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TENSAIRITY®

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Abstract. *Tensairity is a new light weight structural concept. The key principle of Tensairity is to use low pressure air to stabilize compression elements against buckling. The basic Tensairity structure is a beam with the properties of a simple airbeam as light weight, fast set up and compact storage volume but with the load bearing capacity of conventional steel girders. Ideal applications of the Tensairity technology are wide span roof structures, temporary buildings and footbridges.*

1 INTRODUCTION

Compression: From the pyramids in Egypt, the columns of Greek temples, the arches and domes of the Romans to the gothic cathedrals of the Middle Ages, the history of civil engineering is full of astonishing buildings. The masters of these pieces relied all on the same structural principle, compression. Stones were laid on each other to build up the structure, essentially hold together by gravity. As an impressive and monumental demonstration of the power of the owner, these buildings used up incredible resources both in terms of money, material and human power. From a structural point of view, the compression principle of these buildings has a severe disadvantage: buckling. Buckling couples the load bearing capacity of a structure with its length. The longer the column, either the less load it can bear, or the larger the diameter needs to be. Larger cross sections mean more material which often cannot be utilized to the yield limit, thus a waste of resources.

Tension: On the other extreme, ancient nomadic tribes developed tent structures for their housing. Light and deployable as these shelters are, they are ideally adapted to the moving life of these autonomous peoples. Fabrics and ropes, the important elements of tent structures, rely on tension, structurally the most efficient use of a material. The load bearing capacity of e.g. a cable is independent of its length and solely determined by the material properties and the cross sectional area. Today, fabric structures have become more and more attractive, where light weight, cost efficiency, fast set up time and mobility in most cases rule out extravagance, pomposity and eternity. Fabric structures with more than hundred meter span have been built including covers for stadiums and airport halls. The design of new high tech fabrics and the ever improving computational possibilities are key factors for the progress of these tension structures in the 20th century.

Tension and compression: Where tension is, there is compression, too. Tent structures need poles. And these poles have to withstand buckling. The goal of good light weight structural engineering is to find the optimal interplay between tension and compression.

Tension and compression are evenly balanced in the new structural concept Tensairity. In combination with the extraordinary feature of buckling free compression highly efficient light weight structures can be realized based on Tensairity with a tremendous potential for applications e.g. in civil engineering.

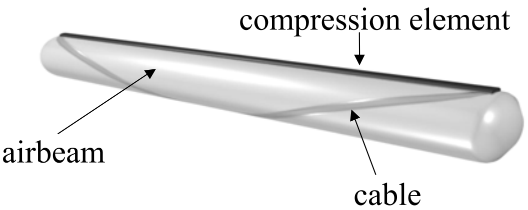


Figure 1. The basic elements of a Tensairity beam.

2 BASIC TENSAIRITY

In its most basic form, a Tensairity beam consists of a simple airbeam (a cylindrical membrane filled with pressured air), a compression element tightly connected to the airbeam and two cables running in helical form around the airbeam (Fig. 1). The cables are connected at both ends with the compression element. The basic theory of Tensairity has been described elsewhere [LUC04]. However, to understand the structural principle of Tensairity, a comparison with a truss girder is instructive (Fig. 2). The truss girder consists of a horizontal compression element with length *L*, vertical struts with length up to the height *D* and a cable which is connected at both ends with the horizontal compression element. The set-up of both structures is very similar. However, instead of the vertical struts of the truss an airbeam is fitted between cables and compression element in the Tensairity structure with important consequences.

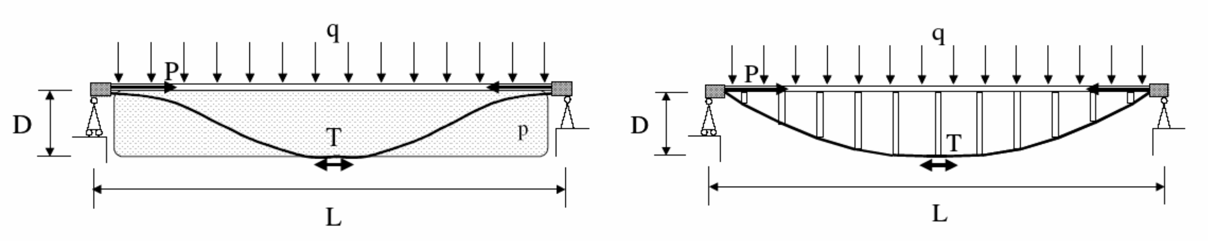


Figure 2 Tensairity girder (left) compared to a truss girder (right). Basically, the vertical struts of the truss are replaced by an airbeam in the Tensairity structure with important consequences.

