Advantages of Tensile Structure Analysis During Construction Stages

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Abstract. *This paper deals with the importance of analysing tensile structures during individual construction stages. This type of analysis is usually related to conventional structures. However, results of the research on this topic imply that problems caused by an insufficient design are solved on a building site on a daily basis. It usually is the engineer's responsibility to find a proper solution and a method of construction. A challenging decision is strongly dependent on experience and current status. This research contributes to a more detailed description of the problem.*

Keywords

Construction stages, form-finding, tensile surface structures.

1. Introduction

It may seem that lightweight structures were invented during the last decades. However, that type of structure has only been improved. Computer technology, modern tools and procedures allowed engineers to analyse and build tensile structures with larger span and higher variety of shapes. Those enormous structures are characterized by very high internal forces. Concurrently, textile materials covered with thin protective layer were improved. That smart combination of modern textile material and technological advance facilitates further development.

Nowadays, membrane structures means a durable, reliable and ecological solution for an entrance roofing, an atrium and even a stadium. There are other advantages from an architectural point of view. The structures are aesthetic, smart and practical. There are almost no limits for shape variations. On the other hand, designing the structures requires cooperation between architects and experienced engineers in this field. The process is a rather interactive cooperation and the final solution is usually a compromise between the architect's idea and the engineer's opinion.

2. Form-finding

Membrane structures are characterized by internal membrane forces due to the fact that the bending stiffness of a membrane material is almost zero. The structural shape of a tensile structure is determined by forces, thus from an inverse formulation of equilibrium [1]. Weak form of the equilibrium condition is based on the principle of virtual work, see Eq. (1). In contrast with standard static analysis, stress is generally independent of deformation [2]. The variation of overall virtual work δW is defined as follows:

$$\begin{aligned} -\delta W &= \delta W^{int} - \delta W^{ext} = \\ &= t \cdot \int_{\Omega} \boldsymbol{\sigma} : \delta \hat{\mathbf{e}} \, d\Omega - \int_{\Omega} \vec{p} \cdot \delta \mathbf{u} \, d\Omega = 0, \end{aligned} \tag{1}$$

where δW^{int} is the variation of virtual work of the internal forces, δW^{ext} is the variation of virtual work of the external forces, t is the thickness of the membrane, $\boldsymbol{\sigma}$ is the prescribed Cauchy stress tensor, $\delta \hat{\mathbf{e}}$ is the variation of the Euler-Almansi strain tensor, $\vec{p}$ is the external load, $\delta \mathbf{u}$ is the virtual displacement and Ω is the area.

In general, the spatial position of all material points of the surface are determined in order to reach equilibrium during the form-finding procedure. Input parameters are external forces and internal stresses acting on the unknown shape of the surface [3].

2.1. Pre-stress states

As has been stated before, internal stresses must be prescribed even before running the form-finding procedure. The magnitude of the pre-stress is selected with respect to the current recommendations valid in the area of membrane structures. For the European Union is valid the recommendation [4].

There are two pre-stress options to choose from. Firstly, the isotropic pre-stress could be an option which reaches the minimal surface [3]. Because the constant orthotropic pre-stress can not be reached for surfaces with double curvature. Secondly, the general anisotropic pre-stress could be used with different magnitudes in different directions and it is usually needed in order to prevent a snow ponding effect or it is necessary for high point regions of conically shaped membrane structures as well. Water from melting snow accumulates in the lowest point of a membrane surface and the load applied to the surface is increased [1].

2.2. Tensile surface structures construction

Although design and detailing is immensely important, it is also necessary to determine the sequence of work [5]. Lightweight tensile structures are, by their very nature, sensitive to the external load increments. Unexpected weather conditions may increase the external load on a structure under construction. Only the final shape of the structure is usually analyzed, so the response of the unfinished structure is unknown. Additional temporary load is also not negligible and may cause irreversible deformations. Especially temporary support may affect stress distribution.

Working steps are planned with respect to the possible states of the structure during the construction. A detailed analysis of the working steps is required in order to provide sufficient information about the structure. The objective of the analysis is not only to avoid undesired extreme deformations, but also to ensure safety on the building site.

Even an excellent design and its implementation does not ensure a proper outcome. Internal phenomena, such as creep, may cause relaxation of the initial tension. Thereafter, the membrane tension is reduced. Restretching of the membrane surface is required otherwise the load capacity of the structure is changed [6].

