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Cable Roofs. Evolution, Classification and Future Trends

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Abstract

Cable roofs have been built over the last 60 years. They have a big attractive from aesthetic, technical, and even environmental aspects (to build with the minimum amount of material).

The objective of the article is to analyze, after a short analysis of the historic evolution and a typological classification of some existing buildings, future trends in the design of cable roofs. Special attention will be given to the secondary structural envelope system and its relationship with the primary cable mesh.

Keywords: Cable mesh, cladding, retractable roof.

1. Introduction

Tensile structures are fascinating because structure, envelope and shape are firmly linked. Although they are attractive from a lot of points of view, cable roofs has not been extensively built. Probably, the main reason behind is that they are more difficult to analyze than conventional buildings. The first step of their analysis is the definition of the geometry (form finding). Most of the methods to solve the initial equilibrium problem (force density method, dynamic relaxation, etc) are not included in general analysis programs and they are not familiar to all the structural engineers.

We can identify an initial period of development of structural systems between 1950´s and 1970´s, when an enthusiastic atmosphere was created around this type of roofs. This enthusiasm was reduced in the 1980´s. Nowadays, the most extended and competitive typology of cable roofs are bicycle wheel systems. The last advances in suitable cladding materials for cable structures and the increasing acceptance of them by the architects predict a promising for the cable roofs.

A schematic tour around the history, classification an evolution of cable roofs will be given in order to review their formal possibilities. This review will also be linked to the current and future design possibilities adapted to the new cladding materials which exist actually in the market. These materials have an aesthetic attractive, durability and fulfilling of functional requirements. They also fit with the large displacements of cable structures.

2. Classification of cable roofs

A classification of cable roofs is presented in this section. Only systems where the cables are the principal element of the primary structural system have been considered. Systems with beams or trusses stayed by cables have been not considered as cable roofs.

Every roof type is presented briefly, just with a simple definition and some relevant examples. More information about them can be found in the references included at the end of the article.

2.1 Synclastic Cable Meshes

Roofs based on this principle are made up of catenary cables. The shape is given by the external applied loads. The stiffness of the system is provided by the weight of the cladding or by an external load.

Only single curvature or double positive curvatures are possible in this category. The outer boundaries are limited (generally) to square or circular shapes. The roofs, according to their geometry can be hung or domed.

In hanging roofs, to avoid the inversion of curvature and fluttering induced by wind loads, heavy cladding materials (like concrete) are needed.

In domed roofs two options are possible.

- *Cable stayed domes:* The geometry of the dome is reached by a system of stay cables (see Millenium Dome in figure 1).
- *Pneumatic supported roofs:* The primary structure is made up of cables and the secondary structure is both cladding and secondary structure (generally fabric membranes or foils). The cladding fills the gap between the cables of the mesh and keeps the air pressure inside the building.

Some examples of synclastic cable mesh roofs are presented in the following figure.

Figure 1: Portuguese Pavilion Expo 98, Lisbon (Portugal, 1998); Tokio Dome (Japan, 1988); Madison Square Garden, New York (USA, 1968); Millenium Dome, London (U.K., 2000).

2.2 Anticlastic Cable Meshes

The curvature of anticlastic cable roofs is two-dimensional. The stiffness of the system is given by the double curvature and no additional external loads are needed.

The double curvature cable meshes have a high geometric range of possibilities. The shape of the boundary edges, the level of pretension, and other parameters have an important influence in the overall geometry of the building.

Further classifications within this group can also be established:

- *Closed meshes:* The tension forces of the roof are transferred to the boundaries, generally arches, which are under compression and keep the forces inside the system.
- *Open meshes:* The tension forces of the roof are transferred to the ground. Heavy blocks or tension anchors are needed in the foundations.

Closed meshes have a reduced range of geometric possibilities with regards to open meshes. The lack of freedom in the design is compensated with the advantage of important savings in terms of foundation elements. Other important parameter in the design of the closed meshes in order to obtain more economic structures is to reduce to the minimum the bending moments in the boundary edges.

Figure 2: Closed Cable Mesh: Raleigh Arena (USA, 1953); Open Cable Mesh: Munich Olympic Park (Germany (1972).

2.3 Ridge and Valley Cable Roofs

The geometry of ridge and valley cable roofs is generated by an alternation of concave and convex primary cables.

A connection between the concave and convex cables should be also provided to generate a mutual prestress between them. The internal prestress in the cables guarantee the overall stiffness of the roof.

The connection between the main cables can be done by cables. In this case, cladding elements (like glass or similar) can be placed over the cables. Other possibility to connect the main cables is with other type of tension elements like fabric membranes, which combines both cladding and structural function.

