Conceptual design of light-weight structures

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Introduction

Most people like light-weight structures. We enjoy their elegance and we appreciate that they are good examples of sustainable building that add to the culture of building.
This paper is an attempt to approach the design of light-weight structures, the term conceptual design and the question what good design stems from. The reasons for light-weight structures and the pertinent design principles will be discussed, also the wide range of possibilities of light-weight structures that are at our disposal today will be illustrated.

Conceptual Design

Conceiving the structure (i.e. developing the structural and formal concept) is the first design step and holistic quality is the predominant aim when we start designing a structure.

Of course a building with a light structure is not necessarily and automatically a quality structure. Therefore, the title of this paper is a bit misleading as “light-weight” is a quality that can be the result of the conceptual design process but it is not an inherent part of it. It maybe the outcome of a design process but it cannot start with it as a goal. As a matter of fact, sometimes lightness or little mass even needs to be avoided. This could be the case for concert halls when acoustic protection is important, for dams and tunnels which are stabilised through weight or for a grand stand which must not vibrate.

In general, it is the various existing boundary conditions that guide the design of a structure and determine its outcome. These conditions may be simultaneously topographical, technical, economical and cultural. It may be the landscape that surrounds the future structure or the "chemistry" of the design team. It is this local and manifold context that defines our designs:

- topographical – physical (terrain, type of obstacle, soil conditions, accessibility, ambient conditions, live loads).
- technical – constructive (available building material, available technology, quality of labour, organisation of the building industry).
- economical – cultural (time and budget, aesthetic demands).

Always, it is the conscious debate on these conditions - based on sound engineering principles combined with creativity - that leads to the concept of the structure. If all boundary conditions were carefully considered we may claim to have developed a holistic design.

The local context and all its boundary conditions influence and sometimes contradict each other. The design of a structure is, therefore, often a compromise of conflicting boundary conditions. However, the more complex and the more contradicting (or challenging) the conditions are, the greater is the chance to achieve an innovative or even surprising design.

Design of light-weight structures

Even though light-weight structures are not necessarily (and only under certain conditions) the outcome of the design process, they are rather frequent. This is not surprising. Light structures are convincing for several reasons:

- cultural: light structures are transparent and show the flow of forces in a natural way. We like what we understand. We also like lightness because we associate elegance with it and because the lighter a structure is the less it obstructs our view and the less we feel threatened.
- ecological: light structures generally require minimum material quantities and, therefore, they are sustainable.
- social: the complexity of light-weight structures requires qualified designers and builders. The outcome not only enriches our culture and but also creates employment.

Now that the “why” is answered, the “how” remains.

For the design of a light-weight structure several structural principles can be followed [1]. At least one of the following requirements is fulfilled in all light-weight structures:

- scale and appropriate spans: as bending moments increase with the square of the span, only short spans yield slender girders. If bending cannot be avoided, composite sections, e.g. with concrete where the section is exposed to compression and steel where tension governs, lead to lighter structures.
- no bending: sections are optimally used if they work only in tension and compression as long as stability can be guaranteed. Therefore, trusses are much lighter than beams in bending.
- low density/strength relation: a very efficient way to achieve lightness is to maximise tension strength Ÿ and to minimise the density of the material ˆ, i.e. to maximise the rupture length Ÿ/ˆ. In this respect the best building material are carbon fibres with their high strength and low weight.
- pre- or post-tensioning: permits to transform unfavourable compression into favourable tension. It adds stiffness to the structure and reduces deflections.
- double curvature: light-weight spatial structures carry the loads with pure axial forces, i.e. membrane stresses. Such structures are not only extremely light, they also open up a whole new world in architecture, an unsurpassable variety of forms which is not yet fully exploited today.

Over the years, whenever reasonable the author and his colleagues have been applying the principles of lightweight design to all types of structures, including bridges, towers and roofs, with concrete shells, cable nets, membranes, and glass.

An order of all structures that gives a bit of orientation is given in Fig.1. Practically all structures can be derived from the simple elements in the centre, the catenary in tension, the inverse catenary in compression – the arch - and the beam in bending. There is a quadrant of mainly tensioned structures, one for structures in compression, one for structures that work in bending and fourth one for hybrid structures. Starting from the simple elements, first we arrive at a first circle where we find linear structures, the bridges. By adding bridges translationally to each other we come to the second circle with roof-type structures and rotating the simple elements will lead to double-curved structure, the area where lightness can be achieved best.

