Frei Otto and the Tensile Structures

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To write a paper about tensile structures it is in fact to write about Frei Otto. And this text will reserve him a central role. Even though it is also possible to start a tale on these fascinating structures long before that the brilliant German architect had been involved with them.
Tensile structures can be defined as load-bearing structures in which most of the elements are not capable of compression and flexural strength. In other words, most of the elements do not have a definite shape of their own but assume what the tension stresses assign to them in mutual contrast with the other elements. This is why tensile structures could be defined as structures deriving from “active tension” in the same manner that timber post form gridshells (of which Otto himself was a sublime interpreter) can be defined as structures deriving from “active bending”.
Thus all the tents belonging to the ancient nomadic and military building traditions as all the “velarium” used to shade and protect parts of ordinary constructions (see for example the coverings of Roman amphitheatres) or even the Tibetan bridges and, at least in part, all types of suspension bridges can all be classified as tensile structures. Actually the modern tensile structures arouse when the three-dimensional complexity of ancient “velariums” and traditional tents shapehad met the almost completely two-dimensional geometric-structural rigor of suspension bridges.

Essentially they are born thanks to the work of the Russian engineer Vladimir Choukhov who in 1896,in the Pan-Russian Exposition of Nijni-Novgorod, built four extraordinary buildings, the most particular of which is surely the “Round”: «*The Round roof as Rainer Graefe accounts (68,30 m in diameter, 15 m in height) consists of two suspended roof structures. Between a rigid ring carried by 16 pillars and a similar compression ring, located on the outer wall, is stretched a network consisting of 640 plates riveted to each other (51,5 x 5 mm, reach of the lattice 21,50 m)*»[1].
And, like Brian Foster underlines,
«*By proposing as a structure a thin three-dimensional surface, Shukhov has achieved a fundamental advance in relation to the concept, essentially two-dimensional, of the suspension bridge, which had so severely constricted the imagination of nineteenth-century designers*»[2].
The reduced circulation of information, amplified from the cultural self-isolation of the Soviet Russia, ensured that in order to see a roof based on the same principles in the West, we have to wait for the French Pavilion at the Zagreb Fair, created in 1934 by Robert Camelot in collaboration with Bernard Laffaille. With a similar structural pattern, made up of 12 pillars that support a circular compressed ring to which, in this case, was suspended a super lightweight metallic veil shaped as an inverted truncated cone of 33 meters in diameter.
This “skin” (of 800 m^2 and 2 mm of thickness) was put in place with the help of metal sheet elements pre-shaped in workshop and welded on site. It reached a new lightness record, at the time, of 18 kg for covered square meter. Once again 17 years later Laffaile, in the Mechanical Industry Centre, used the idea of a horse saddle shaped roof made up of members in tension suspended by two reinforced concrete arches. Almost concurrently in the United States, based on an idea of Matthew Nowicki, a very young Russian architect died at age of 40 in a plane crash, the Norwegian engineer Fred Severud conceived the JS Dorton Arena (become famous as *Paraboleon*), a paradigmatic building of the later defined "Cable network" structures. The large Arena (92 by 97 meters) completed in Railegh North Carolina in 1953, is built with the crossing of two reinforced concrete arches, with about thirty degrees inclination and supported by thin steel studs of variable height.
Along the perimeter is set up the network consisting of two about ninety degrees crossing orders of parallel cables: the first series of cables, with upward curvature, is load-bearing and is counteracting with the second, with downward curvature, that has a stabilising function; the resulting meshes are then patched with squared corrugated iron panels, with a maximum size of 1,80 m. Is exactly from this mutual counteraction among stretched elements, belonging to separated and contrasting systems, that the base principle of modern tensile structures is born.

