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USE OF FIXED LENGTH CABLE TECHNOLOGY IN STADIUM ROOFS

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ABSTRACT

What is a definition of “lightweight structures” ? Personally, I like the quote from Joseph Paxton, the builder of Crystal Palace in London, in 1851: “What is old boring stone and beam compared to these magically slim columns? God who let iron grow wanted great exhibitions, not the servants of the Stone Age”[2]. Was iron the material that allowed us to get closer to godly perfection in design of structures?

Well, …iron grew a lot from the times of tie rods in mid-ages stone arches and the times of chain bridges, some of them over 200 years old.

Now, it took a form of very thin but very strong, high-tension steel cable.

It is a tension technology that revolutionized the long span enclosures, including the stadium roofs and other long span structures.

The advancement of engineering methods and new building technology is the key answer to a question: “how to build more with less”, i.e., how to span larger areas with less materials and therefore lower costs?

These large areas can be stadiums roofs, for example.

This paper and presentation will illustrate the advantages of Cable Structures used in Long Span applications. When designed properly these structures exceed in the efficiency, constructability, economics and a long-term use of any traditional structural systems. In addition, there is very convincing argument for the aesthetics and a unique opportunity of creating forms and shapes of structures, which become instant landmarks, and which would be impossible to achieve with conventional construction methods.

This presentation will demonstrate the fundamentals of engineering design with cables and other structural tension members in comparison to other structural materials and engineering methods. It will also explain the basis of production of roll materials, fabrication of cables and installation process of cable structures.

1. Introduction

Let me quote the definition of one of the funders of the theory of Light-weight Structures, Frei Otto, i.e. “How to build more with less”. Let us have a look at the practical implementation of prof. Otto’s theory on example of the Four Point Structure, one of the first structures built by Frei Otto in Kassel, Germany in 1955. The weight of the entire structure was only 4.9kG/m2. It is not a stadium roof, but this structure is very light.

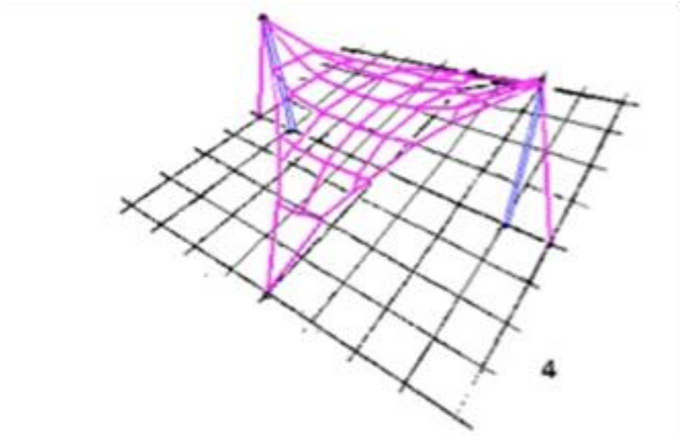

Fig. 1. Four Point Structure, structural model.

What makes it so light? The structure comprises 2 steel masts, working in compression, and system of catenary and tie-down cables with tension membrane, working in tension, to complete the enclosure of the band shell. Of course, there are underground footings for the masts and the tie-down cables. It is the use of tension elements, which makes this iconic structure super light. How is it possible? Let’s have a look at the mechanical properties of a cable vs. a solid steel rod. (Fig. 2).

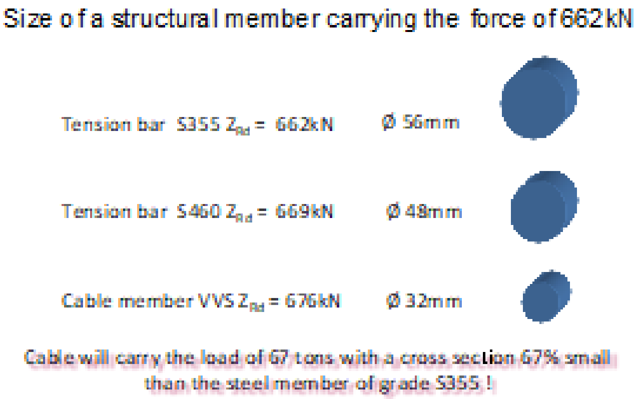

Fig. 2, Comparison of load carrying capacity of steel tension rods and a steel cable.

