Pressure Induced Stability:
From Pneumatic Structures to Tensairity®

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Abstract

Pressure induced stability is very common in nature, although often not perceived. The green tissue of plants is supported by the cellular turgor pressure. This becomes most obvious when plants wilt due to water shortage. Technical realisation of pressure induced stability is found in tires, hot air balloons, airships and airhouses, where air or other gases are used as compressed media. These pneumatic structures do all have a simple geometry close to a sphere, a cylinder or a torus. Either they cover huge volumes with low pressure as in the case of airhouses and airships or have small volumes and high pressure as in tires. In recent years, prospective concepts ag has systematically investigated pneumatic structures in the intermediate pressure range. Technology demonstrators such as a pneumatic park bench or the pneumatic airplane Stingray are the offspring of these studies. It was shown that almost any shape can be made with pneumatic structures and that the load bearing capacity in this middle pressure range is high enough for many interesting and astonishing applications. Nevertheless, as outgrown plants start to lignify for improvement of stability, one can go a technological step further. Airlight Ldt in close collaboration with prospective concepts ag has developed the fundamental new structural concept called Tensairity. Tensairity is a synergetic combination of a pneumatic structure with traditional structural elements such as cables and struts. In Tensairity, cables, struts and compressed air complete each other perfectly. The result is a modified airbeam with the same load bearing capacity as a steel beam, but with a substantial weight reduction. This technology is ideally suited for wide span structures and for deployable applications such as temporary bridges, scaffolds or large tents and opens up many new technical opportunities for pressure induced stability.

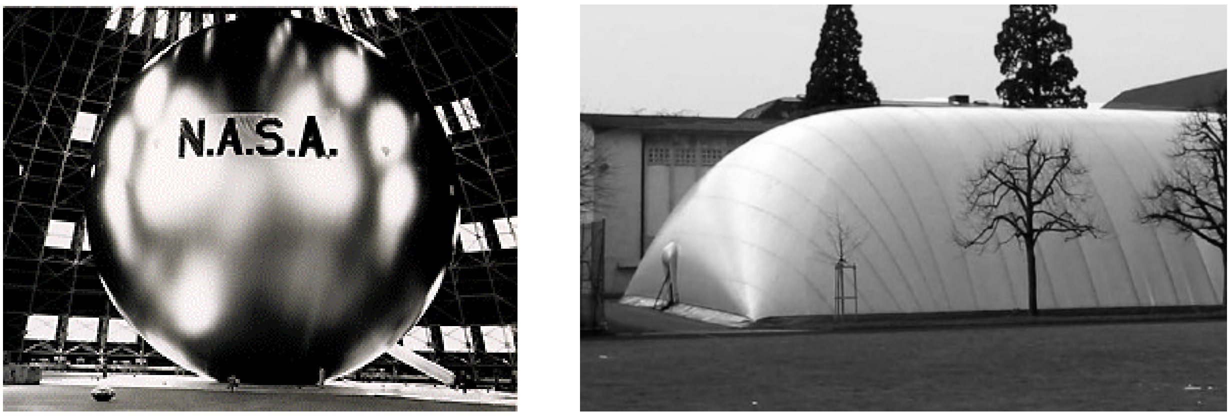
1. Introduction

The fascination of pneumatic structures begins with the fascination of the sky. The first technologically relevant realisations of inflatable devices date back to 1783, when the Mongolfier brothers with their hot air balloon were the first to venture the sky. The Mongolfiers outraced their French countryman Charles who brought the first manned hydrogen filled balloon in the air only a few weeks later. The crossing of the English Channel followed two years later by Blanchard, another French balloon pioneer. The exploration of the sky had a strong impact on the French citizens: the sky belonged to everyone, to seize the sky represented the advent of freedom from the ruling aristocracy with their possession of the land. The French revolution followed a few years afterwards [1]. Nevertheless, the time was not yet ready for the breakthrough of manned air travel. It took more than a hundred years to establish reliable passenger transport through air with gas-filled airships. Dirigibles had a boom in the beginning of the 20th century, but the technology could soon no longer cope with the fast upcoming aircraft industry. The tragedy of the Hindenburg in Lakehurst 1937 marked the abrupt end of the airship boom.

On solid ground, pneumatic structures had a first breakthrough as shelters for radar devices after World War II. The shelter needed to be lightweight, mobile and deployable in short time and without any metallic parts, ideal requirements for pneumatic structures. Walter Bird developed the so called radomes in the US, which were finally in operation on many sites all over the world. A civil application was established with the development of airhouses. Much work in the exploration of the potential of pneumatic structures also beyond architecture was done in Germany by Frei Otto beginning in the 1960s [2]. An excellent overview of the pneumatic constructions up to the 1970s is given by Thomas Herzog [3]. So far the heyday of pneumatic architecture can be viewed as the Expo '70 in Osaka, where many pioneering pneumatic buildings were shown. Since those days, however, next to the establishment of the airhouse for covering e.g. tennis courts as well as for large sport arenas no substantial progress in pneumatic architecture has been seen [4]. Airtecture, an airbeam based architecture by Festo presented 1996 has so far not been developed further [5].

