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Experimental study of the effect of fabric webs on the static response of Tensairity columns to axial compression

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Abstract

Tensairity is a lightweight structural concept consisting of struts and cables stabilised by an inflated tube (Luchsinger *et al.* [1]). One of the latest structural developments is the application of a fabric web inside the air tube. This web, prestressed by the air pressure, is ascribed a positive effect on the stabilisation of the compression elements. Experimental research was performed to study the effect of the inflated tube and, in particular, fabric webs on the buckling behaviour of full-scale Tensairity columns (Wever *et al.* [2]).

Two 5 m long spindle-shaped Tensairity columns were tested: one without and one with internal webs. For different tube pressures the structures were subjected to an axial compressive load. The responses were analysed and compared. In practice the buckling behaviour of both columns appeared to improve for higher pressures, emphasising the stabilising effect of overpressure. Besides, the webs contributed in a positive manner to the response of the column. For every regarded pressure the Tensairity column with webs performed better in terms of axial stiffness and buckling load than the column without webs.

Keywords: Tensairity, lightweight structures, inflatable structures, fabrics, axial compression, buckling, full-scale tests, webs.

1. Introduction

Tensairity is a lightweight structural concept which can be classified as a hybrid pneumatic structure. The basic element is a beam (Figure 1). By adding a compression element and cables to an inflated tube a structural system is obtained in which the strut and cables carry the applied load and the air tube transfers forces between both and stabilises the compression element against buckling. In this way the load carrying capacity is increased compared to a traditional air beam whereas the pressure inside the air tube can be lowered.

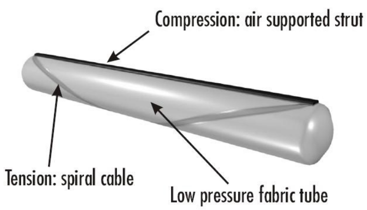

Figure 1: Tensairity concept (left) and Tensairity demonstration bridge (right)

Consequently, a Tensairity structure combines a sound structural behaviour with the advantages of pneumatics: lightness, compact storage and transport volume, fast setup and dismantling and aesthetics. With these characteristics Tensairity is especially interesting for temporary and architectural applications, like roof structures, (temporary) bridges and tent structures.

A first experimental study on Tensairity beams (Luchsinger and Crettol [3]) has demonstrated the strengths of the concept. Tensairity is however not restricted to beams: the concept can also be applied to columns and arches.

One of the main characteristics of Tensairity is the use of overpressure to stabilise the bending stiff compression element against buckling. The inflated tube serves as an elastic foundation which supports the strut along its length and whose modulus depends on the internal air pressure (Luchsinger *et al.* [1]). Earlier experimental research on a full-scale Tensairity column performed by Plagianakos *et al.* [4] showed an improved buckling behaviour for higher tube pressures.

The application of a fabric web inside the air tube, prestressed by the air pressure and supporting the strut along its length, leads in theory to a further increase of the modulus of the elastic foundation and thus to a stability enhancement. Fabric webs were previously applied by Breuer *et al.* [5] to improve Tensairity wing structures.

An experimental research was performed to study the effect of the inflated tube and, in particular, fabric webs on the buckling behaviour of full-scale Tensairity columns (Wever *et al.* [2]). In this paper the design of the columns and the experimental setup and procedures will be discussed. Furthermore, the test results and conclusions will be presented.

2. Design of the columns

Two 5 m long spindle-shaped Tensairity columns were tested, one without webs (plain-spindle) and one with internal webs (web-spindle), as can be seen in Figure 2. Both columns consisted of three curved aluminium struts, carrying the applied loads, which were supported by an inflated hull made of PVC coated polyester fabric. The struts had a rectangular cross-section (30x10 mm^2), were connected to the hull with pockets and mutually fixed at the ends with aluminium end pieces.