We can see from the above, that a cable can carry the tension force the same as the solid steel rod that needs the cross section 3 (three) time larger than the cable’s cross section. If the entire supporting structure could be built with the cables only, there would be a possibility of 66% savings on the weight of the materials only, apart from other advantages.

2. Cable Structures.

2.1. Properties of structural cables.

Attention needs to be given to 4 main properties of cables, which distinguish them from other structural materials. These are as follows:

A) Cables are made from several very thin wires (Fig. 3). Wires have to be cold drawn from high tensile strength steel rods (wires for structural cables cann**ot** be hot rolled!), to achieve the tensile strength of 1770N/mm2 (on average) as opposed to 510N/mm2 of structural steel grade S355 (Fig. 3). In the end the cable bundle is a composite and not a homogeneous material, as shown below:

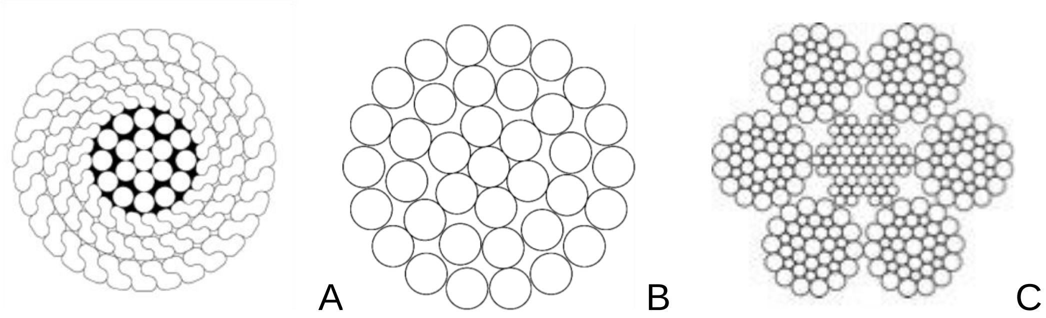

Fig. 3. Section of typical cables: A-Full Locked Cable, B-Spiral Strand, C -Wire Rope.

B) The more wires in a cable, the higher the metallic cross section and higher the strength of a cable. We should note one of the fundamental properties of any cable or wire rope, which defines its load carrying capacity. This is: Minimum Breaking Load (MBL) of cable, which is the force at which the cable fails in destruction tests. MBL can’t be confused with Nominal Cable Strength which is calculated as a function of a cable metallic cross section and the tensile strength of steel wires, from which the cable is made, and is **not** a property of a cable for a practical use. See Fig. 4 for details, below.

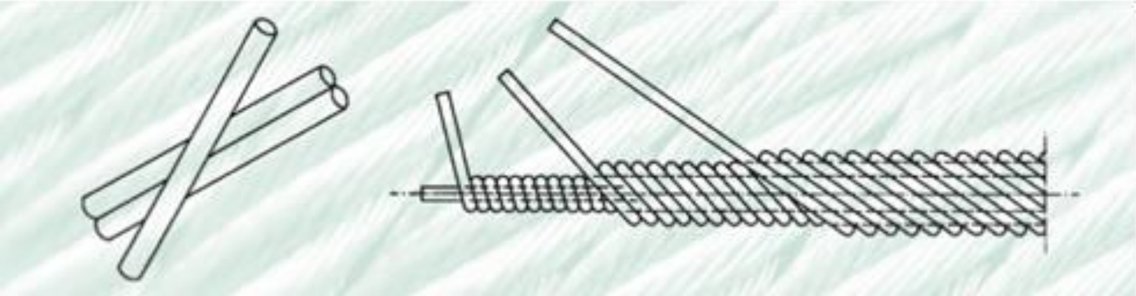

Fig. 4. Layers of wires in a cable strand.

Wires in the strand that forms a cable have different lengths and are of a different shape in each of the layers of wires. Only one, central wire is straight. All remaining wires twist around the central wire or layers of wires, in a helical shape. This means that the wires in one layer are longer than wires in a layer below. See Fig. 5 below.

