Architectural Form and Structural Arrangement

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The principles “form follows function” and “less is more” have had led and still lead to successful architectural designs. On the other hand, “form” and “less” are parameters related also with the structural design and as such are engineer’s special concern as well. From the view point of engineering, optimal design depends mainly on the choice of the most appropriate structural arrangement and material besides the method of construction. Recently, some architects leave the meanwhile traditional architectural principles mentioned above in order to be different and to create an exceptional architecture of their own. The outcome of such endeavors cannot be even an architectural movement because each architect and his style are individual and remain as such. In contrary to such an architectural attitude disregarding the design rules, the design principles of the structural engineer are rationalism and optimization which are obligatory. Therefore, they cannot and should not be abandoned. The discrepancy between these two completely different standpoints of the exceptionalist architect and of the rationalist structural engineer may in some cases make their fruitful cooperation difficult so that the outcome being not optimal and far from rational. This means, the cooperation between the architect and the structural engineer from the very beginning is a must.

Keywords: Architectural forms, principles of structural design, roofs, bridges, stadia, optimization.

Introduction

Besides the choice of the constructional material, two main parameters of the architectural design are function and aesthetics. Any architectural function can exactly be defined and is as such an objective input of the design, whereas aesthetics is indefinable and a subjective outcome of the design process which depends on the feeling and creativity of the architect. A third parameter, namely the form, is not independent and has to be the result of the first two parameters. This fact is expressed as one of the principles of the architectural design: “form follows function”. Another principle of the architectural design is “less is more”. The parameters and principles of the structural design and the order of their importance are in fact the same as in the architectural design, however, with different contents. The function of the structural arrangement is the conveyance of the loads with an adequate safety to the ground.

Therefore, to express this fact, one can make the statement “form follows structure”. On the other hand, for the most convenient conveyance of the loads an optimal structural concept in terms of strength and stability has to be developed. Optimization is the parameter corresponding to the aesthetics in the architectural design as it requires the creativity of the structural engineer, however, unlike aesthetics there are measures and rules to be followed for the structural concept and therefore it is objective. The other architectural principle “less is more” means in the case of structural design “less material, less structural elements and less workmanship”. These are parameters which are decisive for the structural form and compulsory for the structural optimization. All these mean that in working with architects the structural engineer must stand firm, making it clear as to what can be done and what should not be done.

Architectural and structural concerns are not independent of each other and have to be fulfilled by the architect and the structural engineer together. The success of a design depends on the level and success of this cooperation. Until the mid of the 19th Century the contribution of the theories of Engineering Mechanics available for the analysis and design of structures had been very limited and the architect himself had been in charge of the structural design. He could manage this, because there had been a tradition based on the experience gained along the centuries. However, with the industrial mass-production of steel in the mid of the 19th Century a very advantageous and revolutionary new structural material became available to be utilized in structural design for which there existed no experience. This development made a new profession necessary to support the architect in his designs considering the theories of Engineering Mechanics and the properties of the new material to make them applicable in the structural system. The compressive strength of all materials used before steel is much lower than that of the steel and in addition, their tensile strength is very low. For this reason, before steel, the building masters had to use structural elements carrying the load mainly through compression without or with least bending. The structural forms allowing this type of internal stress states are the column, the wall, the arch, the barrel-vault and the dome. The constraint to use only these forms was of course from the point of the architectural design very restrictive but from the standpoint of engineering not as disadvantageous. In contrary, to avoid or at least to minimize the bending moments lead in most cases to structurally optimal solutions. On the other hand, thanks to its high tensile strength, modulus of elasticity and ductility, steel did offer immense possibilities and flexibility regarding both the architectural and structural designs.

The principles of the structural design

The main mechanical principle of the structural theory is based on the “law of the conservation of the energy” of physics. In terms of structural analysis, this law can be formulated as follows: The energy spent by the loading of a structure due to the displacements of the structure is stored in the structure as strain energy which is the work of the internal stresses due to strains. Based on this law, the Italian mathematician and physicist Carlo Alberto Castigliano (1847-1884) has derived and proved the principle named after him stating that “in the equilibrium state the work done through the deformations of a structural system has its minimum value”. This means that, like us human beings, every structure tries to carry the loads to which it is subjected by conveying them further following the shortest possible way to the ground in order to spend the least energy possible. The energy spent for this purpose comprises of three parts, the part spent through the bending moments induced in the structure being the largest one as compared to those parts spent through shear forces and normal forces. In addition, bending moments create in the structure tensile stresses. Least energy means at the same time smallest displacements and rotations and as a consequence, smallest strains caused through the loading. For more than a century the structural concepts reducing the bending moments have been decisive in the structural design and have been applied successfully as explained in the following.

