Comparison of results of an adaptive membrane structure with a numerical model

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Abstract. This paper discusses results of the adaptive membrane device compared to the model created in FEM software. The numerical model was created according to factory parameters of this device. The adaptive membrane device has to be properly set up, than the device is loaded by load piston with saddle and the adaptivity of this device consisted of two actuators used as anchor rods and another two anchor rods are fixed. The actuator is realised as a hydraulic piston. Based on the results obtained by these measurements and the load results in the numerical model, the comparison was evaluated in the conclusion of this paper.

1. Introduction
Nowadays, membrane structures are a very modern and popular way of roofing large spans. Since there is a demand to increase the economy and technological solution of building structures, these requirements can be met by introducing of adaptive systems. Under adaptive systems, it is possible to imagine a set of elements that allow structures to change their geometric and stress configurations.

This paper describes an experimental device of an adaptive membrane structure, whose design results mainly from the requirement to increase the economy of structures. Due to the fact, that tensile stressed systems are subjected to time-dependent influences (rheology of tensile members) and they are strongly non-linear, they are often designed as oversized compared to conventional steel systems. It would be appropriate to prevent of these effects in some way.

As mentioned above, with the adaptive systems it is possible to vary the stress configuration of the structure in real time, and thus that the cross-sections of the tensile members could be more economically designed. If a lower stress state of the structural system could be achieved in the long term by an adaptive system, the rheological impact could be greatly avoided, but under critical load the adaptive system would be able to provide the required stiffness of the structural system [1], [2].

The adaptability of the experimental device described in this work is based on a system of hydraulic pistons (actuators). It is possible to change the stress state of the whole construction system by extensioning or shortening of the pistons. Conclusion of this paper is the comparison of the results obtained from the experimental device with the results gained form a geometrically detailed numerical model, that was created based on the manufacturing documentation of the device.

2. Description of the experimental device
Based on theoretical assumptions and computational models created in the preparatory phase of the experiment, the shape of adaptive hyperbolic paraboloid was chosen as the most suitable variant. The experimental device [3], [4] shown in figure 1, consists of technical fabric with the 2x2 m floor plan. Total height of technical fabric is 1 m. Membrane surface is supplemented by 4 edge stainless steel cables with 8 mm diameter, which are inserted into welded edge sleeves of technical fabric and they are anchored to the steel frame using ball hinges with 2 actuators and 2 anchor rods.
The technical fabric is made by Serge Ferrari, type Précontraint 502. It is the polyester fabric coated with PVC coating. The woven of membrane was set in the directions of the individual vertices and it is positioned within the machine such that the x-axis direction, which has an elastic modulus $E_x = 1,057$ MPa, is anchored between the upper anchor rods (actuator AP2 and anchor rod T2). The modulus of elasticity in the y-axis direction is $E_y = 612$ MPa. Edge cables are spiral, single-strand with open construction 1x19 (1+6+12) and nominal strength 1 570 MPa. Edge cables are connected to a membrane clamping plates. Actuators have a movement range of 100 mm, but this range is limited mainly by the maximum load capacity of the element of 50 kN.

The steel frame construction is fully welded with one mounting joint at the top and bottom of the frame. It is a welded spatial structure consisting of closed RHS (rectangular hollow section) and SHS (square hollow section) profiles made of S235 steel. The basic profiles are columns SHS160×160×8, beams around the perimeter are RHS140x140x8 and both bases of steel frame box are reinforced with the cross-sections SHS140×140×8. Axial dimensions of the frame are 3.34×3.34×2.50 m.

The membrane is loaded by a cylindrical loading with 700 mm of diameter saddle, which has the same shape as the initial shape of the membrane surface. The piston is anchored in the centre of the upper base of the test frame. The capacity of the load piston is 15 kN, but this value is limited by the maximum movement range of the load piston, that is 100 mm.

3. Numerical model
The numerical model of the adaptive membrane structure of the experimental device was created in the Dlubal RFEM software using the add-on module – Form-Finding, which determines the equilibrium positions of membrane and cable elements.

The model [5], shown in figure 2, includes almost all geometrical and material characteristics according to the experimental device. The equilibrium position is determined based on selected boundary conditions such as the prestressing of the membrane surface ($n_x = n_y = 4$ kN / m width) and the required geometry (the sag of the edge cables $s = 0.20$ m). The size of the finite element surface mesh was 50 mm. As the equilibrium shape search process was used the Update Reference Strategy (URS) [6]. This process takes over the originally specified finite element geometry and the surface tension and iteratively shifts the position of network nodes until there is a surface tension in equilibrium with boundary conditions.
After form-finding process, the model was loaded by a free circular load with diameter of 700 mm. The actuators elongation or shortening was simulated by load case using absolute elongation/shortening of anchor rods.

**Figure 2.** The numerical model of the experimental device: (a) before form-finding process, (b) after form-finding process.

4. Methodology of measurement
The test set-up was performed in three series. Each serie has three measurements to cover the minimum statistical set. In the first serie of measurements, the membrane surface was loaded by the load piston with pressure force value 1 kN. Each serie of measurements has begun by adjusting of the initial equilibrium state of the membrane surface and stabilizing the tensile force values in the anchor rods and actuators at about 24 kN.

Subsequently, these values were recorded, including the position of the load piston. For the first measurement, load piston has been in contact with the membrane surface, but showed only a minimal signal from the load cell (the force in the load piston was equal to value 0 kN).