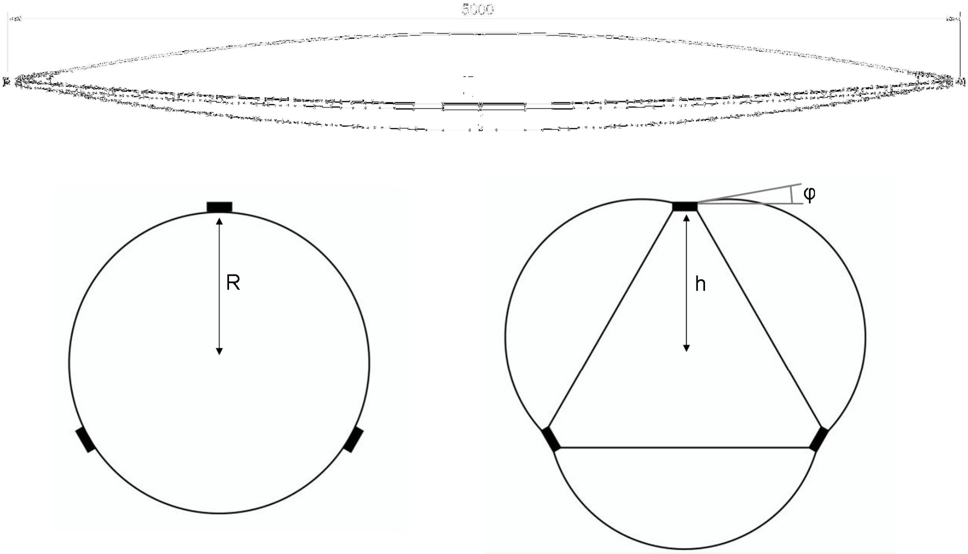

Figure 2: Front view of the columns (top) and mid cross-section of plain-spindle (bottom left) and web-spindle (bottom right), with $R = h$

In case of the web-spindle the three webs ran in the longitudinal direction inside the hull and supported and interconnected the struts. Direct support by a stiff web would in theory improve the modulus of the elastic foundation significantly. Whereas the modulus is a function of air pressure in case of the plain-spindle, it depends on the elastic material properties of the fabric in case of the web-spindle.

However, the webs would only be able to support the struts in case they were well prestressed by the internal air pressure. Therefore the angle φ was introduced (Figure 2). The angle was determined such as to equally prestress the webs along the span of the column. The addition of the webs resulted in a roughly doubled mass of the hull, increasing the total weight of the structure from 18.8 kg (plain-spindle) to 25.1 kg (web-spindle), a 33% increment.

3. Experimental configuration

The two columns were tested in a steel frame under simply-supported boundary conditions (Figure 3). For every experiment the hull was first inflated. Then an axial compressive load was applied on the tip of the column using a hydraulic piston with a calibrated load cell attached. Three loading-unloading cycles up to 6 kN were performed, in order to minimise the effect of hysteresis on the response, after which the column was loaded until buckling. Axial and lateral displacements of the structure were registered by dial gauges. The internal pressure was measured with a digital pressure sensor. The experiments were carried out for four different hull pressures: 20, 50, 150 and 250 mbar. After every test the buckled struts were replaced by new ones.