Under distributed load *q*, the tension in the cable increases in both structures to compensate the bending moment. For slender structures ($\gamma = L/D >> 1$), the total cable tension *T* has approximately the same value for the truss and the Tensairity girder [LUC04]

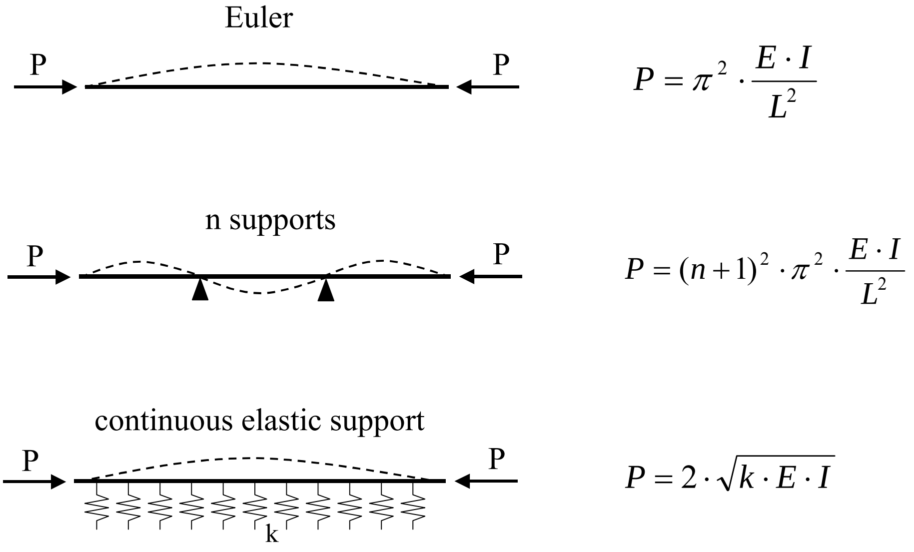
$$T = \frac{1}{8} \cdot q \cdot L \cdot \gamma \,. \tag{1}$$

Due to the connection of the cables with the compression element, the cable force is transferred to the compression element, acting there as a compressive force *P*. The compression element becomes prone to buckling. For the truss, the buckling length of the horizontal compression element is $L/(n+1)$ for *n* vertical struts. The horizontal buckling load in the truss is therefore

$$P_{buckling} = (n+1)^2 \cdot \pi^2 \cdot \frac{E \cdot I}{L^2} \,. \tag{2}$$

with *E* the modulus of elasticity and *I* the moment of inertia of the compression element. The buckling load decreases with the inverse square of the span and is therefore strongly span dependent. In general, the buckling load is much smaller than the yield load meaning an inefficient use of the material and extra weight for the compression element. The situation is analogue for the vertical struts which are also prone to buckling and therefore not used in the most efficient way. By increasing the number of vertical struts, the buckling length of the horizontal compression element decreases. However, the resulting decrease in weight of the horizontal compression element needs to be carefully balanced with the increase in weight given by the added vertical struts. Even in the optimal case, the dimension of all elements under compression is determined by buckling restrictions and thus the truss is not the most efficient structure.

The situation of the compression element is different in the case of Tensairity. The compression element is tightly connected with the membrane of the airbeam. Instead of the *n* supports of the truss, the compression element of Tensairity is continuously supported by the membrane. In fact, the membrane acts as a continuous elastic support for the compression element. The stiffness of this support is determined by the membrane stress, which itself is proportional to the overpressure inside the membrane tube. The different situations for the compression element in the truss and in Tensairity are shown in Figure 3. From the theory of beams on an elastic foundation, the buckling load is given by [SZA77].



$$P = \pi^2 \cdot \frac{E \cdot I}{L^2}$$

$$P = (n+1)^2 \cdot \pi^2 \cdot \frac{E \cdot I}{L^2}$$

$$P = 2 \cdot \sqrt{k \cdot E \cdot I}$$

Figure 3. Buckling load of beams under different conditions.

The situation with *n* supports is found in the truss. The continuous elastic support reflects the situation of the compression element in Tensairity. The buckling load is independent of the length for the continuous elastic support

$$P = 2 \cdot \sqrt{k \cdot E \cdot I}\,. \qquad (3)$$

with the spring constant *k* of the elastic foundation, the modulus of elasticity *E* and the moment of inertia I of the compression element. Thus, in Tensairity the buckling load of the compression element is independent of the span of the beam. In Tensairity structures the spring constant depends on the overpressure p of the airbeam and is given by [LUC04]