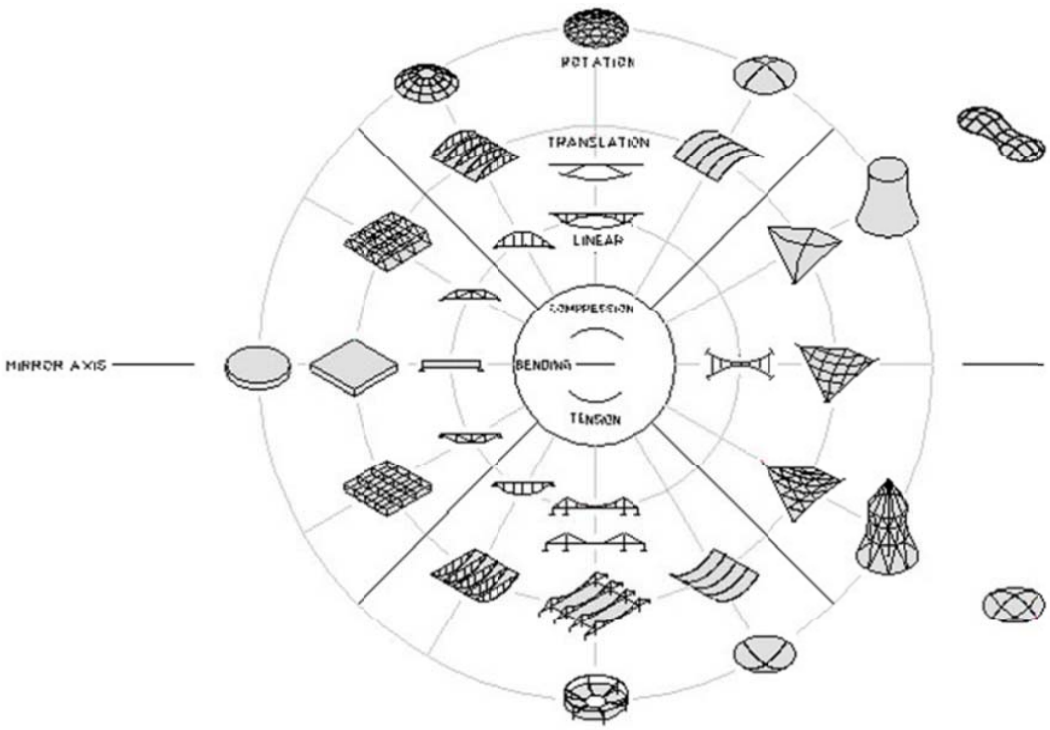

Fig. 1 An order of structures

Double-curved light-weight structures today

The industrial revolution in 19th century created a need for new and long-span structures such as railway stations and bridges. There is no doubt that steel was the material that allowed converting these needs into new lightweight structures and many would name the Crystal Palace by Paxton and the Eifel Tower as the landmarks of that age.

At the turn of the next century, the appearance of reinforced concrete and the thin shell structure this new material permitted mark the beginning of the era of modern double-curved light-weight structures [2]. Nearly all thin concrete or masonry shells all around the world – and there are hundreds of them – were built in the period from 1925 to 1975. Most of them come from the following nine engineers or architects: Eduardo Torroja (1899-1961) and Félix Candela (1910-1997) from Spain; Pier Luigi Nervi (1891-1979) from Italy, Robert Maillart (1872-1940) and Heinz Isler (1926-2009) from Switzerland; Franz Dischinger (1887-1953) and Ulrich Müther (1934-2007) from Germany; and Antón Tedesko (1904-1994) and Eladio Dieste (1917-2000) from the Americas. All of these great engineers and architects have now passed away and with them the art of concrete shells building has come to a halt [3].

In a sense, this is not entirely the case, since concrete cooling towers are really very slender shells and they are still being built today to a height of 200 m. ost concrete silos are composed of cylindrical and conical shells. Still these utilitarian structures and their repetitive shapes represent only a fraction of the range that was used for the previous generation of shells. Factories, warehouses, metro stops, grandstands, theatres, cinemas, churches, restaurants, bars and even houses used to be covered by shells. While some engineers like Candela mainly worked with developable surfaces such as the hyperbolic paraboloid (Fig. 2), one of the largest being a swimming pool roof in Hamburg (Fig. 3). Others like Isler used free form shape found be inverting hanging tensile structures (Fig. 4) or worked with shapes derived from inflated cushions.