Then after the innovative system was declined with various forms and techniques again by Severud together with Eero Saarinen, with the ice stadium of New Haven and with the Terminal of the international airport Dulles in Washington as much as from Laffaille together with René Sarger with the French Pavilion and with the Marie Thumas Pavilion at the Universal Exposition from Brussels in 1958 (made with Guillaume Gillet and Jean Prouvé).
It is precisely the North Carolina Arena that baptizes the entrance on the scene of a very young Frei Otto that during his prize trip, after graduating in Architecture at the Technical University of Berlin, had the occasion to be, thanks to Saarinen's presentation, a curious guest at Severud's studio.
The lively imagination of Otto was so strongly impressed by this singular structural typology that he later choose it as the theme of his PhD thesis dedicated exactly to the suspended coverings and his book entitled Das Hängende Dach, has a picture of the Dorton Arena on the front cover. Still a graduate student, Otto realized that the dynamics between the series of cables of the Arena can be generated alike, on a smaller scale, between the warp and the weft of a normal fabric made of tiny orthogonal cables interwoven together to form a small square shaped grid. He realized that, by subjecting a fabric to appropriate stresses, the non-flexural strength of the threads and the possible variation of the corners of the micro-quadrilaterals can generate a new extraordinary family of shapes.
So he started sending letters to several outdoor tents manufacturers operating in Germany, asking to help him experiment with his theories. One of these, Peter Stromeyer of L. Stromeyer & Co, accepted the challenge of the young scholar and invited him to spend a period of time in the family factory that stood near Konstanz. Mark Zeh reports the atmosphere of this mythical working week spent together by Frei and Peter: «*In his writings, Otto describes his work with Stromeyer during their first week together in Konstanz in 1953 as 'the most productive working weeks in his entire life'. Otto goes on to describe a personal interaction with Stromeyer, starting with them agreeing that in order to understand how to work with membranes, they had to begin with 'the simplest' possible forms. He describes their process of discovery by doing, where the saddle makers, carpenters and other craftspeople at Stromeyer would quickly fabricate prototypes of the ideas created by Otto and Stromeyer*»[3]. From thinking to doing, from simple to complex Zeh's sentence completely gives back the creative atmosphere of the encounter between the two intellects that enhance, in practical doing, first the ability to learn, then that of understanding and, finally, to overlook at the climax of the discovery, of the invention.
The Otto-Stromeyer duo, strengthen by the experiences gained during the "magic week", undertook the design process of the pavilions for

the editions of the Bundesgartenschau (*Federal Garden Exhibition*) between 1955 and 1963.
The projects began with the Four-Point Tent in occasion of the Music Pavilion for the Kassel 1955 edition: a small pavilion with a relatively simple geometry generated by the deformation of a quadrangular sheet in which the angles of a diagonal are held high by small strut, and the two corners of the other diagonal are fixed at the bottom and constrained directly to the ground. In the *Tanzbrunnen Pavilion*, built on a dance floor for the 1957 Cologne edition, following the already cited path from simple to complex, the form is based on an octagonal shape. As Rosalba La Creta notes, «*The roof not only protects the dancers from rain but also reflects sounds and lights on the dance floor of which follows the ring shape with a spatial geometry resulting from the radial aggregation of a series of horse saddle surfaces, according to an undulating shape open in the center.*
The membrane that forms it, made of waterproofed translucent cotton fabric, is stretched between a central tension cable, edge cables and radial ridge and groove cables. The latter, alternating with respectively opposite curvatures, ensure the wave form and the surface anticlasticity»[4].
Ultimately Otto and Stromeyer were the first to make prototypes in which the structural principle of maximizing stretched elements over compressed ones is carried to its extreme consequences, to the point that the shape of the latter depends on that of the stretched membrane. «In other words – write Giulio Pizzetti and Anna Maria Zorgno, rightly attributing the authorship of the construction system entirely to Otto – he succeeded in proposing the equilibrium schemes of these spatial fabrics reducing to the minimum the support elements working in compression and trying to carry the loads to the ground eminently through negative support reactions, that is through constraints still stressed to traction. In this way he could avoid the complex flexural problems that inevitably occur in the arches or in the rings of the previous tensile structures, which still used compressed parts in reinforced concrete or in steel provided with geometries of its own, while an appropriate choice of the positions and inclinations of the struts, as well as of the tracing and anchoring of the edge cables, allowed him a bright enhancement of the tensile structure physiognomic essence»[5].
For the design of these pavilions, Frei Otto develops a technique unprecedented in the construction world: the one based on the "theory of minimal surfaces", worked out in the previous century by illustrious scholars such as Euler and Joseph-Louis Lagrange.
It is possible to realise models that precisely mimic these laws using soap films that naturally arrange themselves according to the minimal surface suitable to connect the edges of a thin metal frame submerged into a solution.

