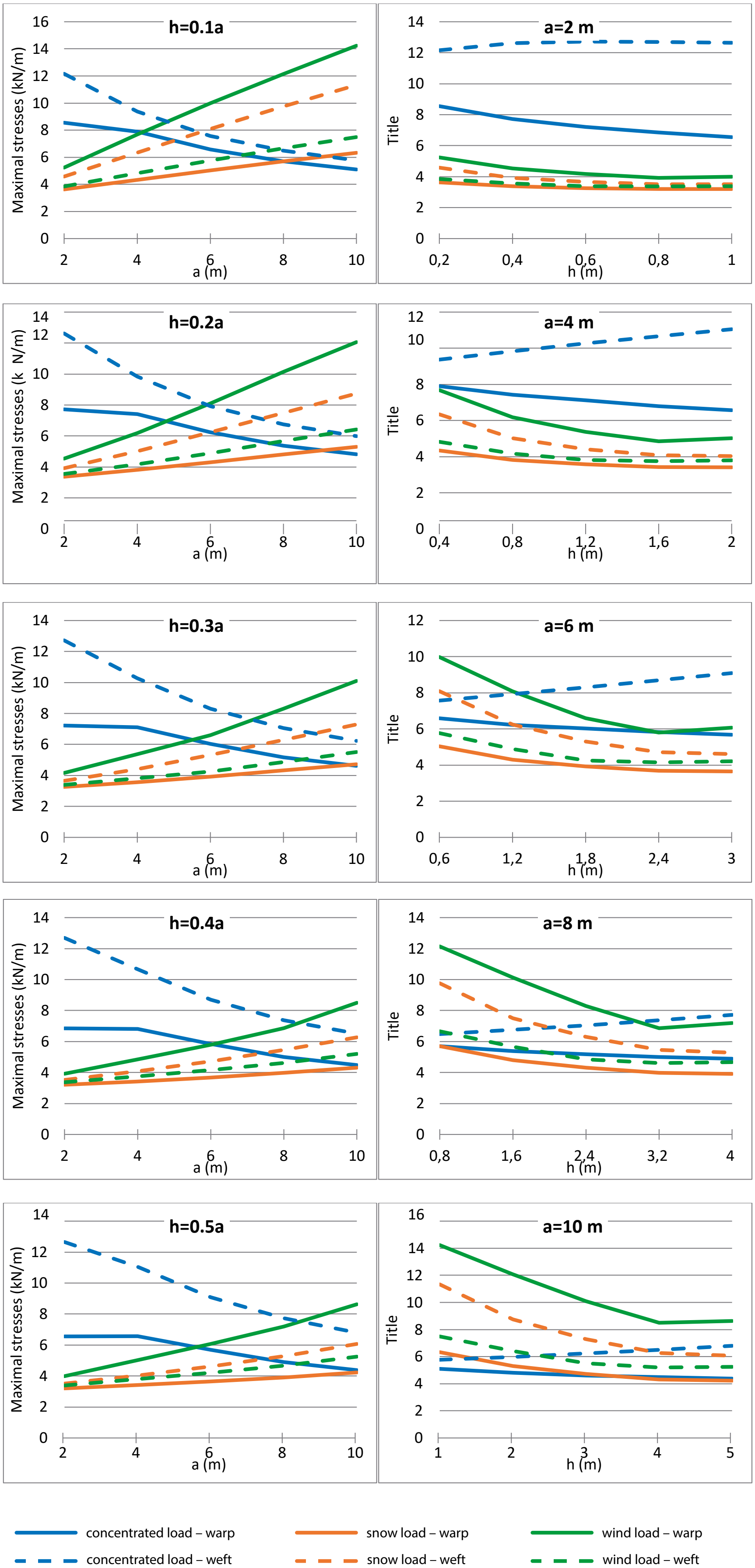

Fig. 3. Maximal stresses under loads

arches in all analyzed cases. During wind load action, the results show that the position of the maximal stresses is related to the height of the structure. For the lower structures, the maximal warp stresses are in the middle of the membrane. As the curvature increases, the position of maximal warp stresses moves to the area close to the straight edges. Maximal weft stresses under wind load are positioned close to the straight edge of the structure in all models.

Discussion

Several observations can be made based on the obtained results. First, it is obvious that membrane behavior under concentrated load is different from the two analyzed area loads (fig. 3.). While with the increase of the size of the base, the maximal stresses increase under snow and wind load, they also decrease in most cases under concentrated load. The only exception can be seen in the warp stresses of the concentrated load when increasing the base from 2×2 to 4×4 m for the largest height of the structure (fig. 3., h=0.5a). A few things need to be considered. First, the loads differ both by their intensity and their application area. For the concentrated load, the application area and the intensity are fixed and independent from all other factors. For the snow load the intensity is fixed per unit of area of the base, however, with the change of the size of the base, the total load also changes. For the wind load it is more complex, since the intensity is fixed per unit of area of the membrane. Therefore, the total load intensity depends on both the size of the base and the height of the membrane. This needs to be taken into account when analyzing the results. It explains why there is an increase of stresses in wind and snow load with each increase of the structure base. As for the concentrated load, the decrease of the maximal stresses that seems to be in collision with the increasing span, can be explained by longer membrane fibers that need to strain less in order to counteract the constant load intensity.

