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Structural behavior of asymmetric spindle-shaped Tensairity girders under bending loads

Rolf H. Luchsinger*, Antje Sydow, René Crettol

Empa, Swiss Federal Laboratories for Materials Science and Technology, Center for Synergetic Structures, Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland

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ABSTRACT

The load bearing behavior of an asymmetric spindle shaped Tensairity girder is studied experimentally and compared to finite element analyses. The influence of the air pressure on the stiffness of the structure is investigated for homogeneous distributed load, asymmetric distributed load and a local load at the center of the structure. An overall good correlation between experiments and finite element predictions was found. An analytical model based on two coupled ordinary differential equations is presented and solved for the homogeneous distributed load case. The role of the form of the Tensairity girder on the stiffness is investigated by comparing the load-deflection behavior of the asymmetric spindle shaped girder with a cylindrical shaped girder.

1. Introduction

Inflatable fabric structures made from plain-woven fabrics combine low weight with compact storage volume, ease to deploy and enhanced damping capabilities. Inflated textile beams (airbeams) can be utilized in a variety of forms to achieve a high level of aesthetics and a free-form design concept and applications ranging from roof structures to inflated airplanes have been demonstrated. In order to understand the load bearing behavior of this unconventional structure, the static response of airbeams under bending loads has been studied [1,2]. Basically, the airbeam behaves as a thin-walled tube structure for small loads. For higher loads compressive stresses exceed the pretension of the hull and wrinkling has to be taken into account [3–6]. Finite elements for predicting the static response of inflated membrane structures were developed [7,8] as well as a Timoshenko beam finite element to predict the deflection and wrinkling load of airbeams at high internal air pressure [9].

A major restriction of airbeams is their poor load bearing capacity which drastically limits their application potential. This deficiency can be overcome by the structural concept Tensairity®, where the airbeam is combined with struts and cables [10]. First applications of Tensairity in the field of civil engineering are roof structures and bridges [11]. In Tensairity, the loads are carried by the struts and the cables while the airbeam stabilizes the system. Thus, minimal cross sections for the compression elements can be used. For example, adding 16% mass to an airbeam by adding a strut and a cable, the stiffness and ultimate load of the airbeam could be increased through the Tensairity concept by a factor 3 and 4, respectively [12]. Investigations of the static response of spindle shaped Tensairity structures to axial compressive loads revealed their potential as columns without [13] and with internal fabric webs [14]. Tensairity beams were studied under 3-point bending [15] revealing the influence of the air pressure on the stiffness of the structure. It was shown that the forces in the compression and tension member can be reliably estimated by simple analytical formulas. An analytical model for Tensairity beams without web under homogeneous distributed bending load has been proposed recently for thin compression members [16]. Some first results of the load-deflection behavior of web-Tensairity beams indicate that an analytical model based on beam theory can be applied in this case [12].

This study is devoted to the investigation of the static response of asymmetric Tensairity spindles to different types of bending loads. The test specimen and the experimental set up are described in Section 2. An analytical model based on the theory of beams on elastic foundation is presented in Section 3. Finite element models, outlined in Section 4, were developed in a commercial finite element code taking into account the textile's orthotropic linear elastic material properties and geometrical non-linearity. Results and discussion are given in Section 5 while Section 6 summarizes the main observations of this study and indicates possible further research.

2. Experiments

2.1. Design of the Tensairity beam

The research project started with the objective to demonstrate the major features of Tensairity in a single structure to be

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* Corresponding author. Tel.: +41 44 8234090; fax: +41 44 8234211.
E-mail address: rolf.luchsinger@empa.ch (R.H. Luchsinger).

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featured in a TV show [17]. It was decided to build a mobile demonstration bridge for cars with 8 m span. The challenging specifications demanded, that the two girders of the bridge can be easily transported in the trunk of a small car, that they can be quickly assembled as well as carried by two persons and that the car can finally be driven over the bridge [18]. An asymmetric spindle design was chosen for the girders in order to have a horizontal bridge deck. Aluminum profiles composed of five pieces of equal length of 1.6 m were used for the straight compression element, while steel cables were applied for the tension elements minimizing weight, transport volume and set up time. A test of the Tensairity demonstration bridge is shown in Fig. 1 and a dismantled Tensairity girder of the bridge can be seen in Fig. 2. The weight of a single girder was 68 kg, with 15 kg for the fabric hull, 42 kg for the compression element, 8 kg for the cables and 3 kg for the bolts. Thus, a girder could be carried by two persons. The two girders fitted well in the trunk of the car and were assembled in less than 30 min. The load bearing capacity of each girder was initially tested with a concrete block of 860 kg [18].