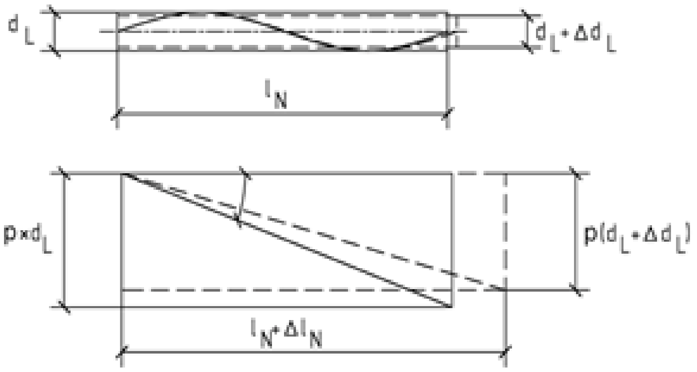

Fig. 5. Helical shape of outer wires in a strand, and their elongation under load.

This also means that under a force, each layer of wires applies lateral pressure on the layer below, which adds to the stress and the elongation of cable. This phenomenon is called: the Stranding Factor, which needs to be calculated for each cable, to learn the MBL of Cable. Stranding Factor reduces the Nominal Strength of cable to the Minimum Breaking Load of cable by a significant value. This value could be as much as 25%, pending the build-up of a cable strand.

C) Very high strength to self-weight ratio, which makes an ideal material for creative engineering solutions, specifically for support long spans.

D) Cables can carry tension loads only. Any applied loads are converted to axial forces in cable after its deformation. This axial force can be 3 times higher than a typical steel member of the same section.

2.2. Structures made with Cables.

The advantages and the properties of the individual structural cables, as listed above, can be most efficient only when combined into a coherent and buildable structure. Let’s start with the highlights of the engineering fundamental rules and requirements based on simple assemblies. This information should help in understanding how complex cable structures are designed and analyzed.

2.2.1. Single Cable.

A) Axial loads.

Any cable will carry axially applied load within its plastic deformation limit (Tension Limit) and by changing its geometry, i.e., undergoing an elongation under the load. The basic equation to calculate the cable elongation under the load is shown below:

$$\Delta L = (T_{max}\, L) / (A_m\, E) \qquad (1)$$

Where: ΔL – Cable elongation under force Tmax [m]
Tmax – max force in cable [kN]
L – cord length of cable [m]
Am – metallic cross section [mm2]
E – modulus of elasticity [kN/mm2]

Please note that even a force applied axially to a perfectly vertical cable is usually not the only load applied to this cable in practice, which makes the simple elongation calculations a little more complex.

B) Lateral loads.

Any non-axial loads applied to a non-vertical cable cause a deformation to this cable and the resultant reaction loads on supports, usually in line of the deformed cable. See Fig. 6., below.

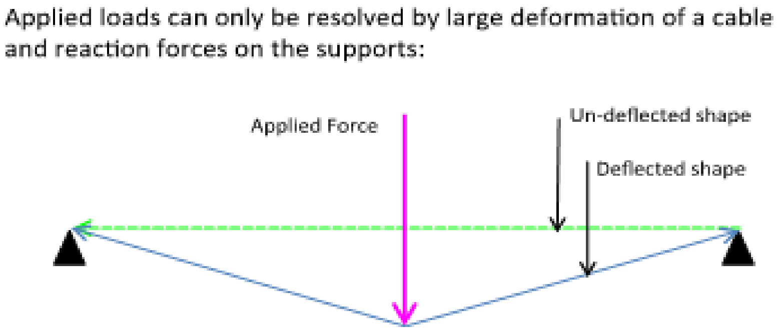

Fig. 6. Behavior of a single cable under a point load.

2.2.2. Cable Truss.

Single cables can be combined into a truss, as per diagram below.
Cable trusses are usually vertical and 2 dimensional with some steel compression elements, i.e., masts (as on the diagram), struts, hangers, diagonals, etc. However, there are more complex 3D cables trusses with top and bottom cords made of several cables. See Fig. 7., below.