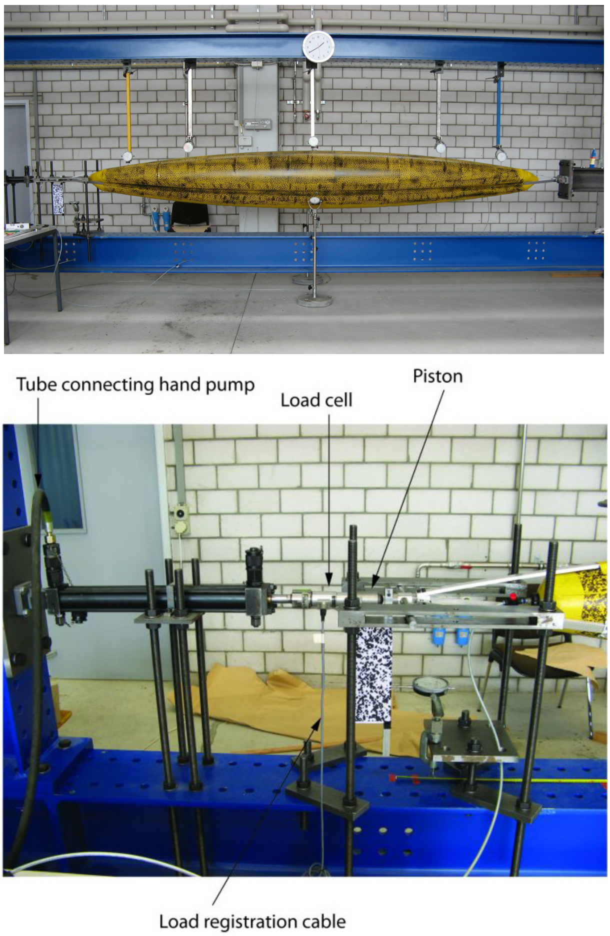

Figure 3: Overview of experimental configuration (top) and load application (bottom)

4. Experimental results

Figure 4 shows a typical measurement of the axial displacement at the tip of one of the columns. The response of the column can be partitioned in four phases. In the initial phase the hull support is activated. This is followed by the main compressive phase, in which the column shows the stiffest response. The slope of the graph, indicating the axial stiffness of the column, is nearly constant here. The main compressive phase illustrates a range of applicability of a Tensairity column in practice. In the pre-buckling phase the struts start to become unstable, indicated by the dial gauges, and the buckling mode becomes apparent. At last the displacements become very large and the column reaches its maximum capacity: the structure buckles.

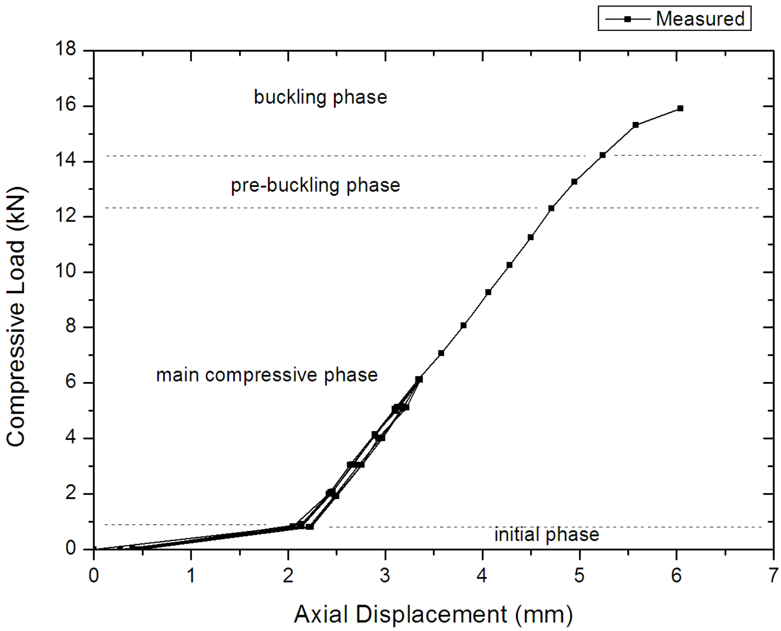

Figure 4: Typical load-axial displacement curve (250 mbar plain-spindle experiment)

In Figure 5 the responses of both columns during the last semi-loading cycle, towards buckling, are shown together for all pressure levels. It becomes clear that the effect of the air pressure on the response is twofold. For higher pressures both the axial stiffness and the buckling load of the columns improve. These effects are attributed to an increasing stiffness of the supporting hull, thus improving the stabilisation of the load-carrying compression elements. Consequently, the experiments show that the concept of pressure induced stability works for this type of structure.