$$k = \pi \cdot p\,. \tag{4}$$

and the buckling load of the Tensairity compression element is therefore

$$P_{buckling} = 2 \cdot \sqrt{\pi \cdot p \cdot E \cdot I}\ . \tag{5}$$

A proper choice of the moment of inertia for a given material and overpressure results in a buckling load which can be higher than the yield load and the yield load becomes the limiting factor of the compression element. This is what we call buckling free compression. Tension and compression can be used with the same efficiency. Together with the tensioned membrane, all components of a Tensairity beam can be stressed to the yield limit leading to the interesting light weight properties of the technology. Therefore, Tensairity beams can be by factors lighter than conventional girders with identical span and identical maximal load [LUC04]. The air overpressure is a very important quantity in Tensairity. To estimate the optimal pressure, the interaction between the cable and the membrane must be studied. Under load, the cables press into the membrane leading to a normal force on the cable analogue to the normal force on the compression element by the elastic support of the membrane. The cable tension is the product of this normal force with the curvature of the helical cable. Since the normal force depends on the pressure, a relation between cable tension and pressure is established and with Eq. 1, external load and pressure are related. Given a load per area q_a as common e.g. in roof structures, the overpressure p is given by [LUC04]

$$p = \frac{\pi^2}{2} \cdot q_a\,. \tag{6}$$

For example a pressure of $p = 5$ kN/m^2 (50 mbar) results for a uniform load of $q_a = 1$ kN/m^2. As a very important feature of Tensairity the overpressure is independent of the span of the structure. The overpressure of a simple cylindrical airbeam (pressurized fabric tube without any struts or cables) to

$$p = \frac{2}{\pi} \cdot q_a \cdot \gamma^2\,. \tag{7}$$

With the square of the slenderness the pressure of the simple airbeam strongly depends on the beam form. For slender structures ($\gamma \cong 30$ the pressure in the simple airbeam needs to be more than a factor 100 higher than the pressure in a Tensairity structure to withstand the same load. Thus the load bearing capacity of simple airbeams is very limited and either a high pressure or a clumsy form is needed for reasonable applications. This difference reflects the fact that the role of the overpressure is very different in Tensairity and in the simple airbeam. In Tensairity, the load is carried by the cables and the compression element with the air used to pretension the cables and to stabilize the compression element. In the simple airbeam, the compressed air together with the pretensioned membrane is itself the load carrying structure. The pressure of Tensairity structures ranges from 50 mbar to a few 100 mbar depending on the application. Given this pressure range, Tensairity opens up a new interesting field for pneumatic structures between the airhouses with an overpressure of a few mbar and simple air beams with an overpressure of a few bar.

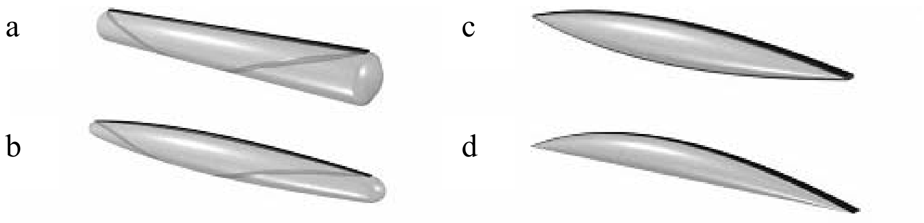


Figure 4. Various forms of Tensairity beams: (a) cylinder, (b) cigar-shaped, (c) symmetric spindle-shaped and (d) asymmetric spindle-shaped.

The Tensairity beam of Figure 1 has a cylindrical form. Other forms based on a circular cross section are possible, too. We have investigated various beam shapes by means of finite element calculations [PED04a]. As it turns out, a cigar-shaped geometry (Fig. 4b) is better adapted to the structural demands than the cylindrical form (Fig. 4a). Membrane material can be saved and the beam is stiffer. The spindle-shaped geometry (Fig. 4c-d), where the tube end converges to a point, is the stiffest configuration. In this case, the geodesic spiral of the cable degenerates to a straight line and the cable can be replaced by a tension rod. Given these advantages, many Tensairity applications will be based on cigar- or spindle-shaped tubes [PED04b].

3 TENSAIRITY DEMONSTRATION BRIDGE

As a first demonstration of the power of Tensairity we built a small car bridge with 8 m span and 3.5 tons maximal load (Fig. 5). The supporting structure of the bridge is given by two parallel cylindrical Tensairity beams with a diameter of 50 cm each. The membrane of the Tensairity beam is standard PVC coated polyester fabric. Steel cables with 6 mm diameter were used. Due to the moving local load of the car, an extra set of cables winding twice around the tube is added to stiffen the structure in the first and last quarter of the bridge. The compression element is made of a carbon sandwich for demonstration and test purposes. Aluminum or steel would have worked equally well. The two Tensairity beams are covered with wood plates to drive on. These plates do not have any structural function. The working pressure in the tubes as shown in Figure 5 was 400 mbar. Each complete Tensairity beam weights 40 kg. The weight of a HEB steel girder with the same load bearing capacity is 370 kg. A simple air beam with the same dimensions would need a pressure of almost 15 bar for the same load bearing capacity.

Figure 5. Tensairity demonstration bridge with 8 m span and 3.5 tons maximal load.