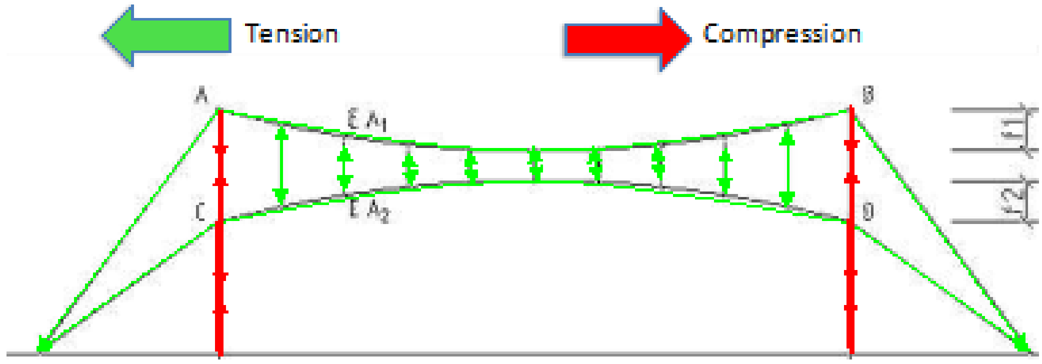

Fig. 7. Cable truss diagram of main forces.

2.2.3. Cable Net.

Several cables can be arranged in the form of a cable net spanning large distances and forming very dramatic three-dimensional shapes.

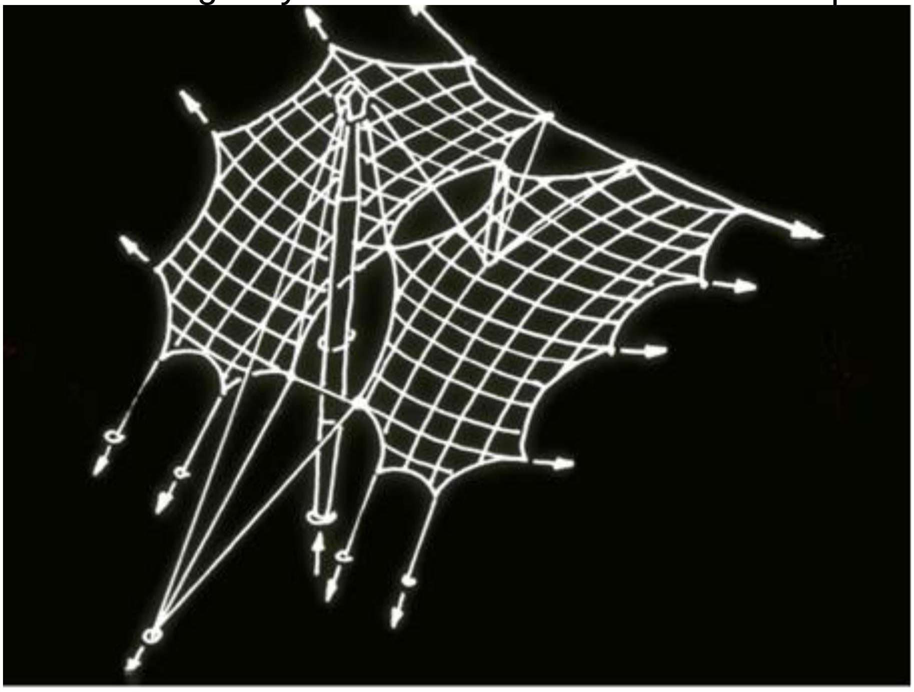

Fig. 8. Diagram of a cable net roof of Munich Olympic Stadium.

2.2.4. Bicycle Wheel.

Simple concept of bicycle wheel was adopted to develop complex structural systems for lightweight roof systems of large stadium roofs.

Despite the complexity of engineering analysis, the basic concept of a wheel remains loyal to an old bicycle wheel: outer rim (compression ring), spokes (cable trusses) and a central hub (tension ring). Fig. 9.

Fig. 8. Good, old bicycle wheel: outer rim, spokes and a hub.