The second observation concerns the relation between the maximal stresses in warp and weft direction. For the concentrated load and the snow load maximal weft stresses are always larger than the warp stresses, while for the wind load the opposite is the case (fig. 3.). The reason for this lies in the direction of the load action, relative to the defined layout of the structure and the direction of the curvature of the arches. The position of the warp is from one straight membrane edge to the other and the position of the weft from one arch to the other. Therefore, when the load is acting downwards, weft fibers are activated more. The opposite is true when the load is acting upwards, and in this case the warp fibers have larger stresses than the weft fibers. Had the direction of the curvature of the arches been set as downward, the results would consequentially show larger weft stresses under upward load and vice versa.

Some other observations can also be made. The wind load produces higher maximal stresses than the snow load, in all cases (fig. 3.). As the size of the base increases, this difference in favor of wind load increases. It can also be seen that with the increase of the base size, the difference between the maximal warp and weft load reduces for the concentrated load, while it increases for the snow load and the wind load. At the same time, as the height of the structure increases, the difference between the maximal warp and weft stresses increases for the concentrated load and decreases for the other two analyzed loads (fig. 3., left). The increase of height of the structure generally results in lowering the maximal stress, except for the weft stress under concentrated load that gets increased (fig. 3., right). Exceptions to this are seen in warp stress under wind load which is in line with the explained increase of the total load due to the increase of the membrane area.

Conclusion

In this research membrane stresses of barrel-vault shaped membranes are analyzed. The dependance of these stresses on the support geometry is examined with the use of numerical models. To define the geometry of the supports, two variable parameters are defined, the size of the base and the height of the supporting arches. For each of these two variables 5 values are selected. These parameters are combined and 25 different models are created. Each of these models is loaded with the concentrated load, snow load and wind load and the maximal stresses are recorded and presented.

The obtained results were analyzed and discussed. The conclusion is that there is no single way in fighting large stresses that can be applied to all analyzed loads. The methods that are effective in reducing the stresses under snow and wind load do not have positive results with the concentrated load. Reducing the size of the base results in lowering the stresses under the snow and wind loads. However, concentrated loads are found to produce larger stresses on smaller structures, compared to the area loads, therefore, they should receive more attention when designing smaller membranes. Increasing the height of the structure will reduce the stresses caused by analyzed area loads, but this reduction tends to get smaller as the height of the arches increases, and can even lead to stress increase after a certain point. Increasing the height of the structure will increase the weft stress under concentrated load and decrease the warp stress, weft stress being the dominant one under this load. These conclusions make it more difficult to reduce the stresses under loads, in case this needs to be done to provide optimal conditions for the integration of the photovoltaics.

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PRAWIDŁOWY SPOSÓB CYTOWANIA
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ABSTRACT:

Membrane stress under load depends on several factors in tensile membrane structures. This research aims to find out how geometry of the supports affects the membrane stress in barrel-vault shaped membranes. A numerical experiment is conducted and the parameters of the support geometry are varied in order to understand their influence on the maximal membrane stress under load. Three load types are applied to numerical models and maximal stresses are monitored. The results show how change of the size of the base of the structure and the change of the height of the supporting arches influence the stress. The results can be used in design of tensile membrane structures, but also in assessing the possibilities for integration with other systems, such as photovoltaics.

KEYWORDS:

Tensile Membrane Structures, Membrane Stresses, Barrel-Vault Shape, Supports Geometry

STRESZCZENIE:

ZALEŻNOŚĆ NAPRĘŻENIA MEMBRANOWEGO OD GEOMETRII PODPÓR W KOLEBKOWYCH ROZCIĄGLIWYCH STRUKTURACH MEMBRANOWYCH. Naprężenia membranowe w rozciągliwych konstrukcjach membranowych powstające pod wpływem obciążenia zależą od kilku czynników. Celem badań jest sprawdzenie, jak geometria podpór wpływa na naprężenia membranowe w membranach kolebkowych. Aby poznać wpływ obciążeń na maksymalne naprężenie membrany, przeprowadzono eksperyment numeryczny, zmieniając parametry geometrii podpory. Do modeli numerycznych stosowane są trzy typy obciążeń i monitorowane są maksymalne naprężenia. Wyniki pokazują, jak zmiana wielkości podstawy konstrukcji i zmiana wysokości łuków nośnych wpływają na naprężenia. Wyniki można wykorzystać przy projektowaniu rozciągliwych konstrukcji membranowych, ale także przy ocenie możliwości integracji z innymi systemami, takimi jak fotowoltaika.

SŁOWA KLUCZOWE:

rozciągliwe struktury membranowe, naprężenia membranowe, kształt sklepienia kolebkowego, geometria podpór