LIGHTWEIGHT STRUCTURES

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INTRODUCTION

Any structure designed intelligently and responsibly aspires to be „as light as possible“. Its function is to support „live loads“. The dead loads of the structure itself are a necessary evil. The smaller the ratio between a structure's dead load and the supported live loads, the „lighter“ the structure.

We realize immediately that a suspension bridge with tensioned cables is obviously lighter than a truss bridge with welded bars which in turn is lighter than a box girder bridge made of concrete. This leads us to the question why so few suspension bridges are being built and only for large spans and we intuitively understand that the demand for lightness is not the only criterion when designing structures.

Indeed, „natural loads“ are the enemy of lightweight structures. These structures tend to deform heavily under snow and temperature changes, they are sensitive towards wind-induced vibrations, they may tear (the structural engineers' trauma of Tacoma), but they easily withstand earthquakes. Another stern adversary of lightweight structures are today's high labour costs and the imprudent use of natural resources. This promotes massiveness and hinders the filigree.

But before we discuss how to design lightweight structures we need to ask ourselves whether or not lightweight structures today are worth the effort to be promoted and developed.

The answer is yes! From an **ecological, social and cultural** perspective lightweight structures have never been more contemporary and necessary than today.

The **ecological** point of view: Lightweight structures are material-efficient because the materials strengths are optimally used. Thus no resources are wasted. Lightweight structures may usually be disassembled and their elements are recyclable. Lightweight structures curtail the entropy and therefore are superior in meeting the requirement for a sustainable development.

The **social** point of view: Lightweight structures create jobs because filigree structures demand carefully designed labour-intensive details with a great expenditure in planning and above all manufacture. The intellectual effort replaces the physical effort, now time and craftsmanship supersede the extruding press - the joy of engineering instead of massiveness. But as long as our modern economy equals working hours with costs, we merely pay the mining costs of the raw materials and the overall „external costs“ are not even added, lightweight structures will be more expensive than bulky structures with the same function.

The **cultural** point of view: Lightweight structures, built responsibly and disciplined, may contribute heavily to an enriched architecture. Light, filigree and soft evokes more pleasant sensations than heavy, bulky and hard. In the typical lightweight structure the flow of forces is visible and the enlightened care to understand what they see. Thus lightweight structures with their rational aesthetics may solicit sympathies for technology, construction and engineers. They may help us to escape the wide-spread monotony and drabness in today's structural engineering which in turn will become again an essential part of the building culture.

PRINCIPLES OF LIGHTWEIGHT STRUCTURES

How to create lightweight structures? When designing lightweight structures we have to

firstly remember a most unfavourable characteristic of the dead loads: The thickness of a girder under bending stress, supporting only itself, increases not only proportional to its span (which is often falsely assumed), but also with the span's square! For example if the girder with a span of 10 m has to be 0.1 m thick, its thickness increases with a span of 100 m not only 10fold but 10 x 10fold. Consequently the girder has to be 10 m thick and its total weight increases by the factor 1000!

Already Galileo Galilei was aware of the importance of scale. He demonstrated this by comparing the tiny thin bone of a bird with the corresponding big bulky one of a dinosaur (Fig. 1). This teaches us that increasing spans increase the weight of structures, consequently gratuitous large spans are to be avoided.

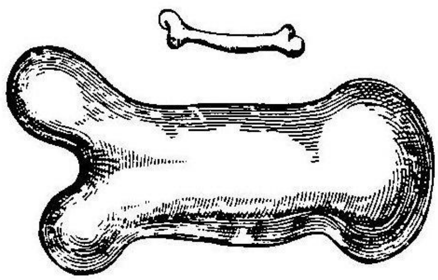

Fig. 1: Galilei's demonstration of the scale effect

But this law of nature about scale may be circumvented with some tricks, by

secondly avoiding elements stressed by bending in favour of bars stressed purely axial by tension or compression, i. e. dissolving the girder. Basically this is always possible as demonstrated by the truss girder. With struts and ties the entire cross-section is evenly exploited without anything superfluous. Bending completely stresses only the edge fibres while in the centres dead bulk has to be dragged along.

Here ties in tension act apparently more favourable than struts in compression because they only tear if the material fails, while slender struts fail due to buckling, i. e. a sudden lateral evasive movement. This can easily be tested with a long bamboo stick. We cannot break it with our bare hands, but if we bear down on it, it buckles quickly. These efficient tension stressed elements become

thirdly even more efficient with increasing tension strength β and decreasing density of the material γ, i.e. with increasing rupture length β/γ. This clear value represents the length a thread can reach hanging straight down until it tears under its dead load. Wood is more efficient than steel and natural and artificial fibres do even better.

