An inflatable wing using the principle of Tensairity

Joep Breuer* and Wubbo Ockels†
Delft University of Technology, Delft, The Netherlands

Rolf H. Luchsinger‡
Empa, Dübendorf, Switzerland

[Abstract] The paper describes the new concept Tensairity which can be used to significantly improve the load bearing capacity of inflatable wings. The basic principle of Tensairity is to use an inflatable structure to stabilize conventional compression and tension elements. So far, Tensairity has been mainly used in civil engineering application like roof structures and bridges. In this work, considerations to apply Tensairity to wing structures are given and the construction of two wing-like Tensairity kite prototypes is described. Test results on the Tensairity structure used in these kites are presented and compared to purely air inflated structures. Finally, the advantages of Tensairity wings are discussed and some application areas of these wings are suggested.

Nomenclature

E	=	Young's Modulus	[N/m^2]
h	=	height	[m]
I	=	moment of inertia	[m^4]
k	=	spring coefficient	[N/m^2]
L	=	length	[m]
M	=	bending moment	[Nm]
P	=	force	[N]
p	=	pressure	[N/m^2]
q	=	distributed load	[N/m]
R_0	=	radius	[m]
T	=	force	[N]
γ	=	slenderness	[-]
φ	=	angle	[rad]

I. Inflatable wings

The idea of using an inflatable structure to build a load carrying wing has a long history. In a patent from 1933, inflatable spars were already suggested. During the 1950's there were two interesting developments in manned flight using inflatable wings (the Inflatoplane from Goodyear and the British ML Aviation Mk1, which is a tailless design)[1]. In the more recent past, from 1990-2000, the Swiss company 'prospective concepts' developed a series of aircrafts with inflatable wings as technology demonstrators[§]. The Stingray, a tailless design with 13m span had webs in chord direction and operated with a very low internal pressure of $0.02\text{-}0.05 \cdot 10^5$ N/m^2 (Fig. 1).

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* Graduate Student, Department of Aerospace Engineering, ASSET Chair, Klyuverweg 1, 2629 HS, Delft, The Netherlands.
† Professor and Head of Chair, Department of Aerospace Engineering, ASSET Chair, Klyuverweg 1, 2629 HS, Delft, The Netherlands.
‡ Head of Center, Empa, Center for Synergetic Structures, Ueberlandstrasse 129, CH-8600, Dübendorf, Switzerland.

§ www.prospective-concepts.ch

Figure 1. The manned inflated aircraft Stingray of 'prospective concepts'.

In the later prototypes Pneuwing and Pneumagic, slender wings were realized with webs in span direction and a higher internal pressure in the order of $0.7 \cdot 10^5$ N/m^2 (Fig. 2). The spacing between the webs is very small (in the order of a few centimeters) to accurately define the airfoil shape.

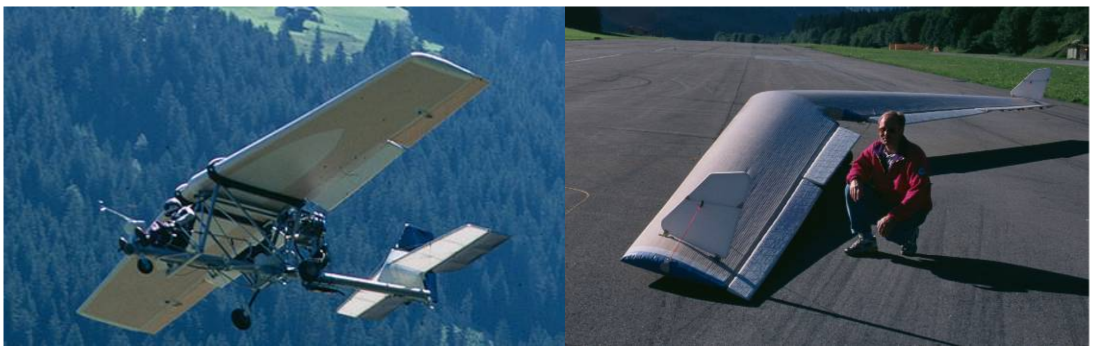

Figure 2. The manned inflated aircraft Pneuwing (left) and Pneumagic (right) of 'prospective concepts'.

Recently the interest in inflatable wings is shifted to un-manned aircraft with examples as the NASA Dryden I2000 inflatable wing and the prototypes of the University of Kentucky in cooperation with ILC Dover[2-5].