After the show, the load bearing behavior of the girder was tested in detail in our laboratory. To this end, the segmented aluminum compression elements were replaced by a single steel compression element while the original hull and cables of the test bridge were used. Geometry and dimensions of the girder are shown in Fig. 3. The straight compression member is a rectangular, hollow steel section of 120 mm × 40 mm × 3 mm. It is placed in a fabric pocket fixed along the top of the membrane within which it is held by friction due to air pressure in the hull. The fabric hull defines the shape of the girder. It has an inclined circular cross section of diameters changing between 150 mm at the ends and 600 mm at the center line. The membrane is made of PVC-coated polyester fabric (Valmex 7318 by Mehler Texnologies) with a thickness of 0.85 mm and a weight of 1000 g/m^2. The fabric orientation was chosen such that the warp direction corresponds to the longitudinal direction of the membrane body. Six spiraling cables were used as tension members, all of them connected at both ends to the compression element. The two long cables span 7.8 m and cross each other at the center line underneath the membrane body. The four short cables, two on each half of the girder, span 3.5 m. Made of 6 × 7 stainless steel wire ropes, the long cables have a diameter of 8 mm and an effective area of 29.1 mm^2, while the shorter ones have a diameter of 6 mm and an effective area of 15.7 mm^2. The Young's modulus of the cables is 100 kN/mm^2. The elastic properties of the fabric were measured in house with our biaxial test rig [19] and found to be $E_{\mathrm{warp}}=1.06$ kN/mm^2, $E_{\mathrm{fill}}=0.53$ kN/mm^2, $G=0.018$ kN/mm^2 and $\nu=0.386$.

Fig. 1. Test under operational conditions of the Tensairity demonstration bridge with 8 m span.

Fig. 2. Compression element, cables and inflatable hull of a single girder of the Tensairity demonstration bridge with 8 m span.

2.2. Test rig

A dedicated test rig was set up at Empa for the experimental investigations of the load bearing behavior of the Tensairity girder (Fig. 4). Different load cases were considered: local load at the center of the girder, homogeneous distributed load and asymmetric distributed load. The local load was applied by a force controlled winch, while two hydraulic pistons instrumented with load cells and a whippletree system with two balance layers and a system of four rollers transferring the force to the compression

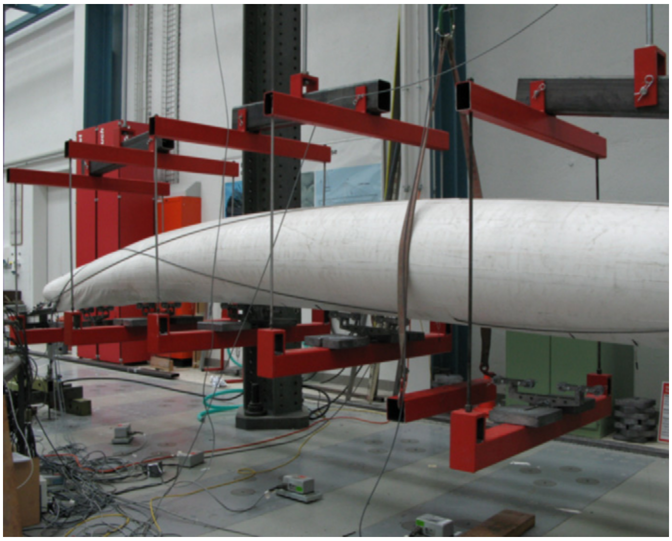

Fig. 4. Test rig for the asymmetric Tensairity spindle.

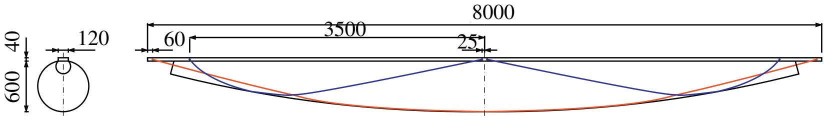

Fig. 3. Dimensions of the asymmetric Tensairity spindle.