These first three approaches to lightweight structures introduce us already to the entire multitude of forms in bridge engineering. We recognize (Fig. 2, starting from the top) the dissolution of the girder into the truss and then (left) the arch structures which carry their loads mainly by compression and their inversion (right) the suspension structures which make use of the especially favourable tensile forces. At the bottom are the most marginal structures, the pure arch or the cable suspended between two rock faces. But these latter ones are useless, because they deform too much under loads. But in between the upper and lower structures there are the most diverse solutions: arches and suspended cables stiffened by secondary girders in bending and all kinds of fastenings, deck-stiffened arches, strutted frames (left) as well as cable bridges and suspension bridges etc. (right). The further we move down in Fig. 2 the lighter it becomes but also the more critical with respect to wind-induced vibrations – and this represents the challenge and the attraction of bridge engineering.

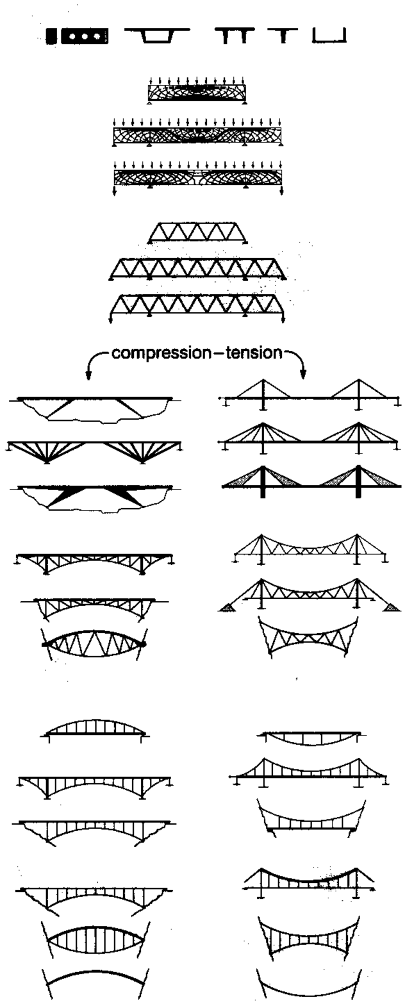

Fig. 2: The evolution of bridges

The keen observer of today's bridge engineering will find that a rather pragmatic attitude prevails, structures are being built "as heavy as justifiable". Solid girders are used up to a span of about 100 m, arches and trusses respectively up to approximately 250 m. Dead loads at least five times the live loads are tolerated. Beyond approximately 300 m the dead load becomes so dominant that, as the only alternative, tensile „lightweight structures" remain: up to about 1000 m self-anchored suspension and cable-stayed bridges and for even greater spans back-anchored suspension bridges.

The Pont de Normandy in France spanning 856 m and the Tatara-Bridge in Japan spanning 890 m are the world's largest cable-stayed bridges soon to be superseded by Sutong and Stonecutters Bridge in China and Hong Kong respectively. The largest suspension bridge with a span of 1990 m is the Akashi Kaikyo Bridge in Japan. The suspension bridge proposed for the crossing of the Straits of Messina spanning 3000 m is to be suspended from 4 cables each 1.7 m in diameter. These cables consume already half of their load bearing capacity to support themselves and only one half remains for the actual bridge and the live load which remains insignificant compared to the dead load of the cables and the deck. By definition this is by no means lightweight, but at such span, today's materials do not permit anything lighter - we have reached the limit - unless, steel cables can be replaced by carbon fibres with a significantly greater β/γ-value.

A strikingly ingenious trick to achieve lightness should be addressed briefly, i. e.

<u>fourthly</u> prestress or pretension which permits to transform unfavourable compression stress into favourable tension stress (Fig. 3). The example shows a quadrangle of slats with crossed cables. The diagonal cable receiving compression will not become slack but shares the load because it is

prestressed. Initially before applying the outer load this cable was exposed to pretension, thus when compressed it will not experience compression but a reduction of tension which is the static equivalent. This procedure permits the creation of very light cable girders an cable nets which act like ideal structures with tension <u>and</u> compression resistant elements or like membrane shells.