Inflatable surf kites can also be seen as inflatable wings although there the definition of the airfoil is much cruder. The front of the airfoil is shaped by a single air tube (with an internal pressure of $0.5 \cdot 10^5$ N/m^2). The rest of the airfoil is a thin membrane behind this tube, tensioned by air struts in chord wise direction and the wind. The development in these kites is advancing quickly as the sport is gaining popularity. Most of the development follows from experiments by surf kite designers, although currently the scientific interest in kites is increasing for their possible use in energy production and ship propulsion[6, 7].

One advantage of inflatable wings is that their flexibility gives them the capability to recover from gusts and crashes. Also it gives an opportunity to actively morph the wing for control. However, this flexibility also has a disadvantage. To get enough stiffness for a certain load capability either high pressure, thick wings, low aspect ratio or a combination of these factors is necessary. A way to improve the load bearing capacity and stiffness of inflatable wings while keeping most of the advantages is to use the structural concept Tensairity.

II. Tensairity®

The basic idea of Tensairity** is to combine an airbeam with conventional cables and struts to improve the load bearing capacity of inflatable structures[8-10]. The name Tensairity, a combination of tension, air and integrity, reflects the relationship with the structural concept Tensegrity. Developed by R. Buckminster Fuller, Tensegrity structures use a combination of cables and struts purely loaded in tension and compression, where two compression elements only interact with each other by means of the cables. In short, Tensairity is Tensegrity plus air.

The basic Tensairity beam consists of a compression element, a low pressure airbeam which is tightly connected to the compression element and two tension elements which run from end to end of the compression element in a spiral way around the airbeam (Fig. 3). Following Ref. 8 and 9, the low pressure airbeam (typical pressures for Tensairity are in order of $0.1 \cdot 10^5$ N/m^2) pretensions the cables and stabilizes the compression element against buckling.

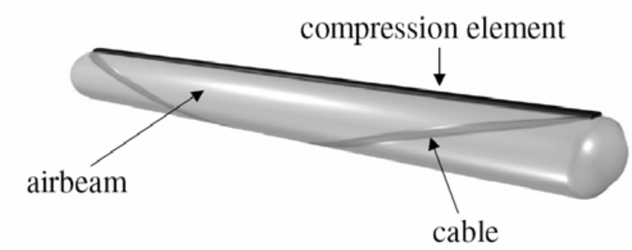

Figure 3. Basic Tensairity beam element.

Some fundamental relations shall be briefly summarized. The slenderness of a girder is defined as:

$$\gamma = \frac{L}{2 \cdot R_0} \quad , \tag{1}$$

with L and R_0 defined as in Fig. 4.

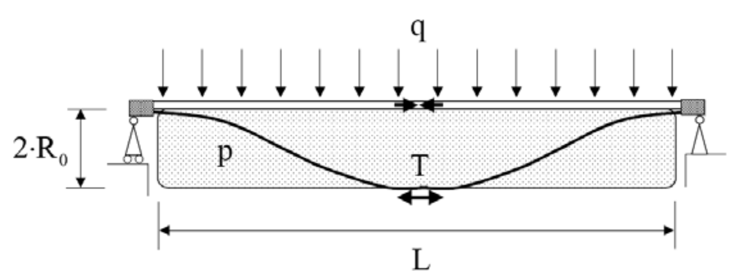

Figure 4. Forces in a Tensairity beam element.

If a distributed load q acts on the structure, the load is transferred by the airbeam to the tension elements (cables). The total force in the tension element is given by

** Tensairity® is a patented technology of the Swiss company Airlight Ltd developed in close collaboration with prospective concepts ag. The Tensairity research activities of 'prospective concepts' have been recently transferred to the Center for Synergetic Structures at Empa, the Swiss Federal Laboratories for Materials Testing and Research.

$$T = \frac{M}{2 \cdot R_0} = \frac{\frac{1}{2} \cdot q \cdot (L/2)^2}{2 \cdot R_0} = \frac{q \cdot L}{8} \cdot \frac{L}{2 \cdot R_0} = \frac{q \cdot L \cdot \gamma}{8} \quad . \tag{2}$$

As the tension element is tightly connected at both ends with the compression element, the horizontal force flow is closed leading to a compressive force in the compression element. For a compression member not only the stresses but also buckling phenomena have to be taken into account. In case of a simply supported structure, the allowable compression load can by approximated by Euler buckling, where the buckling load depends as the inverse square of the length of the element. In Tensairity, the compression element is tightly connected to the airbeam which can be considered as a continuous elastic support. In this case, the allowable compression load is independent of the length and given by [ref. 8.]:

$$P = 2 \cdot \sqrt{k \cdot E \cdot I} \quad , \tag{3}$$

where k is the spring coefficient of the foundation. The spring coefficient of the airbeam in a Tensairity structure depends mainly on the internal overpressure and can be approximated by

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

This means that the allowable buckling load for a compression element in Tensairity is approximated by

$$P = 2 \cdot \sqrt{p \cdot \pi \cdot E \cdot I} \quad . \tag{5}$$

Depending on pressure, Young's modulus and moment of inertia , this allowable buckling load is in general higher than the Euler buckling load and can be higher than the load based on the yield stress of the material.

