Tubular Steel Arch Stabilized by Textile Membranes

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Abstract

Tubular steel arch supporting textile membrane roofing is investigated experimentally and numerically. The stabilization effects of the textile membrane on in-plane and out-of-plane behavior of the arch is of primary interest. First a model of a large membrane structure tested in laboratory is described. Prestressed membranes of PVC coated polyester fabric Ferrari® Précontraint 702S were used as a currently standard and excellent material. The test arrangement, loading and resulting load/deflection values are presented. The supporting structure consisted of two steel arch tubes, outer at edge of the membrane and inner supporting interior of the membrane roofing. The stability and strength behavior of the inner tube under both symmetrical and asymmetrical loading was monitored and is shown in some details. Second the SOFiSTiK software was employed to analyze the structural behavior in 3D, using geometrically nonlinear analysis with imperfections (GNIA). The numerical analysis, FE mesh sensitivity, the membrane prestressing and common boundary conditions are validated by test results. Finally a parametrical study concerning stability of mid arch with various geometries in a membrane structure with several supporting arches is presented, with recommendations for a practical design.

Keywords: textile membranes, prestressing, steel arch, arch stabilization, GNIA, tests

1. Introduction

Design of steel structures cooperating with TSF (Tensioned Fabric Structures) requires geometrically and materially non-linear analysis with imperfections (GMNIA). The essential in such analysis is an appropriate input of the membrane material behavior; see [1], [2], [3], [4], etc. While membrane surface is exclusively tensioned, supporting steelwork is most often exposed to a compression and/or bending. This type of loading, in combination with slender steel elements, results into stability problems. Usually the membrane represents a spring support for the steel structure and the complex structure need to be designed using proper software package allowing integrated modelling, e.g. EASY [5], SOFiSTiK [6], etc., while a separated modelling of the membrane and steelwork is rather limited [7]. This paper demonstrates significant stabilizing effects of membranes to the respective supporting steelwork, based on numerical parametrical studies validated by tests.

2. Validation by Tests

The tested membrane structure supported by two steel tube arches is shown in Fig. 1. The membrane is PVC coated polyester fabric Ferrari® Précontraint 702S (with braking loadings in both warp and fill directions $S_{ult} \approx$ 56 kN/m, working loading $S_{max} = S_{ult}/5 \approx$ 11.2 kN/m and suitable prestressing up to $P_{max} = S_{max}/5 \approx 2.24$ kN/m). Principal dimensions of the vertical inner tubular arch of ø 26.9x3.2 [mm] are LxH = 4500x1200 [mm], while outer tubular arch has inclination of 60° in respect to horizontal.

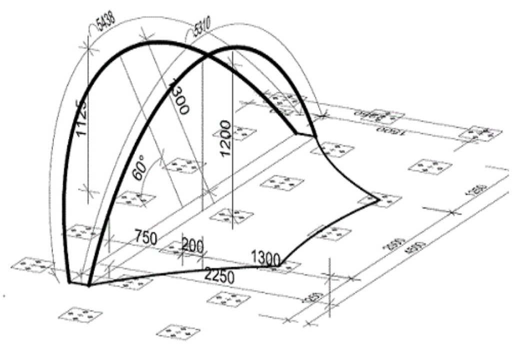

Fig. 1 The layout of the tested model

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The shape and cut of the membranes resulted from formfinder software [8] and the membranes were prestressed roughly with P ≈ 0.2 kN/m. The investigation concerned exclusively the inner steel arch to find stabilizing effect of the membrane to its nonlinear behavior. First the inner arch alone (without fastening the membrane) was loaded and second, after the membrane assembly, the complete membrane structure. For loading calibrated pouches with steel pellets were used and suspended from seven points of the arch (for the symmetrical loading see Fig. 2) or from four points in case of asymmetrical loading.