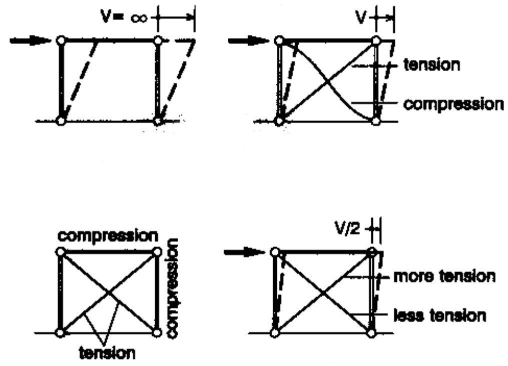

Fig. 3: The principle of prestress (Top left: unstiffened kinematic system; Top right: The diagonal in compression becomes slack and only the diagonal in tension is active; Bottom left: prestress: before loading the diagonals are shortened i.e. pretensioned; Bottom right: in a prestressed system both diagonals share the load)

The basic principles of lightweight bridges also apply to buildings such as roofs over large sports arenas or fair pavilions or industrial plants lending an individual character and a human scale to these structures. Since the gap between these cable girders still has to be spanned with transversal girders using bending and thus resulting in semi-heavy or semi-light roofs, the final step is inevitable

<u>fifthly</u> the lightweight spatial structures, the double curved space structures with pure axial stress, called membrane stresses (Fig. 4). These structures are not only extremely light but they also open up a whole new world in architecture, an unsurpassable variety of forms which is not yet exhausted, by no means. Just like bridges, these structures transfer their loads predominantly by compression shells or domes (Fig. 4, left), or by tension cable nets and membranes (right). In between are the plane space structures - the slabs and the space frames.

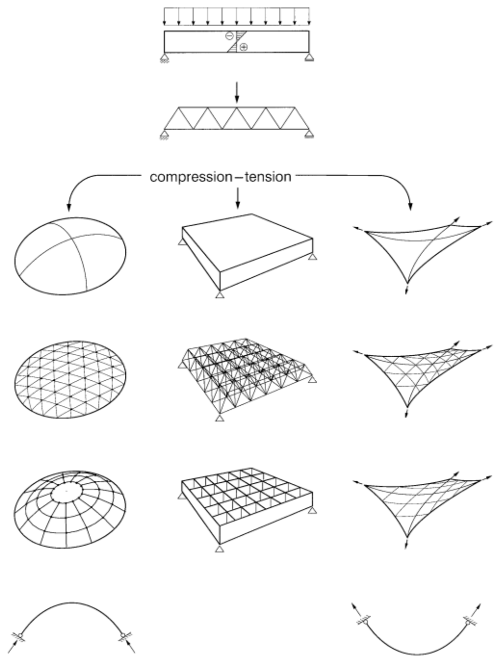

Fig. 4: The evolution of lightweight spatial structures

Despite the extremely thin walls of shells and space domes their curved shape stabilizes and prevents them from the dreaded buckling. And applying prestress protects the extraordinarily lightweight nets and membrane from the effects of wind-induced vibrations. The two principal directions of the nets and membranes are mechanically stressed against each other resulting in the typical saddle-shape with an anticlastic curvature, or, if pneumatically stressed by creating an internal air pressure or a vacuum, resulting in a dome shape with synclastic curvature. This can be mastered with modern computers. Manufacture and, as a consequence, costs are more likely to limit the scope of these lightweight spatial structures. Expensive formwork and complicated cutting patterns are required for the manufacture of these double-curved surfaces (Fig. 5). The details of tensile structures and membranes are complicated and have to be manufactured with extreme precision.

But in recent years the textile membrane structures have made a remarkable progress. Since they may be folded they are even used as convertible structures. This marked the beginning of a whole new era in structural engineering completely changing life in our capricious climate. The future is now!

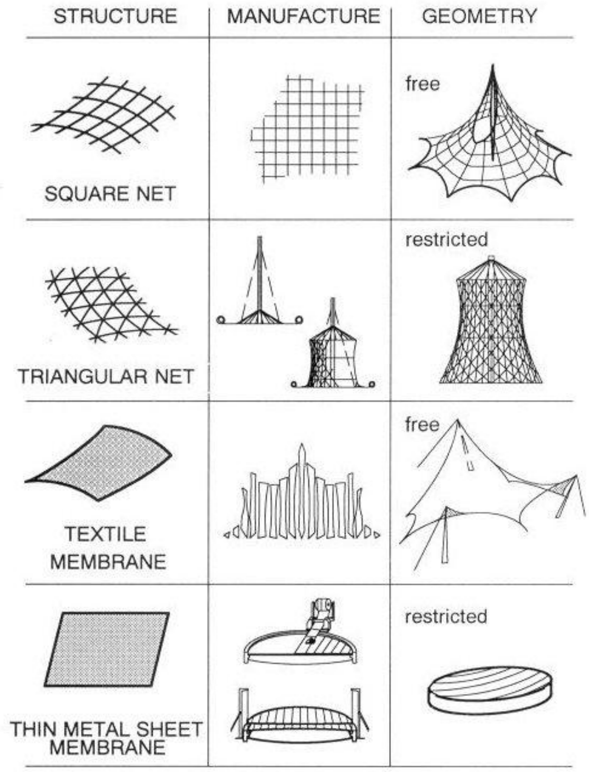

Fig. 5: The geometry and manufacture of typical double-curved lightweight structures

Achieving lightness is a heavy burden, because lightweight structures challenge the boundaries set by the theories of statics and dynamics. The fancy materials put the technologies to the test and the complicated three-dimensional structures dare the manufacturing procedures.