Cable trusses with only tension elements can be also considered part of this group.

Figure 3: Town Hall. Vienna (Austria, 2000).

2.4 Spoke Wheel Roofs

Spoke wheel roofs are based in the concept of bicycle wheels. Two sets of prestressed cables span between an outer compression ring and an inner tension ring.

The structural system is very efficient. The prestress of the cables gives enough stiffness to the system and lead to slender structures because the cables work only under tension, reaching the material its maximum strength capacity. The outer ring works under compression and it is stabilized by the cables. The self stressed state allows important savings in foundations (anchors, concrete blocks, etc) as a result of a minimum transference of horizontal loads to the ground.

Figure 4: Zaragoza Arena (Spain, 1988). Gotlieb Daimler Stadium, Stuttgart (Germany 1992).

Two configurations of boundaries are possible: two compression rings and one tension ring; one compression ring and two tension rings. The system has been applied with success to circular, oval and rectangular shapes.

2.5 Strut-Tie Roofs

Cable roofs make up only by tension and compression elements are included in this group. The equilibrium of the system is guaranteed if one compression element (strut) and at least three tension elements (ties) are merged in each node.

We can identify two subtypes within this category:

- Parallel juxtaposition of one-way strut-tie cable trusses.
- Three-dimensional strut-tie systems.

Tensegrity systems can also be included into the group of tridimensional strut-tie systems.

Figure 5: Canopy in the main entrance to Expo'89 in Yokohama (Japan). Seoul Olympic Gymnastics Hall, Korea (1986).

3. Evolution

The use of tension elements in construction is ancient (ropes, chains, etc). Nevertheless, is only in 1823, when Marc Seguin built the first permanent bridge suspended by cables made up of iron wires.

The application of cables in building roofs is more recent. The first structures regarding cable roofs were four pavilions with hanging roofs built for an exhibition in Nizjny

Novgorod by the Russian engineer Vladimir Shukhov. After that, only during the 1930's some minor cable roofs were built.

The initial important development of cable roof structures, between 1950´s and early 1960´s was located basically in the United States and Germany. It is interesting to analyze this period because many different structural configurations and arrangements were tested. Some of them have been rediscovered in recent awarded projects. Most of the buildings built from 1950 to 1970 were pioneers in the structural typologies and concepts introduced in the second point of this article.

The first relevant building known with a cable roof (close anticlastic cable mesh) was the Rayleigh Arena (see figure 1), built in 1950. In that moment started a slow but constant growing in the number of constructions with cable roofs.

Other important examples (also pioneers in their respective structural typologies) are the US Pavilion in Brussels (first spoke wheel roof. 1958) or Dulles Airport Terminal in Washington (cable suspended roof.1963)

Figure 6: Dulles Airport. Washington (USA, 1963); US Pavilion. Brussels (Belgium, 1958).

After the initial American period of development, Frei Otto started to work in Germany. It is important to mention a visit of Frei Otto to the U.S.A in 1950. He was impressed by the structure of the Raleigh Arena, which influenced him to chose the topic of his doctoral thesis, *The Suspended Roof*.

His first important cable structure was the German Pavilion in Montreal Expo. An open cable mesh designed in 1967. Afterwards, in 1972 he built the Munich Olympic Park with the aid of some important architects and engineers. It is one of the masterpieces of the cable roofs.

At the same time, in the late 1950s, Walter Bird began to develop air supported structures and he was acquiring an important skill building with “air”. As a result of those small steps, in the Osaka Expo (1970), an important number of pneumatic structures were built. The most relevant was the American Pavilion, an oval with of 142x83 m. supported by a net of cables. This type of dome was very popular in the 1970´s and early 1980´s, dominating large span roof construction for more than a decade. Nowadays their use has been reduced because of the high operation costs and problems of collapse under snow loading.

In the late 1980’s some designs of three-dimensional strut-tie systems were developed by David Geiger and Associates. The Gymnastic and Fencing Arena for Seoul Olympics (1988) and the Georgia Dome (1992) are the most relevant examples. Anyway, the use of this typology has not been too much extended. Tensegrity systems have also been extensively researched, but their efficiency and economic viability in roof construction is not yet demonstrated.

In the last 30 years, the impressive work of the engineer Jörg Schlaich and his team has to be enhanced. Their work in cable structures is extensive: footbridges, cable façades, roofs, etc. Their main contribution to the field of cable roofs is the development of the spoke wheel systems.

It is important to mention the Zaragoza Arena roof, built in 1988, where the spoke wheel roof was rediscovered and improved. It was a key project because it was a starting point for other similar projects with more innovative contributions.