Two major shortcomings for pneumatic structures in architecture can be named: strong form restrictions for airhouses and strong load limitations for airbeams. As soap bubbles demonstrate, the natural form of pneumatic structures is the sphere (Fig.1, left). Any inflated elastic membrane tends to be spherical. Elongated forms can be forced by the appropriate cutting pattern of inelastic fabrics. However, a voluminous sausage impression always comes along with airhouses (Fig. 1, right). Another basic pneumatic form not much used in architecture is the torus. Indeed, the tire is the most successful and wide spread pneumatic structure so far.

Fig. 1. Basic pneumatic forms: Spherical ECHO I communication satellite by NASA (left) and mainly cylindrical airhouse (right).



Airbeams, cylindrical membranes filled with pressurized air have been studied to replace conventional girders and trusses. A possible application can be found in space for antennas [6]. Today, tents with airbeams as supporting structure are commercially available. However, as the size of the structure increases, the load demand on the airbeam increases, too. A pneumatic shelter with 25 m overall width and 11 m overall height and 0.76 m beam diameter operates with a large overpressure of 5.5 bar leading to very high membrane forces and the need for expensive high tech fibres [7].

2. Advanced Forms: The Web Technology

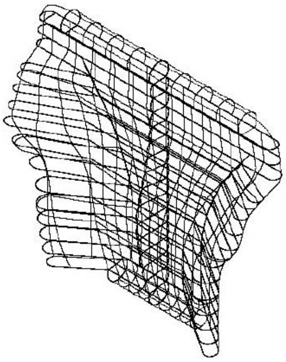
The fascination of the sky was again part of the hype, when prospective concepts made public their manned pneumatic aircrafts Stingray and Pneuwing in May 1998 (Fig. 2) [8]. The Stingray was a successful demonstration of new forms and possibilities of pneumatic structures. A wing span of 13 m and a length of 9.4 m lead to a wing area of 70 m^2 and a total volume of the included gas of 68 m^3. Air was used as filling gas. However, larger versions of Stingray will be filled with Helium to combine static and dynamic lift. Therefore Stingray can be viewed as a hybrid between airplane and airship. This flying wing can take off at a speed of 47 km/h and reaches a maximal speed of 130 km/h with its two 47 kW engines. The maximal take off weight is 840 kg of which the membrane makes up 80 kg. The two person vehicle is designed to withstand accelerations of up to + 4.5 g / -3.0 g. The overpressure in the membrane varies between 20 to 50 mbar with the higher pressure in the outer thinner part of the wing. The pressure is maintained by two redundant 80 W fans.

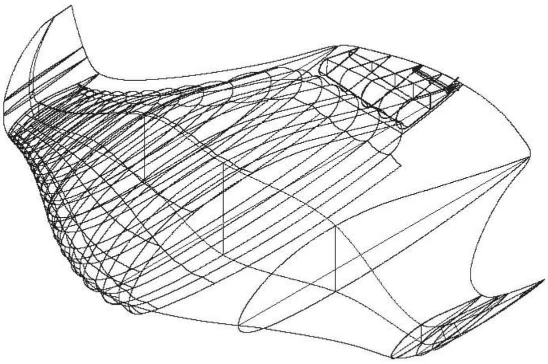
Fig. 2. New pneumatic structures: The inflated airplane Stingray (left) and the inflated wing Pneuwing (right).

The form of an airplane is determined by aerodynamic principles and must be very precise. prospective concepts has advanced the web technology to build pneumatic structures with a prescribed complex geometry. To obtain the desired shape, the inflated volume is divided into chambers by webs. By appropriate design of the number and form of the webs the shape of the inflated structure can be forced to be e.g. a wing profile. The design of such three dimensional pneumatic structures is very involved. It is based on modern CAD tools and requires a lot of experience (Fig. 3). Nevertheless it is very accurate as proven by the Stingray, where the maximal deviation of the blown up body with a size of more than 10 m was less than one centimetre from the calculated design. This is very remarkable, since the envelope changes drastically its form during inflation and the membrane strain is very complex due to the involved stress pattern and different fabrics combined.

Many other interesting applications e.g. inflatable floats for waterplanes and pneumatic seats and backrest cushions have been developed by means of the web technology [9]. The shape of the backrest cushion is also very different from the basic pneumatic forms of the sphere and the cylinder. The web technology proved to be flexible enough for this complex shape, too.

Fig. 3. Complex pneumatic forms made with the web technology. An inflatable backrest cushion (left) and the pneumatic airplane Stingray (right).