First realized applications of Tensairity are bridges and roof structures (Fig. 5). Light weight, fast and easy setup, new formal language and lighting options are properties of Tensairity which make this technology interesting for civil engineering applications. But Tensairity is a general concept for light weight structures and thus by no means restricted to civil engineering applications. It is the purpose of this work to investigate the potential of Tensairity for wing structures.

Figure 5. First applications of Tensairity in civil engineering: test bridge with 8 m span (left) and roof over a parking area in Montreux, Switzerland with 28 m span.

III. Theoretical weight comparison

As a first attempt to demonstrate the potential of Tensairity, the weight of different structures under the same load conditions and geometries are compared. A simple airbeam, a truss, a Tensairity spindle and a Tensairity web spindle are considered. Next to the cylindrical form (Fig. 3), Tensairity girders can also have a spindle shape as in the roof structure of Fig. 5. In this comparison only symmetrical spindles are considered. The spindle shape leads to stiffer structures by using less membrane material compared to cylindrical shaped Tensairity10. A further improvement of Tensairity is possible when a web is placed between the tension and compression element (Fig. 6).

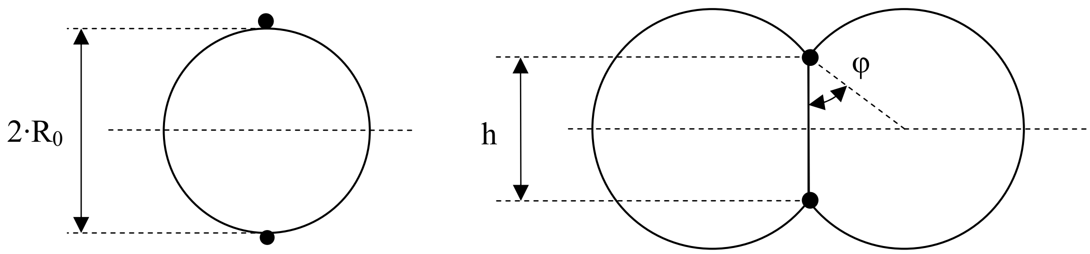

Figure 6. Cross-section of a Tensairity spindle (left) and a Tensairity web spindle (right). The black dots indicate tension and compression element.

This web will give an additional support for the compression element increasing the value of the spring coefficient in Eq. 4. This improves the stabilization of the compression element and can further reduce the necessary internal pressure. The main function of the air pressure for the Tensairity web structure is to pretension the web which then stabilizes the compression element against buckling.

A span of 3m is assumed for all girders in this test and a distributed bending load of 250 N/m is applied on the simply supported beams, while different values for the slenderness are investigated. To have a fair comparison the truss structure has the same spindle shape. The airbeam, however, has a cylindrical shape, because a spindle shaped airbeam would buckle at the thin supported ends. The slenderness of a spindle is defined in the same way as in Eq. 1, where R_0 is the radius in the middle of the structure. In case of the web spindle, the slenderness is defined as the ratio of length over the height of the web in the middle of the structure. The four different structures used in this test are shown in Fig. 7.

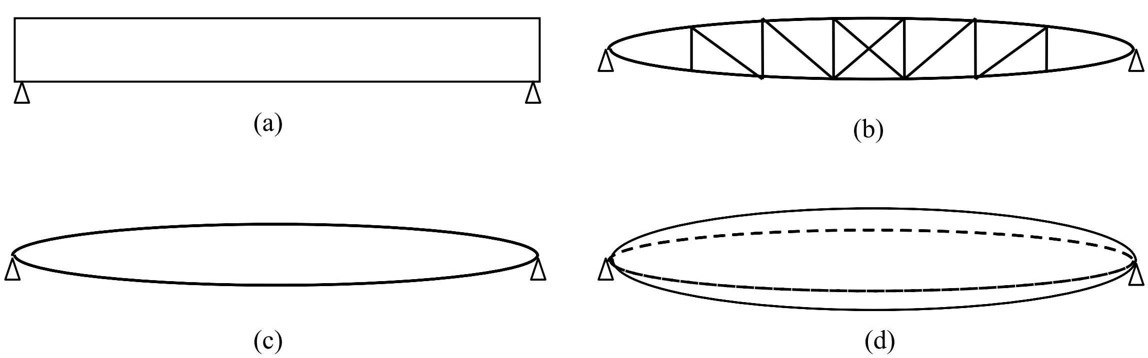

Figure 7. Four structures investigated in the theoretical weight study: a.) simple cylindrical airbeam, b.) truss, c.) Tensairity spindle, d.) Tensairity web spindle.