Each measurement in the serie started from the initial set-up, followed by loading with the load piston with a specific value for each serie of measurements and one minute system time stabilization was done. This time stabilization was performed after each change in each measurement.

After loading by load piston and recording the measured values, the actuators were shortened in the range of 0 to 3 mm, in steps of 1 mm, then the actuators were returned to the zero position and the measurement continued by extending the actuators from 0 to 2 mm. Values were recorded. The movement of actuators in all measurements was synchronous. In each successive serie the force increment in the load piston was 2 kN.

5. Results
On the basis of the measurements obtained from the experimental device test, the mean values were established. The deformation of membrane surface and tensile forces of actuators and anchor rods were observed. The deformation of the membrane surface was equal to extension of the load piston. These values were compared with the values obtained from the numerical model and the relative measurement error was evaluated for each monitored variable. The results of the comparison of the deformations of the numerical model and the mean values obtained by the experimental device can be seen in the figure 3 and figure 4.

Since the measured values from actuators and anchor rods with the same location have small relative differences (actuator AP2 and anchor rod T2 are located at the upper corners of the test frame, and actuator AP1 and anchor rod T1 are located at the lower corners of the test frame), only the comparison of the elements with the maximum relative difference will be shown. The comparison of the results of the axial forces in the anchoring elements or actuators of the numerical model with the average values obtained by the test assembly can be seen in the figure 5 and figure 6.
Figure 3. Comparison of the dependence of the deformation of the membrane surface at individual values of forces in the loading piston, for individual steps of shortening of actuators.

Figure 4. Comparison of the dependence of the deformation of the membrane surface at individual values of forces in the loading piston, for individual steps of extensioning of actuators.

Figure 5. Comparison of the dependence of the axial forces of the actuator AP2 at individual values of forces in the loading piston, for individual steps of extensioning and shortening of actuators.
6. Discussion

Based on the processed results and comparison of deformations between the numerical model and the experimental device test, it can be stated that the minimum relative difference in deformation $\Delta \delta_{\text{R}, \text{min}} = 9.53\%$ was at the load of 1 kN. This occurred when the actuator was shortened by 3 mm and it represents difference of deformation $\Delta \delta = 1.27\ mm$ between test set and numerical model. The deformation of the membrane surface of the experimental device test was minor compared to the numerical model. The maximum relative difference in deformation was $\Delta \delta_{\text{R}, \text{MAX}} = 37.95\%$ at the load of 1 kN and occurred when the actuator was extended by 2 mm, which represents the absolute deformation difference $\Delta \delta = 13.75\ mm$ between the experimental device test and the numerical model. The deformation of the membrane surface of the experimental device test was minor compared to the numerical model.

The comparison of the axial forces in the upper group of elements (AP2 and T2), shown that the minimum relative difference in axial force was $\Delta N_{\text{R, AP2}, \min} = 0.39\%$ at the load of 1 kN and occurred when the actuator was extended by 1 mm, which represents absolute difference between forces from both force sources $\Delta N_{\text{AP2}, \min} = 0.08\ \text{kN}$. The axial force of the experimental device test was minor compared to the numerical model. The maximum relative difference in axial force was $\Delta N_{\text{R, AP2}, \text{MAX}} = 10.10\%$ at the load of 5 kN and arised when the actuator was extended by 2 mm, which represents the absolute difference between axial force $\Delta N_{\text{AP2}, \text{MAX}} = 2.22\ \text{kN}$. The axial force of the experimental device test was minor compared to the numerical model.

The comparison of the axial forces in the lower group of elements (AP1 and T1), shown that the minimum relative difference in the axial force was $\Delta N_{\text{R, T1}, \min} = 0.05\%$ at the load of 1 kN and arised when the actuator was extended by 1 mm, which represents absolute difference between forces from both force sources $\Delta N_{\text{T1}, \min} = 0.01\ \text{kN}$. The axial force of the experimental device test was minor compared to the numerical model. The maximum relative difference in axial force was $\Delta N_{\text{R, T1}, \text{MAX}} = 11.96\%$ at the load of 5 kN and arised when the actuator was extended by 2 mm, which represents the absolute difference between axial force $\Delta N_{\text{T1}, \text{MAX}} = 2.01\ \text{kN}$. The axial force of the experimental device test was minor compared to the numerical model.

From the graphs of the axial forces it can be seen that the differences between the numerical model and the experimental device test, increase at 1 kN with increasing stiffness of the structural system, but this varies with increasing load at the same pretensioning stage, when these differences are decreasing during the increasing stiffness of the structural system.
7. Conclusion
Taking into account the high non-linearity of the whole structural system, the values of relative
differences of the axial forces in the range of about 12% can be considered as satisfactory, but the relative
differences of large displacement in range of about 40% remains as question. The answer to this question
could be the fact that the material characteristics of the technical textiles were taken from the
manufacturer and thus these were not be experimentally obtained.

Another reason could be the fact, that load piston and load saddle of the experimental device is rigid
and creates circumferential local deformations of the membrane surface, while the numerical model is
loaded with a free circular load, and thus the deformation result is concentrated to the centre of the
membrane surface.

Obtaining experimentally determined values of the material characteristics of technical textiles could
be the subject of further research to refine the numerical model of the experimental device and their
subsequent comparison.

8. References
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