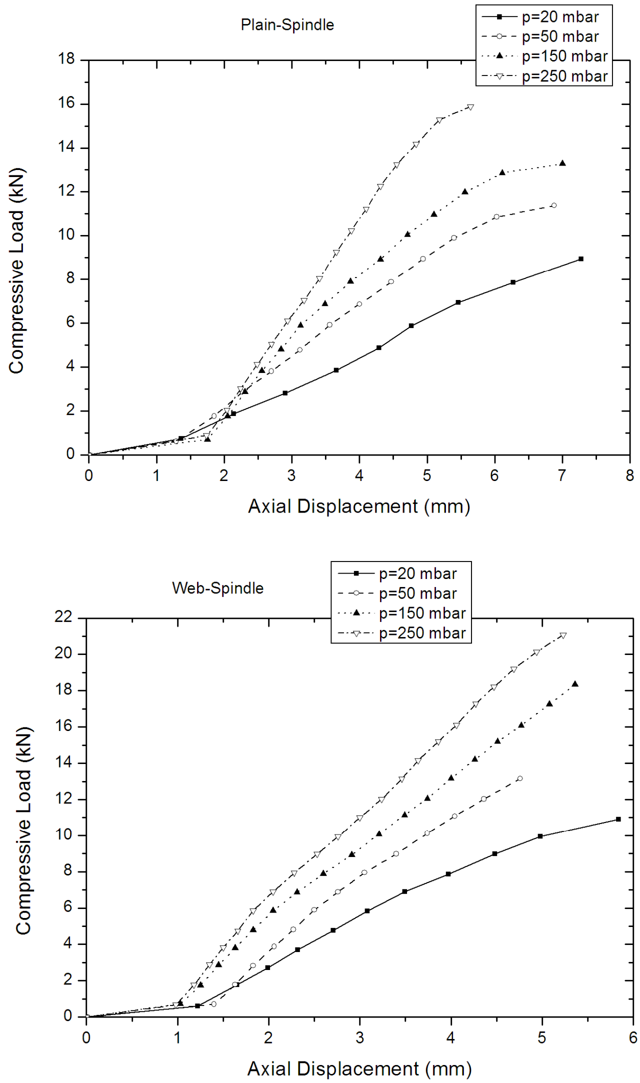

Figure 5: Load-axial displacement curves of the plain-spindle (top) and web-spindle (bottom)

Comparison between the plain-spindle and web-spindle reveals the benefit of the webs regarding the axial stiffness of the column. This is clarified in Figure 6, which shows the slopes of the load-axial displacement curves, between 1 and 6 kN, for both columns. For all pressures the web-spindle performs better than the plain-spindle. For lower pressures the measured improvement in stiffness is even a factor 2. The webs create a stiffer lateral support for the struts, which results in a stiffer response at the tip of the column.

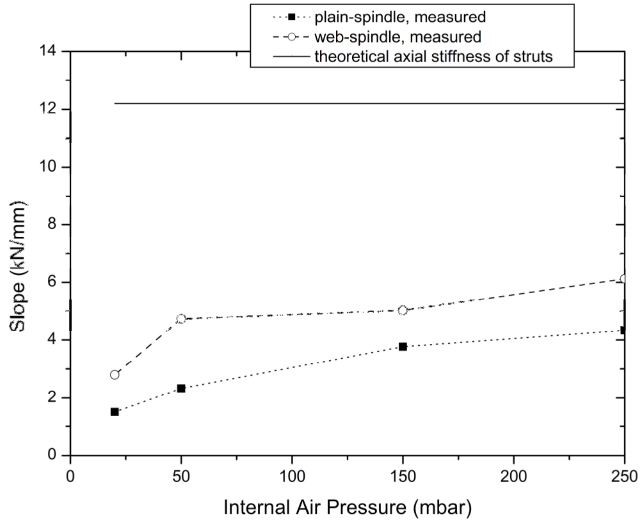

Figure 6: Effect of air pressure on the slopes of the load-axial displacement curves of the columns

The maximum registered stiffness is over 6 kN/mm, i.e. it takes more than 600 kg to shorten the column by 1 mm (0,02% strain). In Figure 6 the theoretical axial stiffness of the three aluminium compression elements is added. The fact that the experimental slopes are not far off this maximally attainable value indicates that the lateral support provided by the hulls is very effective in practice.