Among the numerous reasons why concrete shells unfortunately started to disappear in the 1970s are the high cost for the formwork and the poor insulation properties of the thin shells.

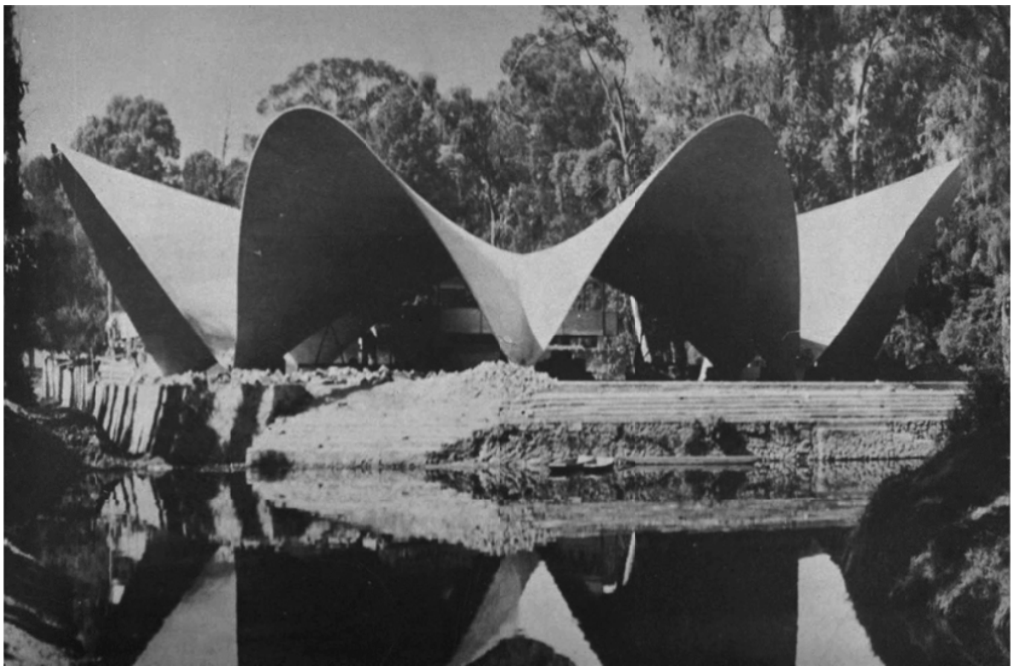

Fig. 2 Félix Candela, Los Manantiales Restaurant in Xochimilco, Mexico, 1958

Fig. 3 Jörg Schlaich, Swimming Pool at Sechslingspforte, Hamburg, Germany, 1967

Fig. 4 Heinz Isler, Petrol Station in Deitingen, Switzerland, 1968

The German Pavilion built for the 1967 World Expo in Montreal by Frei Otto, with the architect Rolf Gutbrodt and the engineers Leonhardt and Andrä, is the iconic building which represents the next generation of light-weight structures [4]. With the help of the new materials now available Frei Otto and his team created shapes never seen before. Tent-like tension structures made of cable-nets covered by membranes became possible. With their double curvature they seem to originate directly from the concrete hypar shells. The main difference, however, is that they are pre-tensioned tensile structures. Their stiffness and stability is achieved by combining double curvature with a high level of pre-stress. Contrary to their concrete ancestors these new structures are so light that wind suction can carry them away. Therefore, it is important to note that these light-weight structures require bulky and costly foundations in order to anchor wind loads and the pre-stress forces into the ground.