The following materials are used in the calculations if appropriate: high E-modulus carbon/epoxy for the compression elements (E = 142.5 GPa, σ_{max} = 490 MPa), high tension carbon/epoxy for the tension elements (E = 115 GPa, σ_{max} = 890 MPa), and an Aramid/PU composite for the membrane (E = 35 GPa, σ_{max} = 550 MPa).

To find the minimum weight for each structure at each slenderness under the given load conditions different parameters were varied. For the Tensairity spindle the pressure was varied. The pressure determines the thickness of the membrane of the airbeam and has an influence on the size of the compression element (Eq. 5). In case of the web Tensairity spindle the angle φ between the top of the web and the center of the adjacent tube was varied (Fig. 5). This angle determines the necessary internal pressure to pretension the web and the area of the membrane.

In case of the truss the number of equally spaced vertical elements was varied. The number of vertical elements has an influence on the size of the vertical elements, the diagonal elements and the buckling of the compression element. For the airbeam, no parameter was varied. However, the pressure needed to sustain the moment in the middle of the beam was calculated[8] and from this pressure the membrane thickness determined. The safety factor for the membrane was set to 2. Local buckling of the thin walls of the square shaped compression elements as well as global buckling were taken into account. No minimum was put on the cross sectional area of the compression and tension elements and the thickness of the membrane. The weight of the connections between the elements both in the truss and in Tensairity were not taken into account and the out of plane stability was not considered.

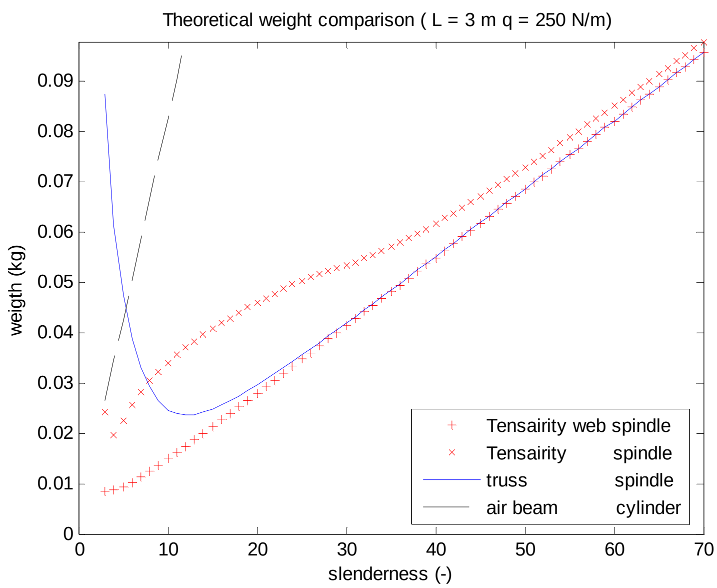

Figure 8. The minimal weight of various structures for given load condition and span as a function of the slenderness.

The result of this theoretical weight study is shown in Fig. 8. For slenderness above 10, the airbeam is the heaviest structure. This is due to the fact that the air pressure of a simple airbeam increases with the square of the slenderness[8]. The high pressure leads to high fabric tensions and thus to a thick membrane. The Tensairity spindle is considerably lighter than the airbeam. The much smaller air pressure in Tensairity allows for a thinner membrane and thus a drastic weight reduction which is by no means compensated by the weight of the additional compression and tension element. The lightest structure is the web Tensairity spindle, where the pressure can again be reduced. For slenderness values above 20, the difference between truss and web Tensairity becomes negligible. The reason is that for high slenderness values the weight of both the truss and Tensairity is dominated by the weight of the compression and tension elements. The weight of the compression element is then determined by the material limit too and no more a function of the type of support (air, web or strut). This tendency can also be seen for the normal Tensairity spindle which approaches the weight of the truss and web Tensairity for high slenderness values.

The major result of this theoretical study is that the weight of a Tensairity structure is comparable to the weight of an optimized truss. The web Tensairity structure is lighter than the normal Tensairity structure by a further reduction of the air pressure. The airbeam is from all structures the heaviest one for slenderness values above 10. Typical slenderness values for wing structures can be in the order of 50. Thus, much weight can be saved compared to the conventional inflatable wing design by using Tensairity.