The distribution of forces in a cable bicycle wheel roof system is shown below in Fig. 9. All Dead Loads (DL) and all applied loads are carried by tension forces in radially arranged cables with a central tension ring (i.e., hub), which form the roof coverage. All tension forces in cables are resolved on the compression ring at the outside edge of the roof. In an ideal situation, the ring would be allowed to slide on supports and to transfer only vertical loads from the roof to the outside columns and the footings of the building. However, the ideal conditions seldom occur on the real construction site, unfortunately, mostly due to the wind loads.

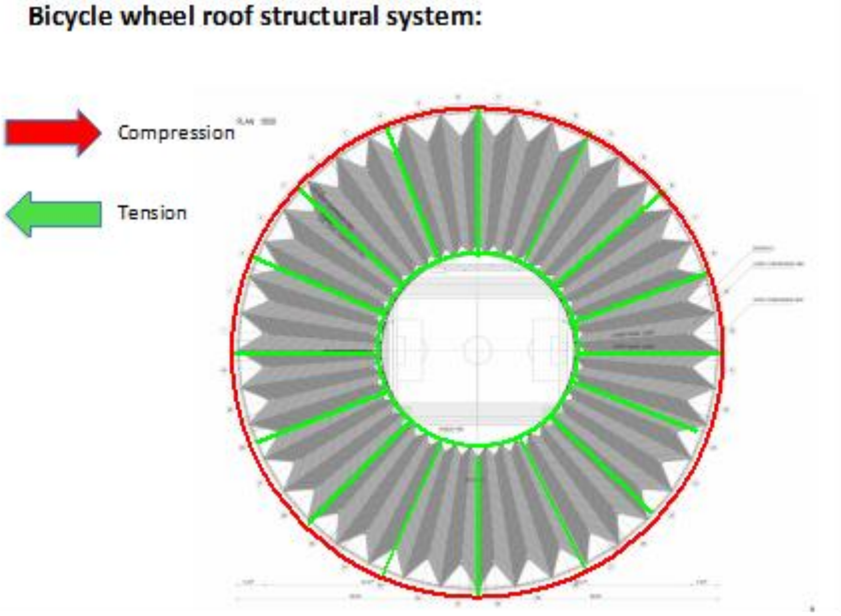

Fig. 9. Diagram of forces flow in a bicycle wheel roof cable system.

2.2.5. Cable Dome.

A three-dimensional arrangement of cable trusses with vertical steel struts and outer compression ring can form a fully enclosed stadium space in a form of a dome. The principals of loads distribution here remain as in case of a bicycle wheel but the analysis are more complex.