3. Membrane roof structure

The following numerical model is based on a structure that was erected on the banks of the river Elbe in Dresden, Germany. The roof has been designed by the architect Robert Kerbl and built by 3dtex. Publicly available basic documentation was published by Dlubal Software [7].

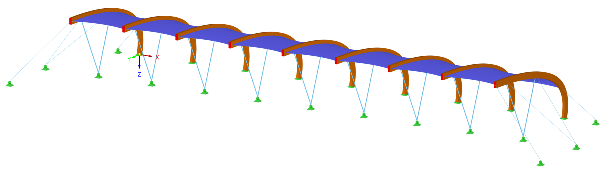

Fig. 1: Computational model of the membrane roof structure.

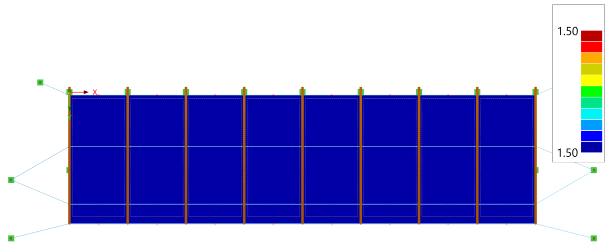

Fig. 2: Form-finding analysis without construction stages - Principal internal forces n_1 (kN/m).

3.1. Finite element model

The membrane roof structure consists of two separate equal structures. Each structure is 48 m long, 13.5 m wide and 10 m high. The whole roof consists of 8 separate parts with a membrane surface which are 6 m long each. Beams made of glued laminated timber are supported by V-shaped steel columns. Longitudinal stiffening is ensured by steel beams.

According to the valid recommendations [4], the appropriate material of the membrane surface has been chosen. Generally, there are five types of PVC coated materials. The exact specifications depend on the manufacturer, however approximate values of density, tensile strength and shear strength are known. PVC type IV is characterized by a density of 1300 g/m^2, a tensile strength of 149/128 kN/m and a shear strength of 1100/1400 N. Strength is given in both directions, warp and weft, respectively and both are inherently significant. Due to the manufacturing process, warp is stiffer than weft [5]. Furthermore, the thickness of the membrane surface is 1 mm. The edges of the membranes are stiffened by steel cables with a diameter of 10 mm.

The membrane roof has been slightly modified in the research work because the original structure was used as an inspiration. In the first place, four steel cables on both edges were added and pre-stressed. The right choice of force in the cables ensures that tension is applied to the longitudinal beams of the structure.

As is stated further, this step decreased stress changes while the temporary beams were being removed at the end of the form-finding process. Figure 1 shows the final computational model with the before mentioned modifications.

The aim of the modifications was to lighten the structure and exploit the full potential of the shape. Before the longitudinal beams were removed, the structure was stiff.

The computational model was created and analyzed using RFEM by Dlubal Software GmbH. According to the recommendation [4] the forces in both directions n_x and n_y are equal to 1.5 kN/m each. A tension of 10 kN is prescribed in the cables on the edges of the membranes. A total of 8 cables on the edges of the structure were subjected to a tension of 10 kN.

At first, the standard form-finding procedure was carried out. This analysis usually does not include construction stages. In figure 2, is the final shape of the pre-stressed surfaces. It can be observed that isotropic pre-stress has been achieved in the whole construction with the required magnitude of forces 1.5 kN/m. The main problem of pre-stressing the whole structure at once is unrealistic symmetry.

3.2. Construction stages

Nowadays, almost all of the static analyses are carried out without consideration of construction stages. Complex issues might be solved only using adequate software tools. Construction stages analysis has been implemented to RFEM by Dlubal Software GmbH in cooperation with FEM consulting, s.r.o. The author of this paper follows and expands the results of the research performed while working on his diploma thesis [8].

The main advantage of the construction stages analysis lies in the possibility to set a deformed state of the structure as an initial state for an upcoming structural or dynamic analysis. The initial state is dependent on the order of pre-stressing within the construction process of the membrane structure. Two variants for the analyzed structure have been calculated.

Both variants include the same first step. At the beginning, eight cables on the edges were pre-stressed. The aim of the first step is to increase the load capacity of the structure. This turned out to be the crucial step for the gradual removal of the longitudinal beams.