IV. Experiments on a Tensairity web spindle

To get a better insight into the loading capabilities of a slender Tensairity web spindle, a test model of a Tensairity spar with the two adjacent tubes was built and loaded in different configurations. The dimension of the girder is defined by the kite model with 2 m^2 area which will be discussed in the next section. The model was made using the same light weight materials as for the kite: Exel carbon tubes as compression elements, an Aramid line as tension element, aluminum connection elements and Icarex polyester rip-stop fabric with a PU coating as restraint. Compared to the kite, only the bladder was of a slightly heavier polyethylene foil, due to availability. The length of the test model was 3.1 m, the radius of the tubes about 45 mm, the maximum height of the web 58 mm and the angle φ varied from 50° in the center of the tube to 78° at the ends of the web,. These dimensions result in a slenderness of 53 (see Eq. 1). Both the tension and compression element have the shape describe a circular arc over the length of the girder and are inserted in pockets sewn at the top and bottom of the web in the restraint. The distributed load was approximated by using 9 load introduction points. The test model was supported at both ends. A drawing of the test set-up can be seen in Fig. 9.

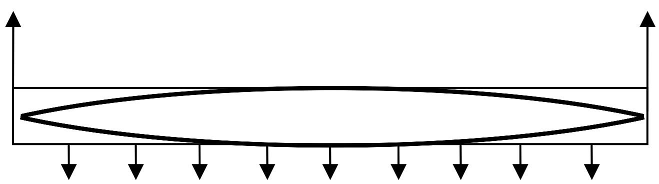

Figure 9. The experimental set-up for a Tensairity web spindle. The arched lines are the tension and compression element. The compression element is on the upper side under the given load conditions. The web is the area between tension and compression element.

In the first experiment, the Tensairity web configuration was compared with a simple inflatable configuration (air tubes), that means the tension and compression element were removed from the structure in this case. In Fig. 10, the load deflection diagram is shown for a pressure of $0.075 \cdot 10^5$ N/m^2.

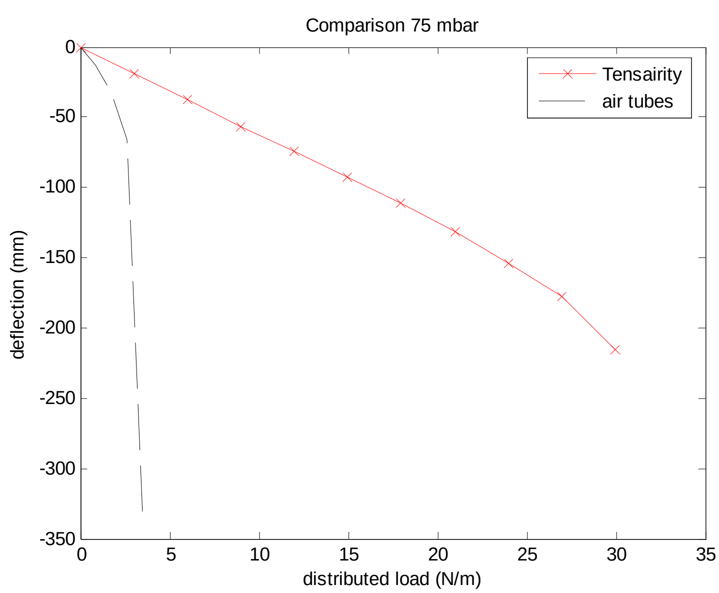

Figure 10. Experimental load-deflection diagram for a Tensairity web spindle and the according air tubes (simple airbeam) for a pressure of $0.075 \cdot 10^5$ N/m^2.

The stiffness and the maximum allowable load of the air tubes are as expected at the same pressure much smaller for the air tubes than for Tensairity. The deflection curve of Tensairity is very straight up to the point of buckling. A similar result is found for other investigated pressure values ranging from $0.025 \cdot 10^5$ N/m^2 to $0.1 \cdot 10^5$ N/m^2. An effect which lowers the allowable buckling load in Tensairity is the moving of the compression element in the pocket under large deformations[10]. This effect can be reduced by a careful design of the pocket increasing the friction or by connecting the membrane after assembling at both ends with the compression element. .