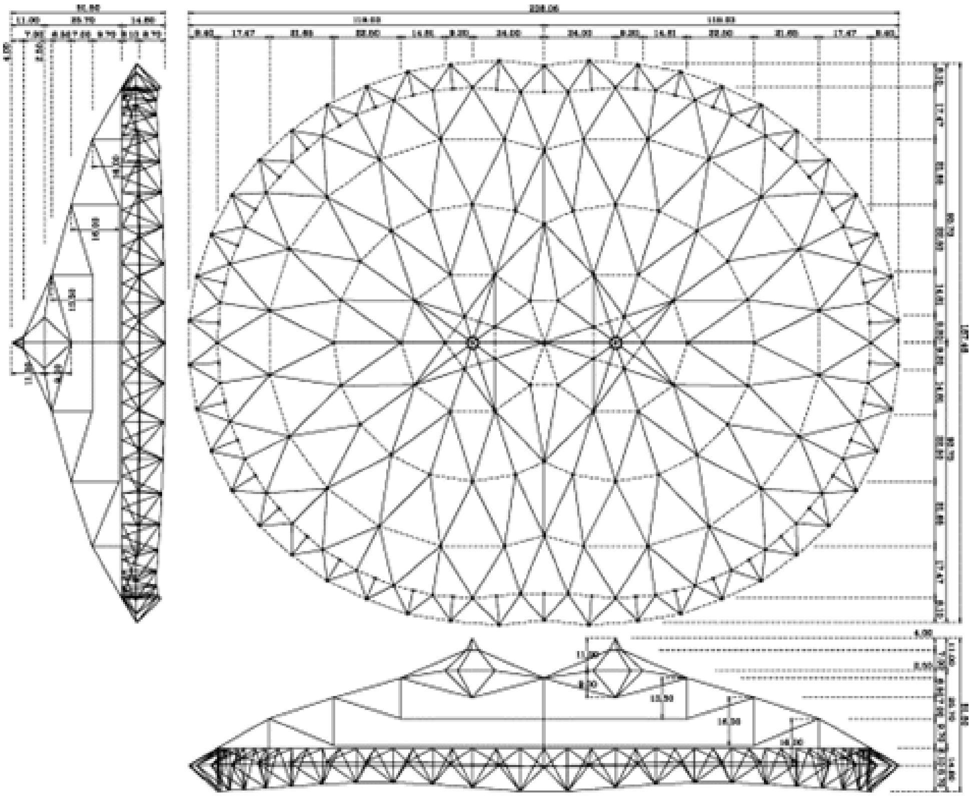

Fig. 10. Diagram of a cable dome structural system.

3. Practical Applications of Cable Structures for Stadium Roofs.

I would like to demonstrate how the theoretical advantages of structural cables and the principals of their performance can be utilized in the design and construction of stadium roofs and other long span practical applications.

3.1. Single Cable.

It is a little difficult to find any practical application for a single cable, with exception of the power lines or cloth line, and alike. These may not find much of any use for a long span structure. However, when several cables are connected to a mast, they become stay cables, back-stays or tie-downs. On the other end, the same cable can pick the load form any other structural member. These, combined can provide a very efficient structural system to form the roofs for large size stadiums, as per samples listed on the figures below:

Fig. 11. Olympic size Velodrome, Abuja, Nigeria

3.2. Cable Truss.

Cables arranged in the form of trusses provide much greater opportunity to span long distances and to carry larger loads. For example: trusses, where the top cord is a bundle of cables and hanger cables carry steel bottom cord, have been known for long time. This invention has been used in the suspension bridge structures for over 150 years, curtesy of Johan Roebling and other early bridge engineers. Now, let’s assume 4 (four) suspension bridge trusses intersecting at 90 degrees at the masts, and we would get the structural system for a very light and efficient stadium roof. A bundle of suspension cables on 4 steel masts picks up the roof load via number of small hanger cables connected at the bottom to the secondary steel purlins. These purlins, braced at the perimeter for diaphragm torsion and stability, carry the roofing material and all applied loads, on the roof. Tension forces from top cord cables are carried via steel outriggers on 2 sides of masts to the anchors. This system is shown on a diagram and an example below:

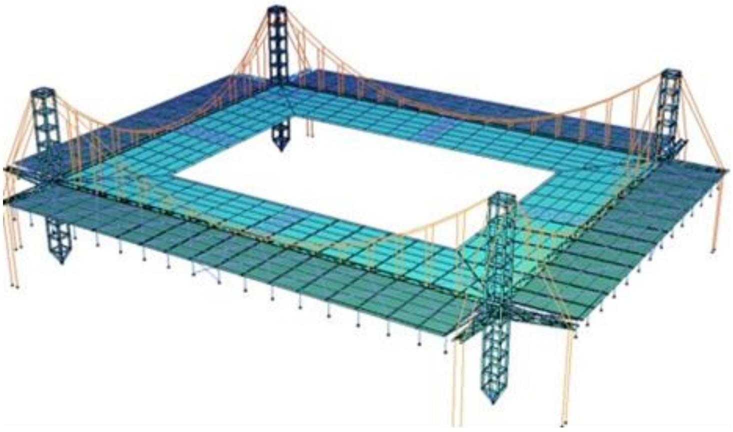

Fig. 12. Structural model of Cologne Stadium roof.

Fig. 13. Complete roof of Cologne Stadium.

3.3. Cable Net.

Cable nets are usually formed by several intersecting cables, which can be arranged into complicated 3D shapes that span large distances. The nodes, where the cables cross are designed and calculated as structural clamps or saddles, which mostly transfer loads between the connecting cables. These add to the complexity of engineering analysis of large cable nets. The resulting tension forces are transferred via masts and back stay cables (i.e., guy cables) to the anchors on the outside.