Lightweight structures tempt the dedicated engineer, because they - exemplary for this profession - equally and simultaneously address his knowledge, his ability and his experience as well as his imagination and his intuition. With lightweight structures the engineer is able to award the adequate visual expression to an ingenious and efficient structure thus contributing to building culture.

When we combine some of the earlier figures an order of all structures light-weight and “massive” could look like the one in Fig. 6

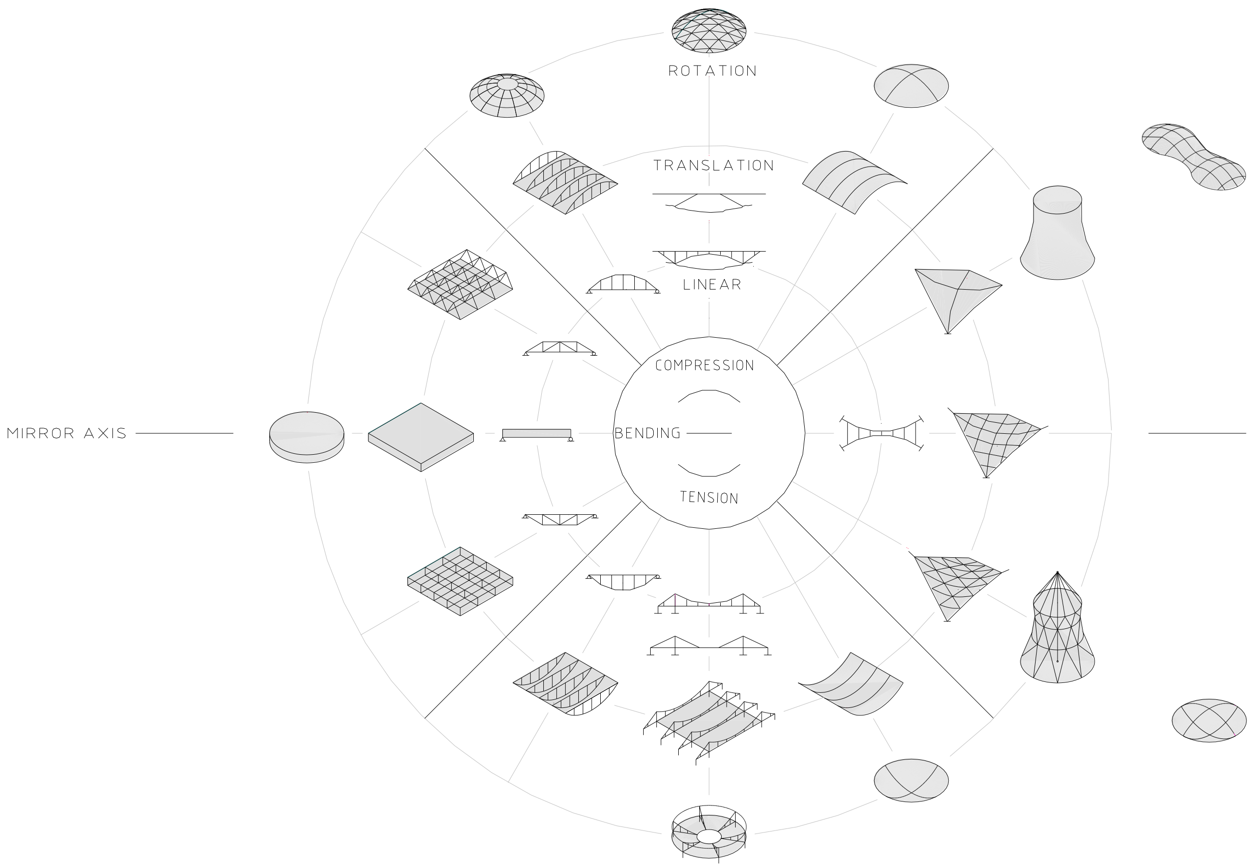

Fig. 6 An order of structures

Over the years, the authors and their colleagues tried to apply the principles of lightweight to all the types of structures shown in Fig. 6 including bridges, towers, concrete shells and cable net, membrane, and glass-covered roofs. Projects will be presented during the fib-days and a selection of photographs can be found at www.sbp.de.