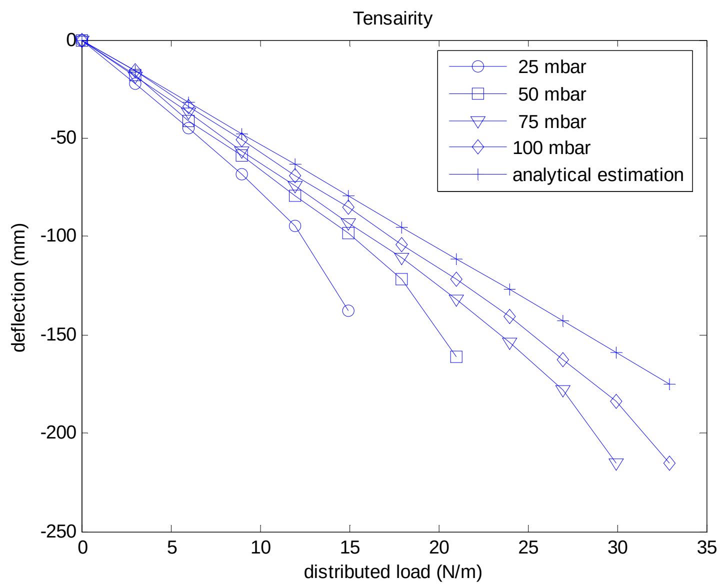

Figure 11. Load-deflection diagram of the Tensairity web spindle for different pressure values.

The load-deflection diagram for the Tensairity web spindle at different pressure values is shown in Fig. 11. With increasing pressure, obviously the buckling point is postponed and the stiffness increases. The positive influence of the pressure on the stiffness can be partly explained by the increased friction between the pocket and the compression element for higher pressure values. However, the major effect of the pressure on the stiffness is a more pretensioned membrane which leads to a more constant spacing between tension and compression element.

An analytical estimation is also shown in Fig. 11, which was made using the modified Castigliano's theorem

$$\delta_i = \frac{\partial}{\partial P_i} \int \frac{M^2 dx}{2EI} = \int \left(\frac{M}{EI} \right) \left(\frac{\partial M}{\partial P_i} \right) dx \, , \tag{6}$$

where P is a dummy load. As a simplification, only the tension and compression element with a fixed distance (infinitely stiff web with infinite pressure) were considered in this model. The bending stiffness EI varies along the length x of the beam due to the geometry of the spindle and the bending moment M varies with x too. However, due to these simplifications, the deflection of this analytical model is independent of the air pressure. Considering Fig. 10 it is a reasonable approximation to neglect the contribution of the air tubes to the stiffness of the Tensairity structure. As can be seen in Fig. 11, the stiffness of the Tensairity web spindle is quite well approximated by the simple analytical model especially for high pressure values.

The increase in weight by adding the compression and tension element to the air tubes in Tensairity is very small compared to the increase in stiffness and allowable load. The weights of the test girder model are given in table 1.

Part	*Material*	*Weight (gr)*	*% of total weight*
Compression element	Exel carbon tube 3.9x2.5 mm	34	10.8
Tension element	2 mm Aramid line	5	1.6
Connection elements	Aluminum	12	3.8
Total Tensairity			**16**
Restraint	Icarex kite fabric 31 gr/m^2	86	27.3
Bladder	Polyethylene 70 gr/m^2	178	56.5
Total weight		**315**	**100**

Table 1. Weights of the different components of the test web Tensairity girder.

The tension and compression elements are only 16% of the total weight of the structure which is dominated by the weight of the restraint and especially the weight of the bladder. Using a thinner bladder would reduce the total weight of the girder. However, this would also slightly increase the portion of the tension and compression element to the total weight.

V. Inflatable Tensairity Wings

Several ways to insert Tensairity in a wing structure were investigated, but eventually a fully inflatable multi spar wing with two discrete Tensairity elements was chosen. The spars with Tensairity are placed at about 15% and 70% of the wing chord. The positions of the tension and compression elements of the Tensairity spars are indicated with the black dots in Fig. 12. In this way the advantages of Tensairity and an inflatable wing can be fully used. As shown in Fig. 12 an outer hull was used to smooth the surface. The trailing edge was made of foam.

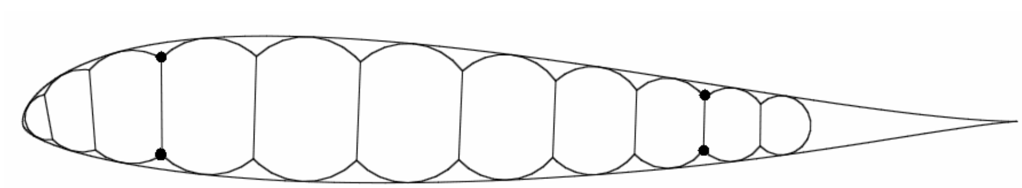

Figure 12. The Tensairity spars in the 4 m^2 kite (MH 91 airfoil).