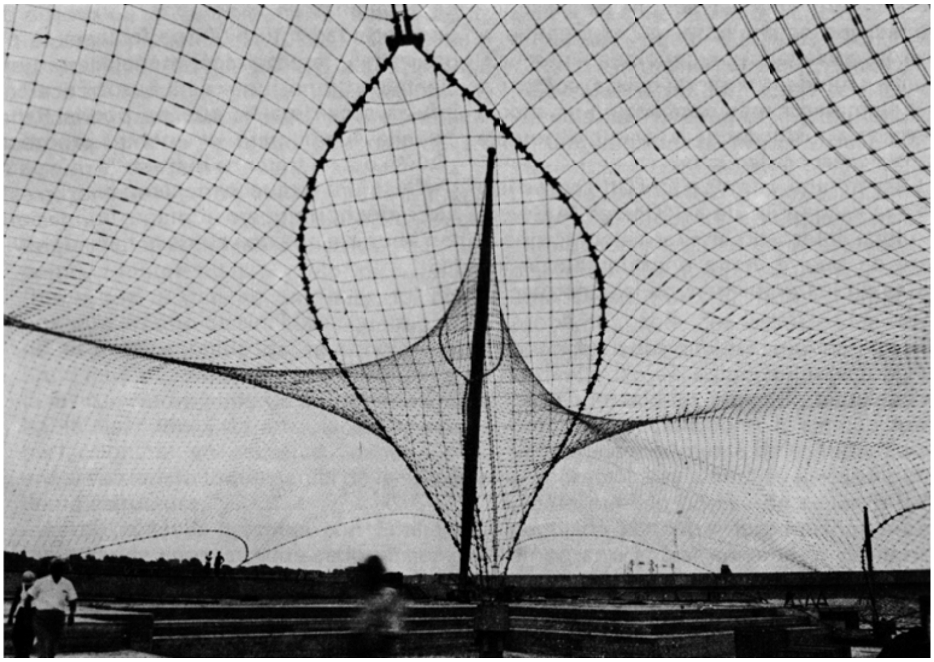

Fig. 5 Frei Otto, German Expo Pavilion, Montreal, Canada, 1967


Fig. 6 Roof of the Olympic Stadium, Munich, 1972

Strongly influenced by the German Pavilion in Montreal, the architect Günter Behnisch and the engineers Leonhardt und Andrä, with Jörg Schlaich as Project Manager and Frei Otto, projected this experience onto a much larger project, the still impressive roof covering of the 1972 Munich Olympic sports fields. The enormous size and elegance of this structure is the climax of cable-net building [5]. To the author´s knowledge no larger roof of this kind has been built since. At the same time the Munich roof reveals that such structures are costly not only because of their heavy foundations but also due to the combination of a load-bearing cables with a membrane cladding .

Today, pure cable-nets are mainly successful as special purpose structures such as covers for aviaries and in cable-net façades (Fig.6). Of particular interest in this case is also a 180 m high cooling tower that was built as a cable-net structure in the Seventies (Fig.7) [6].


Fig. 7 The First Cable-Net Glass Façade, Hotel Kempinski, Munich, 1993


Fig. 8 Cable-net Cooling tower during construction, Schmehausen, Germany, 1974

Since the 1980s two new tendencies have emerged, opening the way for a whole new generation of light-weight double curved structures:

1. Long-span membrane roofs, often self-anchored, with a minimum of primary steel structure (spoked-wheel roofs) (Fig. 8).
2. Very transparent steel grid shells covered with glass (Fig. 11-14).

Once again it was advances in material technologies, for example, high-strength membranes and affordable tempered safety glass that contributed to this progress. However, the new structural systems such as spoked-wheel roofs and translational surface grid shells contributed greatly in paving the way for these advances [6].

Nowadays, double curved pre-tensioned membrane structures are amongst the most successful long-span light-weight roof structures. They are surprisingly economical (provided they are self-anchored) i.e. that the spoked-wheel concept is used [7]. More than two dozens of such stadia membrane roofs have been built so far. They have with a weight (dead load) of approximately 25 kg/m² and span areas of 200 x 300 m without interior supports and capable to carry loads of 100 kg/m² (i.e. around four times their own weight).

Fig. 9 Spoked-wheel roof covering the Gottlieb Daimler Stadium, Stuttgart, Germany, 1993

Light-weight steel grid shells covered with glass have the advantage that the lightness of the structure is fully visible. As long as the steel grid is composed of triangles (or rectangles with cable diagonals) the structure behaves exactly as a shell. If translational surfaces are used, plane glass panels can be used on a quadrangular steel grid which leads to rather economic structures. While the builders of concrete shells like Candela used to align the formwork for their hypar shells along the straight generator lines, for glass covered shells curved generator lines are used in order to achieve plane glass rectangles [8].