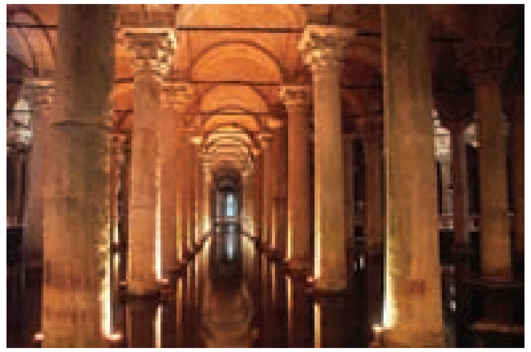


Figure 1. Basilica Cistern, Constantinople, 537 A.D.

Form - structure relation in systems carrying the load through compression

If supported appropriately, arches, barrel vaults and domes carry the load mainly through compression with least bending. Structural forms of these types were known at least five millenniums ago and have been used since than. They provided a rich variety for the architectural design in masonry, later in the 19th Century also in iron and at the first three quarters of the 20th Century even in reinforced concrete. Among many striking historic examples the Basilica Cistern and Hagia Sophia, both built in 537 upon the order of the Byzantine Emperor Justinian in Constantinople, are typical. The roof of the Basilica Cistern which is buried deep in the ground and has to carry the earth layers on it consists of many cross vaults and arches which are supported by more than 340 columns of 9m height in 5m spacing. In this way a very efficient structural arrangement had been realized because the many columns are by no means disturbing, so far the function of the cistern is considered (Fig. 1).

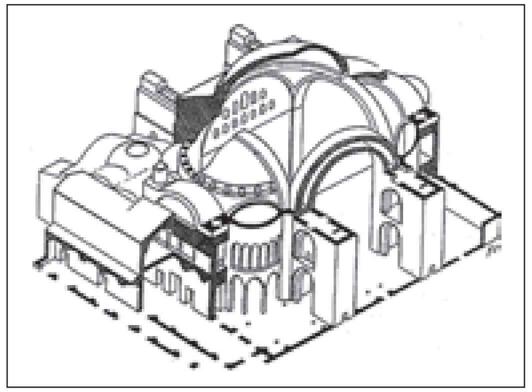


Figure 2. Structural System of Hagia Sophia, Constantinople, 537 A.D.

In Hagia Sophia, however, the situation is completely different because a very large column free space is necessary for the architectural function of the first large basilica of the Christian World, and the number of the main piers is for this reason only four (Fig. 2).

In Hagia Sophia the central dome has 32.5m base diameter and the interior is elongated by means of semi-domes at the east and west sides to cover a rectangular plan of 32.5mx65m providing a more than 2100m2 column free space for worship. The central dome, semi-domes and the curved triangular surface elements called pendentives are supported by means of arches resting on four main piers. The structural arrangement of the roof as such is optimal and ingenious so far the architectural function is considered, but has some deficiencies due to the difference in the stiffness of the east/west arches as compared to that of the north/south arches. This deficiency was eliminated a millennium later by the genius Turkish Architect Sinan in his domed mosques as for example in the Selimiye Mosque (Fig. 3).


Figure 3. Selimiye Mosque, Edirne, 1575

Iron domes of the 19th Century have the same structural arrangement as those in masonry, however, they are transparent as for example in the case of Vittorio Emanuele II Galery’s iron-glass roof in Milan (Fig. 4). Being 36m, the base diameter of the central dome in Milan is only 4m larger than the masonry central domes of Hagia Sophia and Selimiye which are 75cm and 70cm thick, respectively.