That is, given the exact perimeter, the soap film naturally assumes the shape provided with the minimum area which is also the one with zero mean curvature. The designs of the pavilions for the *Bundesgartenschau* were therefore generated by fixing the contours of the forms and finding the surfaces.
In practice, the project arises from the definition of an operational process that starting from a theory formulated in the field of geometry, finds a modelling method based on a natural phenomenon that respects the same law and generates the form using a simplification of this model.
The resulting form is a reasonable intermediate between the expressive will of the designer and the matter behaviour which, given the imposed constraints, is distributed according to a *law of nature*: the designer does not impose the form on the object but it is inspired by the natural laws for the for form-finding. Perhaps the interest in the laws of nature is what drove Otto to found in 1961, with his friend biologist Gerhard Helmcke, the Biology and Building Research Group in which biologists helped designers to use nature as a model for resistant forms and architects explained to biologists the structural reasons for some natural forms.
This stimulating process of interdisciplinary research quickly leads Otto to desire an equipped and available space that allows him to resume the path taken with Stromeyer. So he first of all founded the Institute for Development of *Lightweight Construction* in Berlin, a small private research centre, and then, some years later, to take the leadership of the new Institute for Lightweight Structures (*Institut für Leichte Flächentragwerke - "IL"*) at the University of Stuttgart.
In these research facilities, physical modelling methods such as those based on the analysis of soap films are flanked by other systems, such as those based on elastic fabrics, on upside-down models and others more. These methods will also be used for other types of structures designed in the following years. In 1964 the German Federal government announced a competition entitled "The man and the world" to assign the design of the German Pavilion at the Montreal Universal Exhibition; Frei Otto, at the age of 40, won, in collaboration with Rolf Gutbord and with the technical assistance of the engineers Fritz Leonhardt and Wolfhart Andrä, the first prize with a project that covered an area of 8.000 m^2. The Montréal pavilion represents the end point of the innovative path that will lead to the definition of the structural type of the tensile structure and, to some extent, a symbolic closure of the circle. From the cable network of the Raleigh Arena we move to Otto's fabrics until the German architect himself proposes, for the first time, a cable network structure again.
From the first pavilions of Choukhov, the first to cover buildings using only a few compression stressed supports and a membrane composed exclusively of stretched elements, we move to

Severud's cable networks, where the structure is still set on massive reinforced concrete compressed elements, integrated in counter-action with the cables system; we then move on to the experiments of Sarger, and in particular to the Marie Thumas, in which the compressed members resemble the spars that Otto will use later on, but where the stretched part of the structure is still a brace for the compressed metal struts; and finally we reach the Montreal Pavilion, where the stretched part and the compressed part are two almost independent systems; the metal struts are cable-stayed among them and on the ground with large strands of 50 mm in diameter, while the cable network is made with another series of much thinner elements, with a diameter of 12 mm.
The translucent envelope is made of a polyester fibre fabric coated with PVC and is suspended from the network of cables from the inside. It is impossible to close this largely incomplete review of Otto's tensile structures without citing the most relevant event also in size: the giant cable network roof for the Munich Olympic Village built in 1972 with the same structural principles described for Montreal: here the complex tensile structure covers an area of 74.000 m^2, including the stadium, the swimming pool and the sports hall as well as all the passages and connections between the various facilities.
The covering shell, designed by Otto in collaboration with Günter Behnisch & Partner, differs from the 1964 Pavilion because it uses panels of translucent acrylic material which, viewed from the outside, break up the continuous surface of the roof into an infinity of small planar elements that give the complex the image of a gigantic prehistoric animal.
In the conception/design/realization of tensile structures, more consistently than in his extraordinarily interesting others realizations, Frei Otto refers to the *discovery by doing*, resorts to physical models which use the laws of nature to activate processes of form finding. This extraordinary coherence makes his tensile structures an emblematic whole of a type of structure that will condition a generation of lightness fanatic builders in the following thirty years.
Frei Otto was certainly a prophet for this group to the point that Shigeru Ban begins his tribute to the German master, on the occasion of the posthumous victory of the Pritzker Price in 2015, with these words: "*What do you want to become, brick?" The brick answered, "I want to become an arch". I think that Frei Otto was an architect who kept asking the "air" what it wanted to become*»[6].