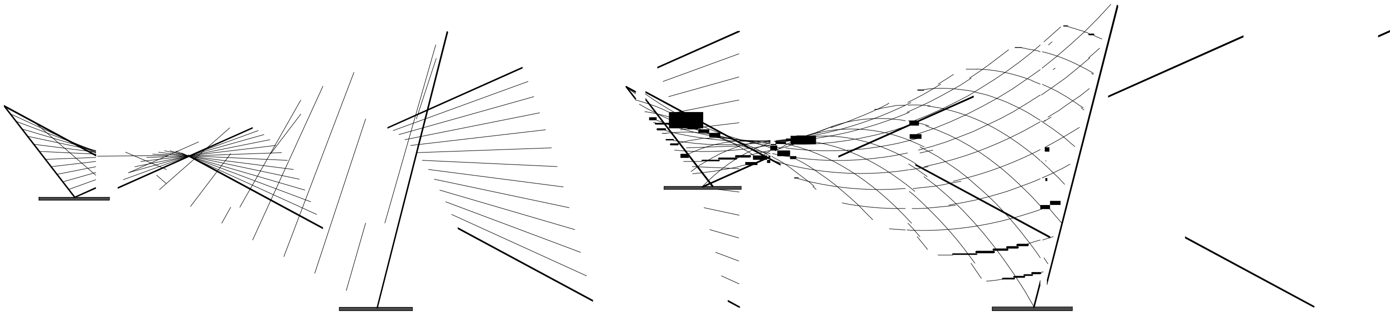

Fig. 10 Hypar Shells made of Straight Generators (for concrete shells) and curved ones (for grid shells covered with plane quadrangular glass panels)

Fig. 11 Glass Hypar Roof with plane quadrangular Glass Panels, Schubert Club Band, Minneapolis, USA, 2001

Fig. 12 Glass Grid Shells with plane quadrangular Glass Panels, Berlin, Main Station, 2006

When the shape of a shell cannot be represented by translational surfaces as in Fig. 10 – and a shell designed by Heinz Isler was to be made of glass – the only way left to develop the surface is to work with triangles. In this case a steel grid made of bars that form triangles covered in triangular glass panes works as a shell (Fig. 13 and 14).