Figure 4. Vittorio Emanuele II Galery, Milan 1877

Larger domes were designed in the 20th Century, during the first three quarters in reinforced concrete, later in steel or as membranes which are prestressed by means of cables or air pressure. In Germany of the 1930s there was a strong group of structural engineers researching on concrete and working on the theory, analysis and realization of shell structures. These were Franz Dischinger (1887-1953), Ulrich Finsterwalder (1897-1988), Hubert Ruesch (1903-1979) and Wilhelm Fluegge (1904-1990). They worked in the design office of the building company Dyckerhoff & Widmann and realized the early large reinforced concrete shells having positive Gaussian curvature mainly for industrial purposes. To give an example, the roof of the Market Hall in Leipzig built in 1930 consists of two ribbed domes each having 65.8m span but only 9cm wall thickness (Fig. 5).


Figure 5. Market Hall, Leipzig 1930

The upsurge in shell design however, did occur after the Second World War, namely during the third quarter of the 20th Century. The most prominent shell designers of this quarter were Ulrich Finsterwalder, Felix Candela (1910-1997), Pier Luigi Nervi (1891-1979), Nicholas Esquillan (1902-1989) and Heinz Isler (1926-2009). Thanks to the many artistic designs by Candela, Nervi and Isler as Torroja’s followers, all of whom we may collect under the name ‘Latin School’, in this quarter the architectural dimension became as equal important, even in the designs of the rather conservative and rationalistic ‘German School’ under Finsterwalder’s leadership. For example, the roof of the Auditorium at the Hamburg University is an exicitingly shallow spherical cap having a radius of curvature of 65m and covering an irregular plan (Fig. 6, left). In the design of this shell roof Finsterwalder worked together with the architect Bernhard Hemkes (1903-1995). To take the shell forces at the free boundaries, the


Figure 6. University Auditorium, Hamburg 1957

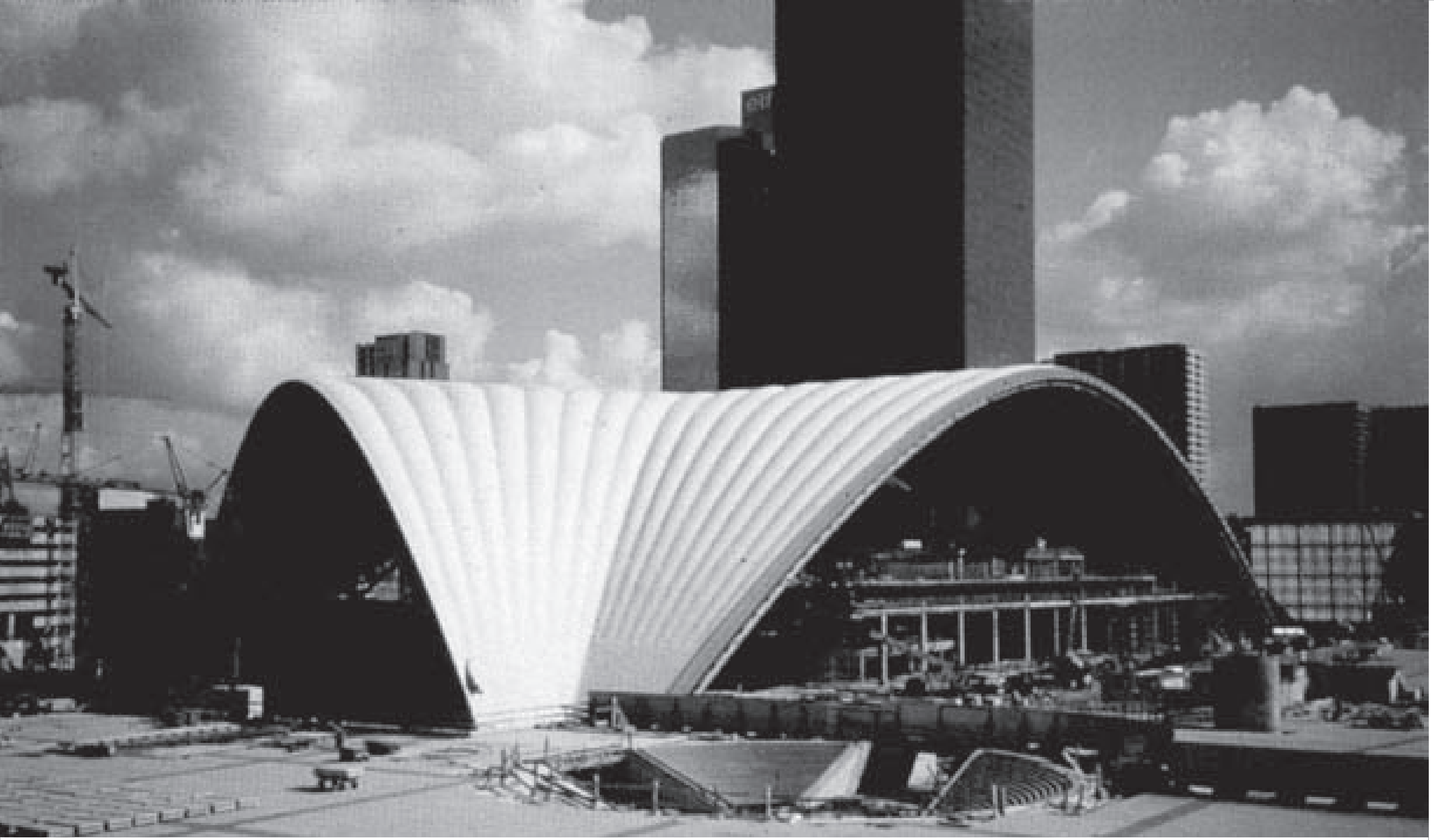
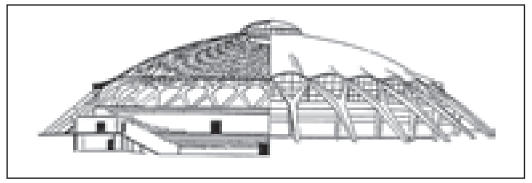