To investigate the applicability of Tensairity in wing structures, two kites were constructed. These kites enabled construction of prototypes in a short time and allowed to test Tensairity wings in flight without the need of power and/or radio control. The first full-scale model was a 2 m^2 kite with a span of 3 m. This size generates enough power to do measurements and is big enough to ease production. For production reasons the taper ratio was chosen equal to 1. A second prototype has a surface area of 4 m^2 and a span of 4.5 m to generate more force and to make the period of the oscillations in the flight dynamics of the kite a bit larger (Fig. 13).

Figure 13. The complete 4 m^2 Tensairity kite after inflation.

Because of the low internal air pressure in the order of 5000 N/m^2 in the Tensairity wing lightweight materials can be used. For the restraint and the outer skin, kite fabric (rip-stop polyester (Icarex, 31 gr/m^2) or rip-stop nylon (Chikara, 42 gr/m^2) with a thin PU coating) is used. The bladders are made of thermoplastic polyurethane (56 gr/m^2) or Mylar (MC2, 21 gr/m^2). To fix the shape to the trailing edge of the wing low density polypropylene foam (Eperan, 20 kg/m^3) is used. The Tensairity compression elements are carbon fiber kite tubes (Exel) and the tension elements are made of Aramid (Edelrid)/Vectran (Marlow ropes) lines. These materials lead to a total weight of about 600 gr/m^2 for both kites. Depending on the size of the wing and the number of cells of the restraint, the tension and compression element make up only between 10% to 15 % of the total weight. The tension and compression elements of both kites are designed such that the wing can take up a maximum load of 250 N/m^2. The use of kite fabric meant that the restraints could be made with a simple sewing machine resulting in fast and simple production.

The kites where tested on different beaches at the coast of the Netherlands, dependent on the wind direction, because a sea-wind is preferred. The wind speeds ranged from 4 m/s to 12 m/s (3-6 Beaufort). The test flights had in general a short duration (up to 5 minutes) and after each flight the kite was adjusted, especially in the bridle, or the test was canceled. First tests were made with 2 lines but a 4 line bridle proved to give more control. In the final bridle the power lines were connected to the front spar at the compression element, while the steering lines where connected to the compression element of the rear spar or even at the tips of the kite. To reduce the deflection at high loads and to increase the maximum allowable load of the kites, an extra attachment point was added in the middle of the front spar (Fig. 14).

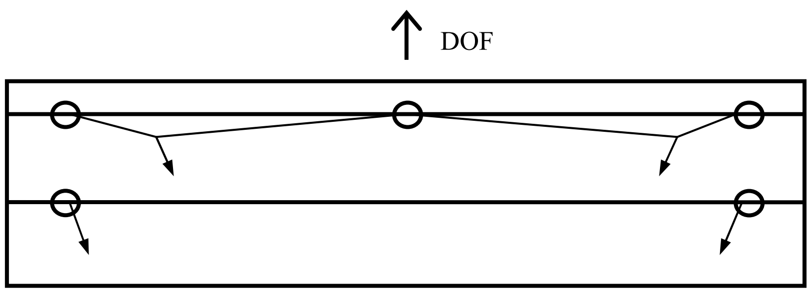

Figure 14. The final bridle of the Tensairity kites (the arrows indicate the kite lines).

Figure 15. The 2 m^2 Tensairity kite with 4 control lines in full flight

Due to the high L/D of the kites and the very flat shape, the kites were very responsive and fast. Only experienced kiters were able to fly with the kites. Because of the airfoil the small kite tended to be unstable at small angles of attack and the 4 m^2 kite proved difficult to handle (on the ground) in high winds, because of its size and stiffness. During the test flights the tips of the bladders (especially the thin Mylar bladders) proved to be very vulnerable,

VI. Conclusions

The new structural concept Tensairity does have interesting properties for wing structures. Theoretical investigations show, that the weight of a Tensairity structure is comparable to an optimized truss structure and much lighter than a simple inflatable structure for slenderness values typical in wings. Experimental tests with a Tensairity web girder confirm that the stiffness is much higher in Tensairity compared to a corresponding conventional inflatable structure with the same internal pressure. Therefore, compared to conventional inflatable wings, either a considerable amount of weight can be saved at a comparable stiffness or a considerable increase of stiffness at a comparable weight can be gained with Tensairity wings. The increased stiffness can be used to increase the span, for better performance or to increase the load bearing capacity of the wing. The lower pressure has consequences for the weight (use of lighter and cheaper materials) and the survivability. In case of a leakage it is much easier to compensate the air leakage with a small integrated pump, while still keeping structural rigidity. On the spot repairs of fissures are possible with simple methods at low pressure, too. Since the rigid elements are placed inside the wing and thus protected by an aircushion, the Tensairity wing has a good crash resistance. The ability to flex under gusts and overloads of a Tensairity wing is slightly less compared to a normal inflatable wing due to the presence of the rigid compression elements, but this is compensated by the higher allowable load. A disadvantage of the Tensairity wing presented in this work compared to conventional inflatable wings is that the Tensairity wing can not be deployed by simple inflation due to the rigid compression elements. The set up requires some small assembly by inserting the compression elements in their pockets, making the Tensairity wing not feasible for some special applications.