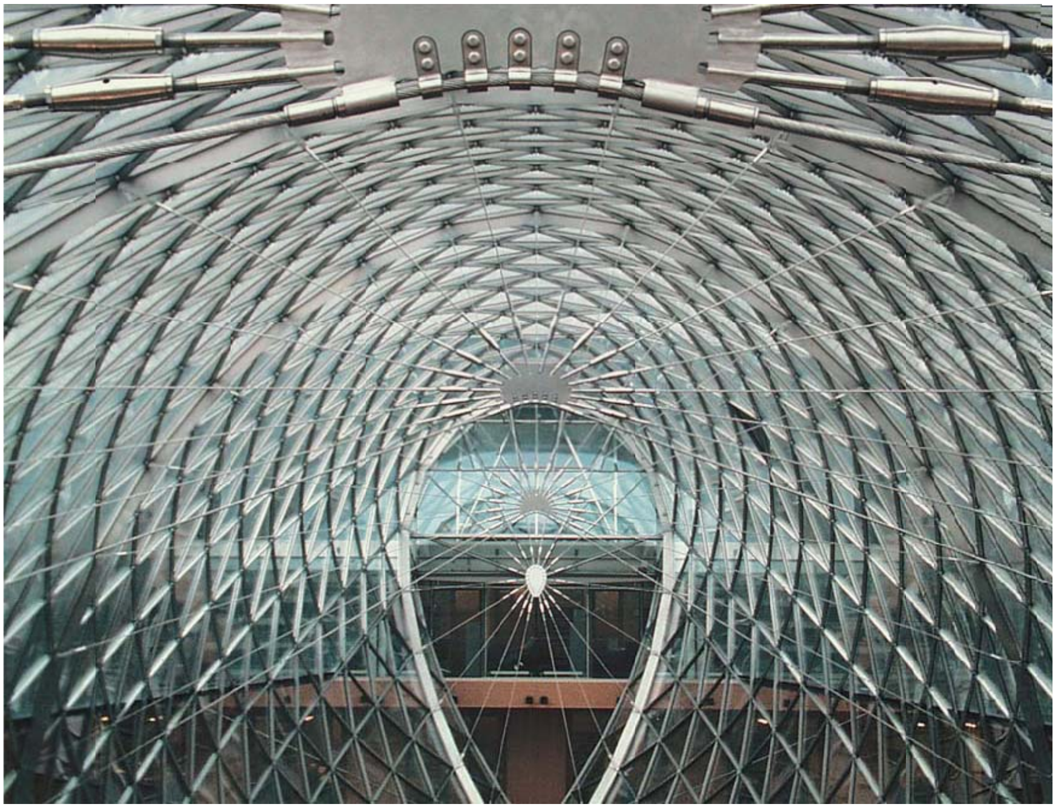

Fig. 13 Triangular Steel Grid Shell, Roof of DZ Bank, Berlin, 1998

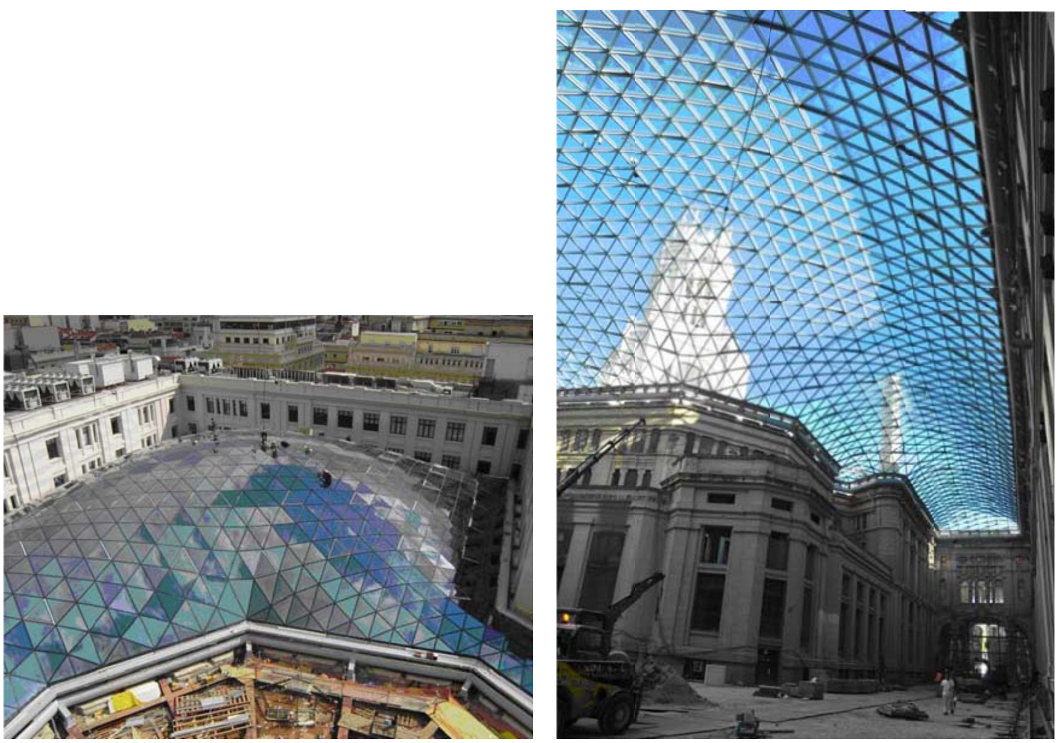

Fig. 14 Triangular Steel Grid Shell covering the "Palacio de Comunicaciones" in Madrid, Spain, 2009.

As we have just explored, today there are many options if we want to build light-weight structures:

- Predominantly in compression we can build not only concrete shells but also glass covered steel-grid shells.
- Predominantly in tension we can build cable nets and membrane roofs.

Due to this choice in light-weight structures, double-curved surfaces have become once again very popular. This is also because in contemporary architecture there is a trend towards natural shapes. Parallel to this development the possibilities of 3-D computer graphics have opened the way to more ephemeral designs and virtual structures. They are very convincing on the computer screen and, if at all, can only be transformed into reality with the help of double-curved light-weight structures. At the same time the evolution of structures in general is continuing, again thanks to progress in material science. Glass, for instance, is being glued together directly leading to all-glass structures without any supporting steel work. High strength carbon fibre materials are also being used more and more frequently and even in the field of concrete new tendencies appear, such as ultra-high-performance and infra-light-weight concretes as well as new fibre- and textile-reinforced concretes. Further, a number of reasons that made design and construction of light-weight double-curved structures difficult are disappearing:

- Modern analysis software and CNC-guided machines allow to analyse the most complex shapes and to fabricate the pertinent structural components or formwork elements.
- With the present paradigm change in energy production all over the world there is a chance that soon sustainable, clean and cheap energy will be at our disposal. In this case, thermal insulation - a main problem of thin concrete shells and all other light-weight structures - will not be as important anymore.

Once again it seems that double-curved light-weight structures, thin concrete and grid shells as well as membrane covers and cable-nets have a chance to make an important contribution to the future of our structures. For all future complex structures of quality we need master builders, well trained engineers (who know about architecture) and architects (who are interested in understanding how structures work). Then I think we can be full of hope.

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