Figure 7. National Center of Industry & Technic, Paris 1958

shell was prestressed as shown in the left lower part of Fig. 6, so that the roof could be built without edge members and therefore, it looks from outdoors very thin. In addition, because prestressing counteracts the bending moments and the horizontal thrust, it was sufficient to support the roof on slender columns to attain a very aesthetic look (Fig. 6, right). Structurally, although the shell has a span of nearly 60m and is extremely shallow, it is only 13cm thick.

Before discussing the aesthetical shells created by the members of the Latin School, it is worth to start with Esquillan's roof structure built 1958 for the 'Palais des Expositions du Centre National des Industries et Techniques (CNIT)' in Paris, as it is the largest shell-like roof ever built in reinforced concrete and carrying the load through compression. The roof is supported at three points to cover a plan in form of an isosceles triangle having 218m edge length (Fig. 7). The structure consists of three two layered arch segments meeting at the top at 50m height. The wall thickness of the flanges of the hollow box section of the arch segments is only 6,5cm and the prefabricated webs connecting them are 6cm thick. These slender webs are stiffened by means of 6cm thick lateral ribs in 9m distance. The system as such has a cellular structure with 1,90m depth at the top and 2,75m at the supports, carrying the load mainly in the meridional direction. Although it looks like a huge shell, from the view point of mechanics the CNIT-roof cannot be accepted as shell because of its one axial load carrying behavior.

Figure 8.: Little Sport Palace, Rome 1957



One of the early architectural masterworks in reinforced concrete is Nervi's Little Sport Palace in Rome (Fig. 8). The engineer Nervi composed the shallow spherical cap roof through joining precast shell elements having curved ribs and extremely thin flange to create a decorative interior, whereas through the wavy lower edge of the roof and by means of the Y-shaped columns as supporting elements an exceptional artistic view from outdoors is achieved (Fig. 8).

If the Spanish (after immigration Mexican) architect Candela is the master designer of shells mit negative Gaussian curvature, the Swiss structural engineer Isler the master in designing shells of positive Gaussian curvature. Candela and Isler are famous because of their artistic shells in number 800 and 1000, respectively. Candela derives his forms with the help of aesthetics whereas Isler uses physical models by hanging wet pieces of textiles at single points and freezing them afterwards to fix their funicular shapes which are free of bending moments. Candela's Los Monantiales Restaurant in Xochimilco (Fig. 9) and Isler's Gasolin Station in Deitingen (Fig. 10) show their exceptional talents in design. On the other hand, today form finding and morphogenesis are matters which are solved by means of numerical analysis for the shape and topology optimization.