In figures 3 and 4, the membrane surfaces have been labeled. In variant A, the scheme of the membrane surfaces pre-stressing is 1-8-2-7-3-6-4-5. It simulates the procedure of pre-stressing from the edges to the centre of the structure. In variant B, the scheme of

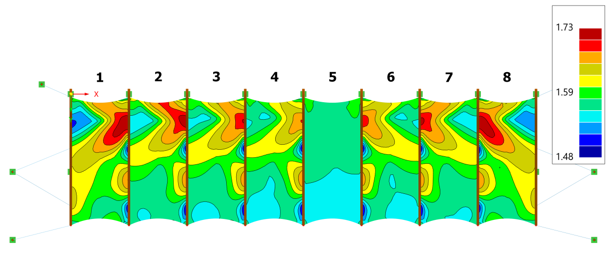

Fig. 3: The last stage of pre-stressing scheme A - Principal internal forces n_1 (kN/m).

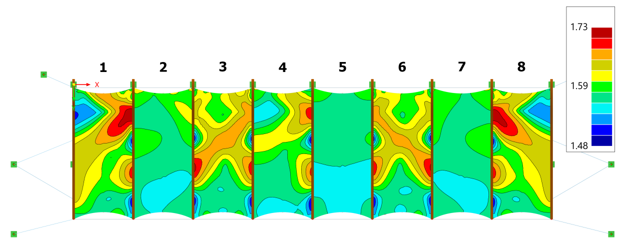

Fig. 4: The last stage of pre-stressing scheme B - Principal internal forces n_1 (kN/m).

the pre-stressing simulates balancing of the extremes of the internal forces. The prescription of the variant B is 1-8-3-6-2-7-4-5. Both variants have been chosen with respect to the same start and end point so the final states could be compared.

The removal of the longitudinal beams was done in the same way according to the pre-stressing schemes. Due to the first step, the internal forces in the beams were approximately zero after the membrane surfaces pre-stressing. This state ensures easy and fast removing during construction.

3.3. Results and discussion

There are final states of the principal internal forces in the figures 3 and 4. This stage represents the final structure without the longitudinal beams. In both structures the highest value the principal internal force n_1 is 1.73 kN/m and the lowest value is 1.48 kN/m in both structures. Although the extremes of the principal internal forces n_1 are the same, the distribution of the forces has to be taken into consideration.

Firstly, figure 3 represents variant A, which is gradually pre-stressed from the edges to the centre of the structure. As you can see, the distribution has been affected by the gradual pre-stressing. The direction of the principal internal forces n_1 is towards the centre of the structure.

Secondly, variant B is represented in figure 4. The specific direction of the principal internal forces n_1 in variant A, has been disrupted, therefore the principal internal forces n_1 are more evenly distributed. This is due to the skipping of the following membrane surface area (phase).

Furthermore, the percentage of occurrence of the high principal internal forces n_1 is above 1.50 % in variant A. Not only a more uniform distribution is achieved in variant B, but also more effective. A lesser percentage of the extremely high principal internal forces n_1 has been reached. The final result is only 0.74 %, which is almost half as large as the previous result. Not only one direction of the principal internal forces has been discussed. Similar, but lower values have been achieved in the other direction. Briefly, the principal internal forces n_2 are not dominant hence have not been published, but could be found in [8].

It is important to state that the choice of the prestressing scheme had a low effect on the adjacent beams and cables. The final internal forces in the elements are quite the same for both variants. However, it cannot be concluded that the impact on the elements is negligible. Weaker elements could fail due to the accumulation of the internal forces during construction. Construction stages analysis may help with the optimization of the structure design.

4. Conclusion

This paper focuses on the importance of construction stages analysis of tensile surface structures. Lightweight structures represent a sustainable and elegant roofing solution. In order to reach sufficient efficiency of the individual elements it is important to include each response in the calculation.

Tensile surface structures are very sensitive to any change as has been stated and proved. The state of the elements has changed many times during the construction process. Firstly, the whole structure was prestressed. In the next stage, some of the elements have been compressed just to be tensioned in the next stage. This alternation of states may lead to a combination of loads which is not included in the initial assessment.

This approach for analyzing the membrane surface structures may help to suggest new construction methods. Many construction schemes have been designed and compared. Only the best schemes have been described and commented on. Load distribution appears to be one of the most important objectives. A more uniform distribution of the principal internal forces n_1 ensures a better initial condition for further loading. Another important objective is to reduce the overall amount of extreme internal forces. Then it is possible to choose smaller and less noticeable steel parts of the surface. Thus, the design of the structure is more effective and ecological.

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