Practical testing of Tensairity wings by using them as kites worked well, although they are difficult to fly. This however is not related to the Tensairity concept but to the critical stability behavior of a rectangular wing which was chosen to simplify the manufacturing of the Tensairity kite in this work. Other wing shapes e.g. delta wings can be realized with Tensairity without conceptual problems. But using a Tensairity wing as a kite was a fast, cheap and easy method to get a first impression of the flight behavior of a wing and to refine the constructional details

The application area of a Tensairity inflatable wing is very wide. It can be used in Ultra Light aircrafts like the Pneuwing of ‘prospective concepts’, or hang-gliders like the Pneumagic. It would also be very interesting for small UAV’s like the ones developed by ILC Dover and the University of Kentucky, which have a comparable restraint shape. Currently the research with Tensairity wings is mainly focused on kites, because the L/D of a Tensairity kite is due to the good airfoil at least twice as high as in conventional kites. This makes the Tensairity kite interesting for use as a high altitude record kite (research on this subject was conducted at the faculty of aerospace engineering as part of an ESA project[11, 12]), as part of a wind power plant or for ship propulsion.

References

[1] Brown, G., Haggard, R., Norton, B., Inflatable structures for deployable wings. Vertigo, Inc. AIAA-2001-2068.

[2] Cadogan, D, Smith, T., Lee, R., Scarborough, S., Graziosi, D., “Inflatable and Rigidizable Wing Components for Unmanned Aerial Vehicles,” AIAA No. AIAA-2003-6630, 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Norfolk, VA, April 2003.

[3] Simpson, A., Santhanakrishnan, A., Jacob, J., Lumpp, J., Cadogan, D., Mackusick, M., Scarborough, S. ‘Flying on air: UAV flight testing with inflatable wing technology’. AIAA-2004-6570 AIAA 3rd”Unmanned Unlimited” Technical Conference, Workshop and Exhibit, Chicago, Illinois, September 2004.

[4] Simpson, A., Jacob, J., Smith, S., “Inflatable and Warpable wings for Meso-scale UAVs,” AIAA 2005-7161, Infotech@Aerospace, Arlington, Virginia, September 26-29, 2005

[5] Cadogan, D.P., Scarborough, S.E., Gleeson, D., Dixit, A.,“Recent Development and Testing of Inflatable Wings,” AIAA-2006-2139, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and 14th AIAA/ASME/AHS Adaptive Structures Conference, Newport, Rhode Island, May 1-4, 2006

[6] Ockels, W.J., “Laddermill, a novel concept to exploit the energy in the airspace”, *European Wind Energy Conference,* Nice, France, 1-5 March, 1999

[7] Ockels, W.J., “Laddermill-sailing, ship propulsion by wind energy independent from the wind direction”, *Journal of the International Shipbuilding Progress,* 2007 (submitted for publication).

[8] Luchsinger, R.H., Pedretti, A., Pedretti, M., Steingruber, P., ‘The new structural concept Tensairity: Basic principles’, *Progress in Structural Engineering, Mechanics and Computation*, A.A. Balkema Publisher , London, 2004.

[9] Luchsinger, R.H., Pedretti, A., Steingruber, P. & Pedretti, M., ’Light weigth structures with Tensairity. In Motro, R. (ed.), *Shell and Spacial Structures from Models to Realizations*, Editions de l’Espérou, Montpellier, 2004.

[10]Luchsinger, R.H., Crettol, R., “Experimental and Numerical study of spindle shaped Tensairity girders,” *International journal of space structures,* Vol. 21, No. 3, 2006, pp 119-130.

[11]Veldman, S.L., Vermeeren, C.A.J.R., Bersee, H.E.N., Bergsma, O.K., Conceptual design of a high altitude kite, Faculty of Aerospace Engineering, Delft University of Technology, AIAA-2002-1735.

[12]Breukels, J.,”KitEye: work packages 3 to 8,” internal report, faculty of aerospace engineering, Delft University of Technology, Delft, 2005