Figure 9. Los Monantiales Restaurant, Xochimilco 1958

Figure 10. Gasolin Station, Deitingen 1968

Form - structure relation in systems carrying the load through tension

Steel cables and textile membranes are structural elements with zero stability under compression, but with a high tensile strength. In this kind of structural elements stability against compression can be attained if they are prestressed to such an extent that the resultant axial forces acting are always and everywhere tension. In the case of membranes the prestress is induced either by cables or by air pressure. The membrane roof of the Bilkent University Amphitheater in Ankara is an example for the prestressing by means of cables (Fig. 11). The roof covering a semi-circular area of nearly 8000m2 consists of seven membrane panels supported by steel truss arches. Each panel is produced by membrane strips of sufficient number cut according to an appropriate cutting pattern and then glued. The membranes are prestressed by means of cables running along their boundaries to create a stable surface of negative Gaussian curvature always standing under biaxial tension.

On the other hand, 181m measuring Tokyo Dome is an air inflated and air supported structure stiffened additionally by means of crosswise arranged steel cables along the diagonals of the rectangular plan rounded at the corners (Fig. 12). To sum up, every form may be considered as appropriate, independent of the material carrying the load directly under compression (masonry or concrete) or under tension (membrane), provided that the necessary structural requirements are considered and fulfilled.

Figure 11. Bilkent Amphitheater, Ankara 1999

Figure 12. Big Egg / Tokyo Dome, Tokyo 1988

Prestressing versus hanging as structural arrangement

If only the result is considered, there is no difference between prestressing and hanging. Both measures aim to reduce the bending moments and in both cases


Figure 13. Rhine Bridge, Worms 1951

steel has proved to be the most appropriate material because of its high tensile strength. Through prestressing internal moments are activated which counteract the moments resulting from own weight and live load so that even very long cantilevers in concrete can be built with least depth. Fig. 13 shows Finsterwalder's Worms Bridge on the Rhine, Germany, built applying his own ingenious 'free cantilever system' Differently from the conceptual arrangement of prestressing tendons, the hangers of the suspension bridges and the inclined cables of the cable stayed bridges act like elastic supports for the girders of the bridge deck and contribute in this way substantially to the reduction of the bending moments. With decreasing inclination of the stay cables, however, a transition from the supporting to prestressing takes place, because in slightly inclined stay cables the vertical component of the cable force is much smaller than the horizontal component so that the cables act as 'external tendons'. Such bridges are called 'extradosed' and one of the most aesthetic examples of the extradosed bridges is surely Christian Menn's Ganter Bridge on the Simplon Highway in Switzerland (Fig. 14).

Roofs for stadia

Roofs covering the grandstands of large stadia are formed mostly by means of relatively long cantilevers as beams or trusses connected at their free ends and supported ends through tension and compression rings, respectively, to give a spatial structure. Until the 1970s concrete was the material preferred, either as plain reinforced or prestressed. However, cantilevering conoidal shell elements having negative Gaussian curvature have also been used. The roof of La Zarzuela hypodrome near Madrid which was designed by the renown Spanish engineer Eduardo Torroja is a masterwork of both architecture and engineering. Although the free cantilevering length of the shell elements is 13m, the shell thickness is only 5cm (Fig. 15).


Figure 14. Ganter Bridge, Brig-Glis 1980


Figure 15. La Zarzuela Hypodrome, Madrid 1935

In the last three decades mostly as roofing for stadia 40 to 50m long steel truss cantilevers are used. These trusses are formed either through bars or cables and covered by membranes or glass. There is a rich variety of such roofs the most elegant one being Jörg Schlaich's design for the Gottlieb Daimler Stadium in Stuttgart (Fig. 16).

Other new developments are retractable and deployable structural systems.