Regarding the load bearing capacity of the Tensairity columns the web-spindle also performs better than the plain-spindle (Figure 7). Whereas the buckling load is slightly larger for 20 and 50 mbar, the difference increases for higher pressures. The improvement is ascribed to the extra stability offered by the supporting webs, and the better cooperation they create between the struts.

The largest buckling load occurred in the 250 mbar web-spindle experiment and amounts to 21 kN. The theoretical yield force of the three compression elements is 144 kN, less than a factor 7 higher. When considering the high slenderness of the aluminium struts (500), this result clearly illustrates the stabilising effect of the inflated hull.

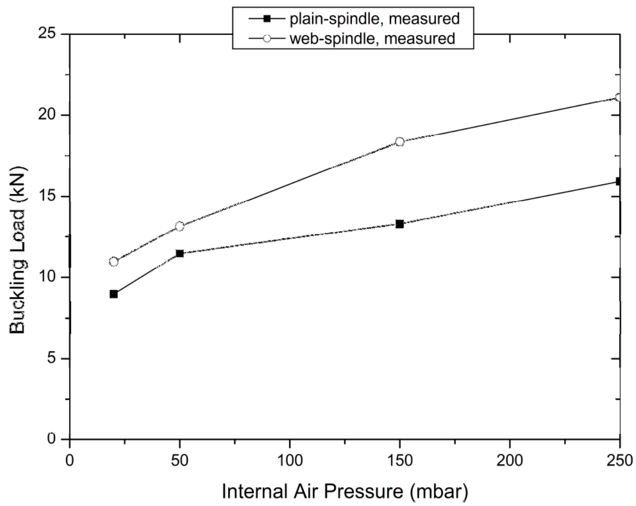

Figure 7: Effect of air pressure on the buckling loads of the columns

When the columns reach their load bearing capacity, a buckling mode develops. Once again differences between the plain-spindle and the web-spindle can be observed. For lower pressures the plain-spindle failed due to buckling of an individual strut; for higher pressures the buckling modes became global, i.e. the cooperation between the struts improved due to the stiffer connection created by the hull. The web-spindle however showed a global, 2nd order, buckling mode for all pressures (Figure 8). The extra connection between the struts improved the mutual cooperation, leading to a global response in all cases.

Figure 8: Web-spindle before loading (top) and after buckling in a global 2nd order mode (bottom)

5. Conclusion and discussion

Experiments on two spindle-shaped Tensairity columns have demonstrated the stiffening and stabilising effect of air pressure in this structural concept. Both axial stiffness and buckling load increase with hull pressure. The inflated hull offers an effective contribution to the stability of the structure, indicated by the relatively optimal exploitation of the strut's material properties.

The application of prestressed webs inside the hull further improves the structural behaviour of the column. The webs create an additional lateral support for the individual struts, thus increasing the modulus of the elastic foundation, and a better cooperation between the struts. This results in a higher axial stiffness and load bearing capacity of the column (approximately a 35% improvement for an average and realistic pressure of 150 mbar) and a more global response under loading.

The benefits of the webs could however be exploited more effectively in practice. For example, the webs are not directly connected to the struts, but to the pocket. Consequently, the modulus of the elastic foundation is lowered compared to a situation in which strut and web are directly fixed to each other. Furthermore, imperfections in the membrane hull due to the manufacturing process have a large effect on the action of the webs and therefore on the response of the column.

Adjustments in detailing and fabrication could further improve the structural behaviour of the web-spindle and thus diminish the influence of the aforementioned increased total weight. This would add to the applicability of a Tensairity column in practice, for instance as a pole in a tent structure. Future studies will focus on these improvements, as well as on the application of webs in Tensairity structures subjected to bending.

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