Among these innovative contributions we underline the application of the system to: oval and rectangular boundaries, different tension and compression ring arrangements, and lightweight retractable roofs (Schlaich [17]).

4. Future Trends

Among the history of the construction of cable roofs, a lot of different arrangements and typologies have been tested.

When something is new, in the early stages of development there is always some different formal and material experimentation. In the end, only the most advantageous systems (economically, aesthetically, functional, etc) will remain.

If we analyze the main characteristics of the latest designs in the field of cable roofs we can identify some common key points:

- Most of the designs for large cable structures are self balanced systems of loads, because they are cost competitive even with regard to conventional systems.
- The use of cable meshes in roofs with reduced distances (1.0-1.5 m) between the cables of the net has been reduced. Actual design trends are focus on a higher separation between the cables. A lower number of cables allow a cost reduction because there are less anchors and connection elements.
- The reduction of cables is only possible if a secondary self supporting envelope is placed over the cable mesh. Prestressed membranes have been extensively used.

For large spans (over 60 m) the spoke wheel solutions are very competitive, even economically, regarding to traditional steel solutions. They have been used in an important number of big sport stadiums in the last fifteen years.

Other important aspect to establish new trends in the design of cable roofs is based in the properties of cladding materials. In cable roofs, the cladding is also a secondary structure and it has to fulfill mechanical and functional requirements. The cladding has also to be able to support the large deflections of cable roofs.

Fabric or foil materials are the perfect solution to be used as skin and secondary structure in cable roofs. Traditionally single layer PVC coated polyester or PTFE coated fiberglass have been used for permanent applications. They have some problematic aspects which have been improved in recent material developments. These improvements will enlarge the range of applications of cable roofs.

One of the most suitable applications for cable roofs could be found in growing market of retractable roofs. Cables are the perfect solution for retractable roofs. They are light (cheaper open mechanisms) and can be used not only as structural element. The cables can also play an important role in the opening and closing system.

In retractable roofs, PVC coated polyester has been used as cladding material because other materials like PTFE coated fiber glass can be damaged during the folding and unfolding process.

One of the disadvantages of PVC is the ageing. For many applications and clients it could be a problem to have to replace the fabric only 10 or 15 years after the installation. PTFE fibers have been developed in the last years. They have very good foldable behavior, self cleaning properties and they have excellent resistance to ageing. They are expensive, but their good properties could predict an increasing demand for them in the future.

Other traditional problem of fabric and foil structures is to fulfill some functional requirements regarding the building physics. Single layer systems do not work well when thermal behavior has to be strictly under control.

To keep thermal behavior under control it is necessary to build a multi layer system. In the past, in these systems an opaque insulation had to be placed between two layers of a fabric membrane. With this operation, one of the main advantages of fabrics (translucency) was lost. That is one of the reasons of a non extensive use of fabric structures when important thermal control has to be achieved.

The last advances in transparent thermal insulation materials open a new field to a more extensive use of membrane structures for a wider range of applications. Within this context, an increase of the cable roof construction can also be expected.

It is important to point out the role of ETFE in the last years. ETFE is a material discovered in 1940´s, commercialized in 1970, and with its first applications to the architecture in the 1980´s. The construction of the Allianz Arena in Munich (2005) and the Water Cube for Beijing Olympics (2008) were very important to spread its popularity among the architects. The range of possibilities of ETFE in architectonical designs is still open.

Figure 7: Cyclebowl Hannover, Germany (2000). Experimental pavilion. Some passive environmental strategies were investigated.

If it is used in double or triple layer systems it has acceptable thermal properties and it has some advantages with regard to glass. One of the advantages is the permeability to the UV radiation. This property allow the material to be used in green houses and buildings where the possibility to have vegetal life should be considered. Some studies have been carried out to build football stadiums (with natural grass) and permanent ETFE roofs. There is an important field of development for cable roofs if the use of ETFE is extended to cover large sport stadiums.

In our opinion, the major development for cable roofs can be expected based in the advance of cladding materials. The innovation in new structural systems seems to be more difficult. Anyway, some structural arrangements like tensegrity systems (Motro [17]) or curved boundaries in membrane and cable nets (Wagner [18]) are still under research.

More intensive use of cable roofs will be done if economic and attractive designs can be carried out. The economy of cable roofs has been demonstrated in some projects of large span roofs, mainly spoke wheel roofs. Aesthetics are also important. In smaller buildings, cable roofs can be considered as a design option if attractive and suitable cladding materials (like ETFE in the latest years) are offered and spread among the architects.

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