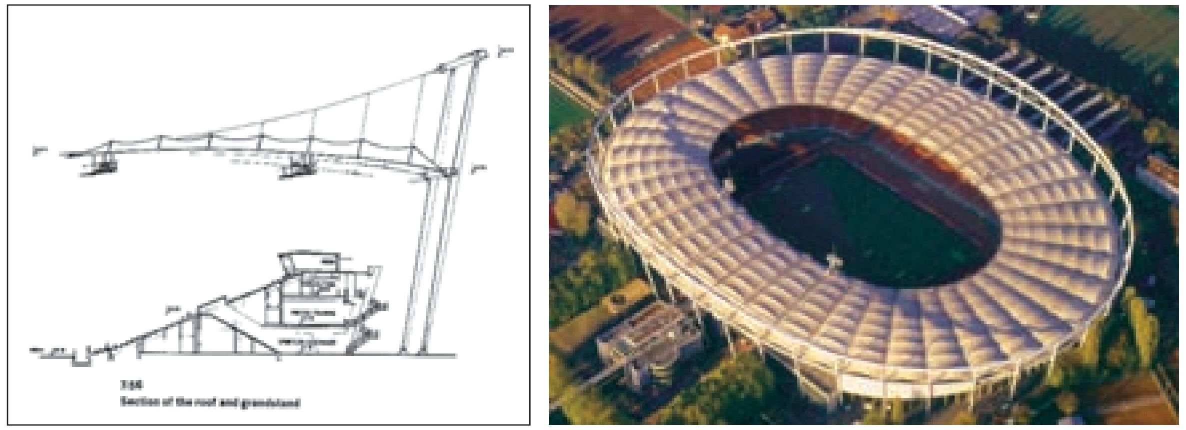


Figure 16. Gottlieb Daimler Stadium, Stuttgart 1993

Toronto SkyDome is an example for retractable roofs in which opening or closing the roof is attained through sliding of the heavy steel arches on rails (Fig. 17, left), whereas in Commerzbank Arena Frankfurt a very light deployable membrane is used (Fig. 17, right).

New architectural trends

Like all other artists, architects are in search after an individual style and the forms they create for their works are considered by them to be the most appropriate and easy means to develop such a style. That means, first a striking form is created and the architectural function is fitted into this form. In such a design approach what the structural engineer has to do is reduced to the development of a stable and load resistant structural system to make the form stand, whatever it costs. Structural optimization is sacrificed for the sake of aesthetics. This fact becomes clear if some extraordinary examples of the individualistic architecture are considered.


Figure 17: SkyDome,Toronto 1989 and Commerzbank Arena, Frankfurt 2005

Figure 20. Art-Museum, Milwakue 2001; City of Arts, Valencia 2005

The idea behind the Alamillo Bridge in Sevilla is to anchor the stay cables not in the ground or in a neighboring span but in the pylon. This results in a shape like a harp (Fig. 18). Although this architectural design concept is very attractive, it is from the structural point of view against the concept of cable stayed bridges. The main effect in the pylons of the Alamillo Bridge is bending. And for the stay cables to act as supports and in this way to release the girders of the bridge deck, the pylons need a very high bending stiffness. Prestressed concrete or steel girders as simple beams having the size of fully effective pylons would perhaps be sufficient so that additionally no expensive pylons and stay cables would be necessary. As another example for an architecturally very attractive structure is the National Stadium in Beijing. The structural elements are used primarily as ornamental members to create a 'bird nest' texture as architectural expression, whereas the rule of structural optimization is completely abandoned (Fig. 19). In order to be attractive, there is also the trend to use complicated forms (Fig. 20, left), textures (Fig. 20, right) or both needing a big amount of constructional work.

Figure 18. Alamillo Bridge, Sevilla 1992

Figure 19. National Stadium, Beijing 2008

Conclusion

For the structural design there are many models in the nature. The skull of mankind and animals, shells of different nuts and of oceanic animals due protect the organs and the fruits, respectively, against external effects and have served as model for shell structures. On the other hand, the 'function-form-structure relations' are followed in the nature strictly. These relations can be explained easily considering two great animals, namely the giraffe and the elephant as follows. The giraffe is a very elegant animal which is useless to carry loads. Therefore thin legs are sufficient to carry the own weight. To reach the top of trees for food the giraffe needs long legs and a long neck. Because of the long neck the head has to be relatively small and light (Fig. 20, left). The elephant, however, has completely different functions like for example carrying loads. The elephant makes use of the trunk to carry loads and to reach the food and water. Therefore, the neck doesn't need to be long. In turn, the head can and has to be heavy and strong to act as a support for the trunk (Fig. 20, right). Such a head can easily be carried by the short neck. On the other hand, the animals themselves are perfect designers. The spider and the bee design like structural engineers, whereas the birds are the individual architects of the nature (Fig. 22).

Figure 21. Function-Form-Structure in Giraffe and Elephant

Figure 22. The Engineers and the Architect of the Nature