The Stingray operates in an intermediate pressure range between the airship with a few millibar and the tires with more than 2 bars overpressure. The airplane Pneuwing (Fig. 2, right) has a pneumatic wing and a conventional metal fuselage. The much higher aspect ratio and considerably reduced airfoil thickness of this wing compared to the Stingray lead to an overpressure of 700 mbar to maintain the stability. As discussed in case of the airbeam, the consequence of an increased slenderness is increased pressure. Therefore the application of slender air-supported structures as beams is very limited, a fact which cannot be changed by the web technology.

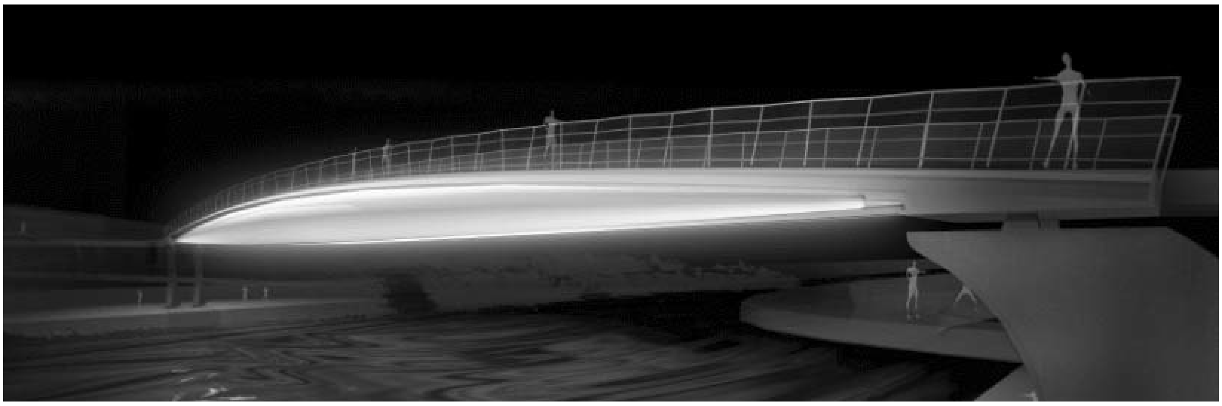
3. Advanced Strength: Tensairity®

The new pneumatic beam concept of Airlight Ldt. in close collaboration with prospective concepts solves the problem of load limitations of slender pneumatic structures. Tensairity, the registered trade mark is a word combination of tension, air and integrity. It is a hybrid technology between the airbeam and conventional beam structures. By this combination, the load bearing capacity of the airbeam can be improved by up to two orders of magnitude [10] opening a large new field of applications for pneumatic structures. But still, it is an ultra light and deployable structure.

Fig. 4 Strong pneumatic structures with Tensairity: Tensairity demonstration bridge with 8 m span and 3.5 tons maximal load (left) and an ultimate load test of a Tensairity beam (right).

The basic Tensairity structure consists of a cylindrical airbeam, a compression strut tightly connected with the membrane along the whole length of the airbeam and at least one pair of cables spiralled around the airbeam that are firmly connected with the compression element at both ends of the beam [10]. The loads are carried by the cables and the compression element. The role of the compressed air is to pretension the cables and to stabilize the compression element against buckling. Therefore minimal cross sections can be used both for the compression element and the cables leading to the extraordinary light weight properties of Tensairity. The overpressure lies in the range of 50 to 500 mbar depending on the application at hand. In one word, Tensairity is pressure induced stability of conventional struts and cables.

Fig. 4 Tensairity footbridge with 72 m span. The interesting illumination possibilities of Tensairity can be seen. Proposal for the Leamouth bridge design competition 2003, London (with Blue office architecture, Bellinzona, Switzerland).