The design of the bridge was done in two steps. In a first step, the dimensions of all components were calculated based on our analytical model [LUC04]. In a second step, the bridge was modeled with FEM for fine tuning of the structure. The commercial software ANSYS 7.1 was used [PED04a]. The mesh model of a single 8 m Tensairity beam as well as the calculated longitudinal stress of the membrane are shown in Figure 6.

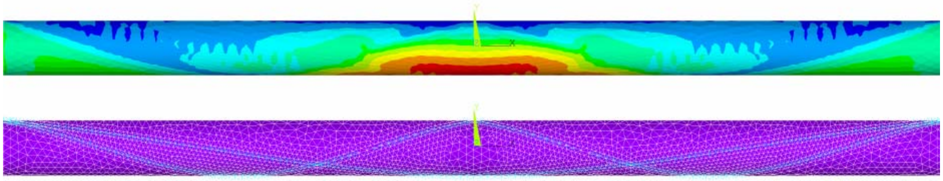


Figure 6. FE analysis of the 8 m Tensairity beam. The mesh (top) and the calculated longitudinal membrane stress (bottom) are shown.

Next to the light weight property, the fast and easy set up of Tensairity structures is an other important advantage. Assembling of the Tensairity beams of the bridge is very easy. The membrane has to be rolled out, the compression element stuck together and connected with the membrane in this case by means of a keder. In the next step, the cables are positioned and connected with the compression element. Finally, air is pumped into the membrane and the Tensairity beam is complete. The beam can be designed such that no screws or rivets are needed for the assembling allowing a very fast set up. The dismantled Tensairity beam of the bridge can be compactly stored and easy transported. Membrane and cables can be rolled together. We have also performed ultimate load tests with the Tensairity beams of the demonstration bridge. A frame was constructed to fix the Tensairity beam while it was put under load by means of a hydraulic piston. Two cases were investigated: a central load in the middle of the structure and a load at one quarter of the structure (Fig. 7, left). At the central position we were not able to break down the structure due to the limited extension of the piston. However, the maximal applied load was 30 kN. The beam operated still in a completely elastic range as all deformations were reversible by unloading of the structure.

Figure 7. Limiting load test of the Tensairity beam with 8 m span. Deformation of the beam at the maximal applied load of 35 kN shortly before failure (left). Shear failure of the compression element (right).

The measured deformation of the beam for a given load at the quarter position is shown in Figure 8. A maximal load of 35 kN was determined. Slightly above 35 kN, the compression element failed due to the high shear forces at the end of the wooden beam used to distribute the high local forces of the hydraulic piston (Fig. 7, right). The membrane remained intact during failure and the airbeam was still air tight. Thus, the Tensairity beam still had a significant load bearing capacity after failure.

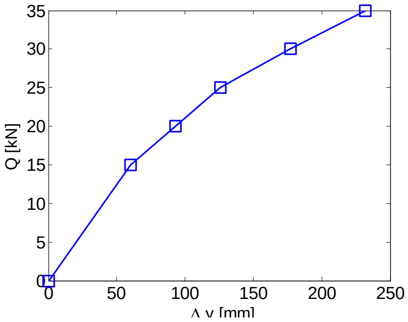


Figure 8. Measured load versus deflection at the piston for the Tensairity beam with 8 m span from the demonstration bridge. The data is for the load at the quarter position (Fig. 7, left).

The experimentally investigated ultimate load of the Tensairity beam was close to the theoretically estimated value. An other important lesson learnt from these tests is, that the limit of the Tensairity structure seems to be predictable. The Tensairity test bridge fulfilled all the expectations of this new technology. It clearly demonstrates that real loads can be carried by Tensairity with low structural weight and small overpressure. The basic Tensairity concept of pressure induced stabilization of compression elements has been confirmed. Theory, FE-analysis and the experimental model are in good agreement proofing the soundness of the technology.

4 CONCLUSIONS

The historical evolution from compression towards tension, from heavy to light is by no means completed. Tensairity seeks the stable balance between tension and compression by eliminating the disadvantages of compression. This is made possible through introduction of the new mediating structural element air. Light weight, efficiency, functionality and other important properties arise from this revolutionary combination. Given this excellent properties Tensairity is ideally suited for deployable applications as large tents, seasonal covers for tennis courts and swimming pools, scaffolds or temporary bridges. Wide span roof structures can take profit of the excellent light weight properties of Tensairity. New design opportunities e.g. fascinating illuminations due to the translucency of the membrane make Tensairity very attractive for modern architecture [PED04b] and can lead to a new formal language. Other interesting fields for Tensairity might be aviation or spaceflight, the spectrum of possible applications of this fundamental new structure is almost not limited. Above all, light weight structures mean a sensible and intelligent dealing with the resources of this planet. Tensairity has a tremendous potential for reaching this goal.

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