Fig. 2 Symmetrical loading of the tested model

During the tests the deflections and stresses were carefully monitored in 9 locations (with No. 4 at midspan). In this paper the symmetrical test and deflections only are described due to a space limit. The deflections (vertical in Fig. 3 and transverse in Fig. 4) demonstrate that the arch without membrane buckled out-of-plane at total loading of F_0 = 5.5 kN, with vertical deflection along all span down, while the test of the arch stabilized by the membrane was terminated under total load of F_M = 8.3 kN, showing the enormous stabilizing effect of the membrane.

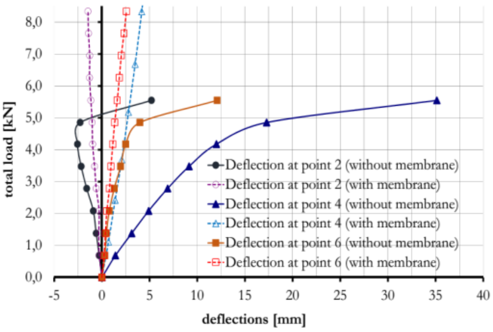

Fig. 3 Symmetrical loading - vertical deflections

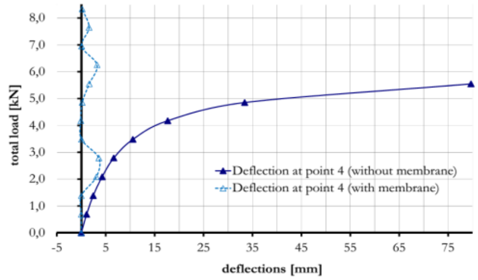

Fig. 4 Symmetrical loading – transverse deflections

SOFiSTiK software [6] was used to perform GNIA (using N-R iteration) both for the inner arch alone and the complete membrane structure, employing orthotropic model with 5 parameters according to [3]. Various meshing of the membrane was analysed (square sizes of 25, 50, 100 and 200 [mm]) with differences ≤ 0.2 % and optimum size of 50 mm was used in the analysis. The equilibrium state and final unloaded shape of the membrane structure was found under initial SOFiSTiK software calculations. Both arch alone analysis and membrane with the two arches were performed and results compared with tests showing excellent agreement. The results of GNIA for the symmetrical loading under various prestress of the membrane *P* [kN/m] are shown in Fig. 8 and with the prestress of 0.2 kN/m (corresponding to test) justify use of the model for following parametric studies.

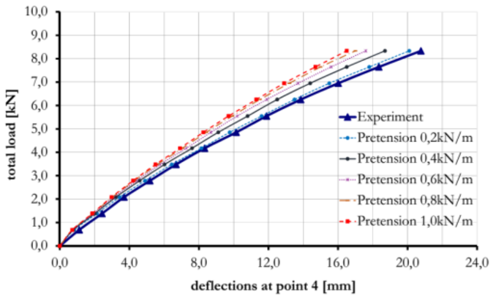

Fig. 5 Comparison of the test and GNIA vertical deflections under various prestressing

3. Parametrical Studies

In-plane and out-of-plane stability of 132 central arches in the 5 arches assembly (see Fig. 5), where the edge arches were continuously transversely supported, have been studied under various geometries, loadings and membrane prestressing. More details and results are ready for publication, but due to limited space not shown here.

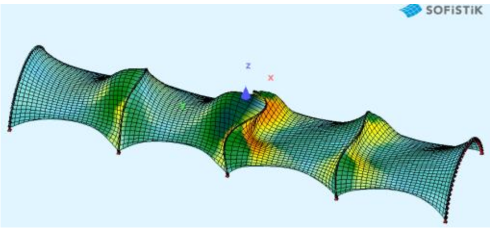

Fig. 5 Mid-arch with out-of-plane buckling

4. Conclusions

(1) The effect of textile membranes on both in-plane and out-of-plane supporting arch stability and strength is enormous.

(2) GNIA (by SOFiSTiK) proved to be adequate, provided the right value of the membrane prestressing is used.

(3) Large parametric studies of barrel membrane structures supported by a row of steel arches show enormous increase of both in-plane and particularly out-of-plane buckling loads in comparison to the ones of an arch alone. Provided the outer arches are transversely supported, the out-of plane buckling of the mid arches due to membrane support may always be neglected.

Acknowledgement

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