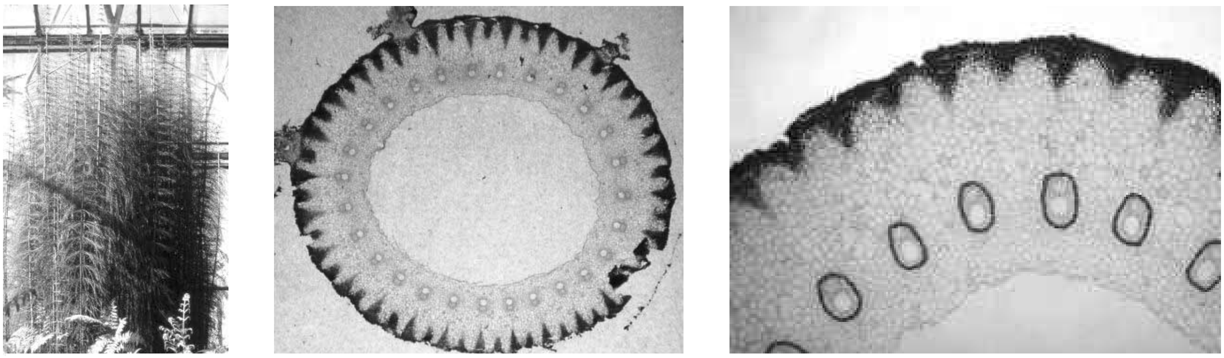


First applications of the patented Tensairity technology will be in the field of civil engineering. Roof structures based on Tensairity are on the verge of realisation. Footbridges is an other field of strong activity (Fig. 4). The outstanding light weight properties make the technology ideally suited for wide span structures. And as any pneumatic structure, Tensairity constructions can be made deployable, too. Therefore Tensairity is as well ideally suited for large tents, mobile factories and temporary bridges. But the use of Tensairity is not at all limited to civil engineering. Possible applications of this light weight structure can be envisaged in aviation, in space, for masts and so on.

4. Pneumatic Structures, Tensairity® and Bionics

Pressure induced stability is common in nature as well. Turgor, the cell pressure in plants is with 5 to 10 bar remarkably high. *Equisetum giganteum* is an example for a turgor-stabilized system (Fig. 5). It was shown that the structural Young's modulus in the tangential direction of *Equisetum giganteum* decreases with decreasing turgor pressure and thus the bending stiffness of the plant decreases as well [11]. The cross section of the *Equisetum giganteum* stem reveals that a thin outer ring of fibrous mechanical tissue (dark outer ring with wedge shaped ridges at its inner surface) is stabilized by an inner layer of pressurized parenchymatous tissue (Fig. 5, right).

Fig. 5. The horsetail *Equisetum giganteum* is an example for a turgor-stabilized plant (left). Cross section (center) and detail of the cross section (right) [courtesy of Th. Speck].



However, plants use liquids as pressurized media while Tensairity mainly operates with gases. And the structural complexity of plants is on a completely different level compared to the simple set up of Tensairity. Thus, Tensairity is a model for the fundamental principle of pressure induced stability and as such it can help to understand the involved construction plan of plants.

A very interesting aspect of pneumatic structures is that they are a ‘biological’ technology. Very often nature and technology are considered as two opposites. Attributes such as soft, round, light, flexible, multifunctional, structure optimized and transient are given to nature, while hard, square-edged, heavy, rigid, mono-functional, material optimized and durable belong to the world of technology (Tab. 1). Pneumatic structures are obviously soft, round and light. Flexibility of the structure can be obtained simply by pressure variations. Multi-functionality is e.g. achieved in the Stingray, where a lighter than air gas adds the static buoyancy to the stabilization function. Tensairity is structurally optimized by the constructive separation of tension and compression. And the limited lifetime of today’s fabrics give pneumatic structures an inherent transient character. Indeed, the fabric of a Tensairity roof has to be renewed after about 20 to 30 years. This offers the opportunity to decide 20 years later, whether the object is still the right building at the right place. Who can say today, that a parking house in the middle of a railway station will still be the best use of that space in 25 years? The strategy with pneumatic structures is to build fast and cost effective with a minimal amount of resources for a limited time period with an inherently easy dismantling option. Truly a very biological principle which we think should have much more weight in the architecture of today’s fast changing world. Given these biological properties, pneumatic structures bring nature and technology together, probably the prime goal of bionics.

Tab. 1. Nature versus technology: Pneumatic structures have many attributes of nature.

Nature	soft	round	light	flexible	multi-functional	structure optimized	transient
Technology	hard	square-edged	heavy	rigid	mono-functional	material optimized	durable

5. Conclusions

The exploration of the sky made possible by pneumatic structures more than 200 years ago fuelled the spirit of the people to free themselves from the yoke of the ruling aristocracy. Pneumatic structures have many advantages but also some important shortcomings. They have found their market niches with up and down popularity e.g. as airships or airhouses with the tire as the only great success story so far. The research of prospective concepts has freed the pneumatic structure technology from its shape restrictions by advancing the web technology. Tensairity, the most recent development by Airlight, eliminates the serious drawback of the limited load capacity of pneumatic structures. These two major improvements of pneumatic structures likely make the exploration of new skies possible. Together with their inherent bionic character, pneumatic structures have a strong potential to fuel the spirit of today's people to free themselves from the burden of outdated concepts and technologies.

Acknowledgements

prospective concepts started to do research of pneumatic structures more than ten years ago. Many people have contributed to its progress in the meantime. A special mention get Fred To, Ruedi Leutert, Joe Steffen and Res Kammer. On the side of Airlight, Andrea Pedretti and Patrick Steingruber have contributed essentially to the development of Tensairity. And without Festo, the leading company in automation pneumatics, this work would not have been possible.

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