Notes

1 - GRAEFE, R. (1997), *Nijni-Novgorod (Rotonde de l'Exposition Panrusse à),* s.v. Picon, A. (ed. by), "L'art de l'ingénieur", Le Moniteur, Paris, p. 334. In French: «La couverture de la Rotonde (68,30 m de diamètre, 15 m de hauteur) se compose de 2 structures de toit suspendues. Entre un anneau rigide porté par 16

piliers et un anneau similaire de compression, situé sur le mur extérieur, est tendu un réseau constitué de 640 fers plats rivetés les uns aux les autres (51,5 x 5 mm, portée du treillis 21,50 m)».
In Italian: «La copertura de la Rotonda (68,30m di diametro, 15m di altezza) si compone di due tetti sospesi, Tra un anello rigido sostenuto da 16 pilastri e un anello simile compresso, situato sul muro esteriore, è tesa una maglia costituira da 640 piattine in ferro rivettate tra di loro (51,5m x 5mm, luce del graticcio 21,50m)».

2 - FORSTER, B. (1997), *Structures tendues*, s.v. Picon, A. (ed. by), “L’art de l’ingénieur”, Le Moniteur, Paris, p. 486. In French: «En proposant comme structure une mince surface tridimensionnelle, Choukhov vient d’accomplir une avancée fondamentale par rapport au concept, essentiellement bidimensionnel, du pont suspendu, qui a si fortement bridé l’imagination des concepteurs du XIX siècle».
In Italian: «Nel proporre come struttura una sottile superfice tridimensionale, Chukov ha compiuto un avanzamento fondamentale in relazione al concetto, essenzialmente bidimensionale, dei ponti sospesi, che aveva così fortemente imbrigliato l’immaginazione dei progettisti del XIX secolo».

3 - ZEH, M. (2012), *Zusammenarbeit: Collaboration of Frei Otto and Peter Stromeyer. The transformation of tensile architecture*, July 1st 2012, [on-line] available at https://fabricarchitecturemag.com/2012/07/01/zusammenabeit-collaboration-of-frei-otto-and-peter-stromeyer. In italiano: «Nei suoi scritti, Otto descrive il suo lavoro con Stromeyer durante la loro prima settimana insieme a Costanza nel 1953 come ‘la più produttiva settimana di lavoro di tutta la sua vita’. Otto continua raccontando che la sua interazione con Stromeyer, inizia dall’accordo sul fatto che, per capire come lavorare con le membrane, dovevano iniziare con ‘le forme più semplici’ possibili. Descrive il loro processo di scoprire facendo, mentre i sellai, i carpentieri e gli altri artigiani di Stromeyer fabbricavano rapidamente i prototipi delle idee create da loro».

4 - LA CRETA, R. (1976), T*re opere di Frei Otto: una logica alternativa nella costruzione*, in Vittoria, E. et al., “Mmm. Unità micro e macro-modulari per la costruzione dell’Habitat”, Roma, p. 9. In italian: «La copertura vale non solo a proteggere i ballerini dalla pioggia ma a riflettere suoni e luci sulla pista di cui segue l’andamento anulare con una geometria spaziale che risulta dall’aggregazione radiale di una serie di superfici a sella, secondo una forma ondulata aperta nel centro. La membrana che la costituisce, di tessuto traslucido di cotone impermeabilizzato, è tesa tra un cavo di tensione centrale, cavi di bordo e cavi radiali di cresta e di gola. Questi ultimi, alternandosi con curvature rispettivamente opposte, assicurano la forma ad onda e l’anticlasticità della superficie».

5 - PIZZETTI, G., ZORGNO, A. M. (1980), *Principi statici e forme strutturali*, Utet, Torino, p. 491. In Italian: «In altri termini egli riuscì a proporre schemi di equilibrio di questi tessuti spaziali riducendo al minimo gli elementi d’appoggio lavoranti a compressione e cercando di riportare a terra i carichi eminentemente attraverso reazioni di appoggio negative, ossia mediante vincoli ancora sollecitati a trazione. In tal modo egli poté evitare i complessi problemi flessionali che fatalmente si verificano negli archi o negli anelli di bordo delle tensostrutture … mentre una scelta

appropriata delle posizioni e delle inclinazioni dei piloni, nonché del tracciato e dell'ancoraggio dei cavi di bordo, gli permise una luminosa valorizzazione dell'essenza fisionomica della tensostruttura».

6 - Cited in Pritzker Price website: https://www.pritzkerprize.com/laureates/frei-otto. I In Italian: «Louis Kahn chiese al mattone, "Cosa vuoi diventare, mattone?" Il mattone rispose, "Voglio diventare un arco". Penso che Frei Otto sia stato un architetto che continuava a chiedere all'aria cosa volesse diventare».