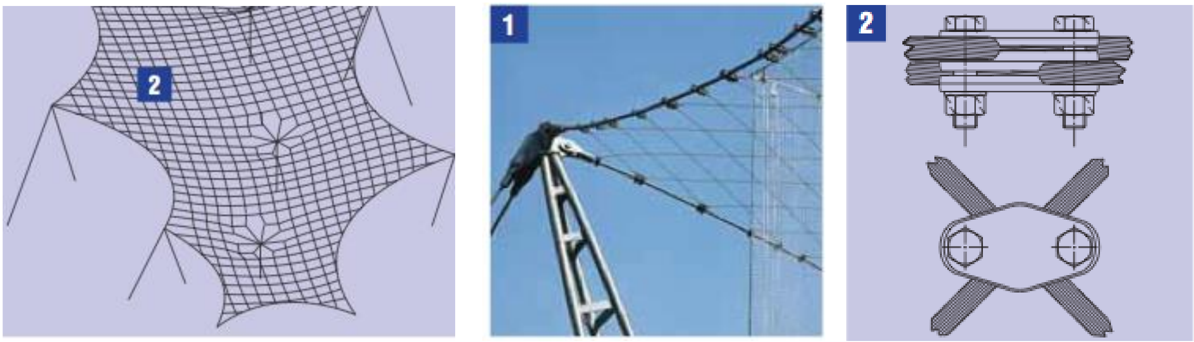

Fig. 14. Intersecting cables with clamps (2) form a shape of Cable Net.

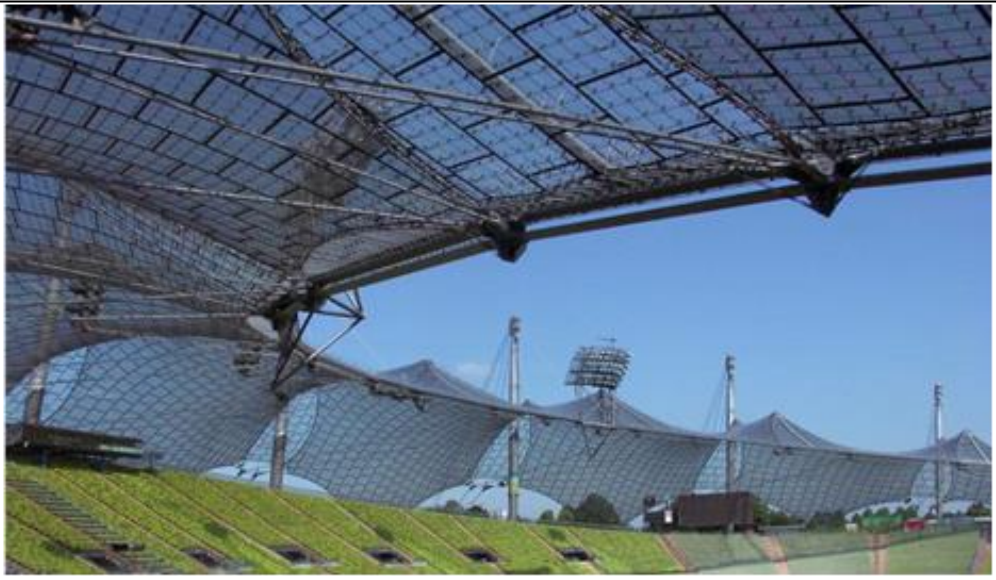

Fig. 15. Cable Net Roof of Munich Olympic Stadium, 1970

3.4. Cable Bicycle Wheel.

A roof structure following the concept of Bicycle Wheel is one of the most efficient structural system developed to date for large span structures. Its efficiency can be measured by the unit weight of roof structure, self-weight ratio, expediency of construction, ability to receive various roofing materials, and, consequently, its overall costs. These roof systems truly represent a practical definition of lightweight structures where small number of structural members provide the enclosure for Olympic size stadiums of 80,000 seats or more.

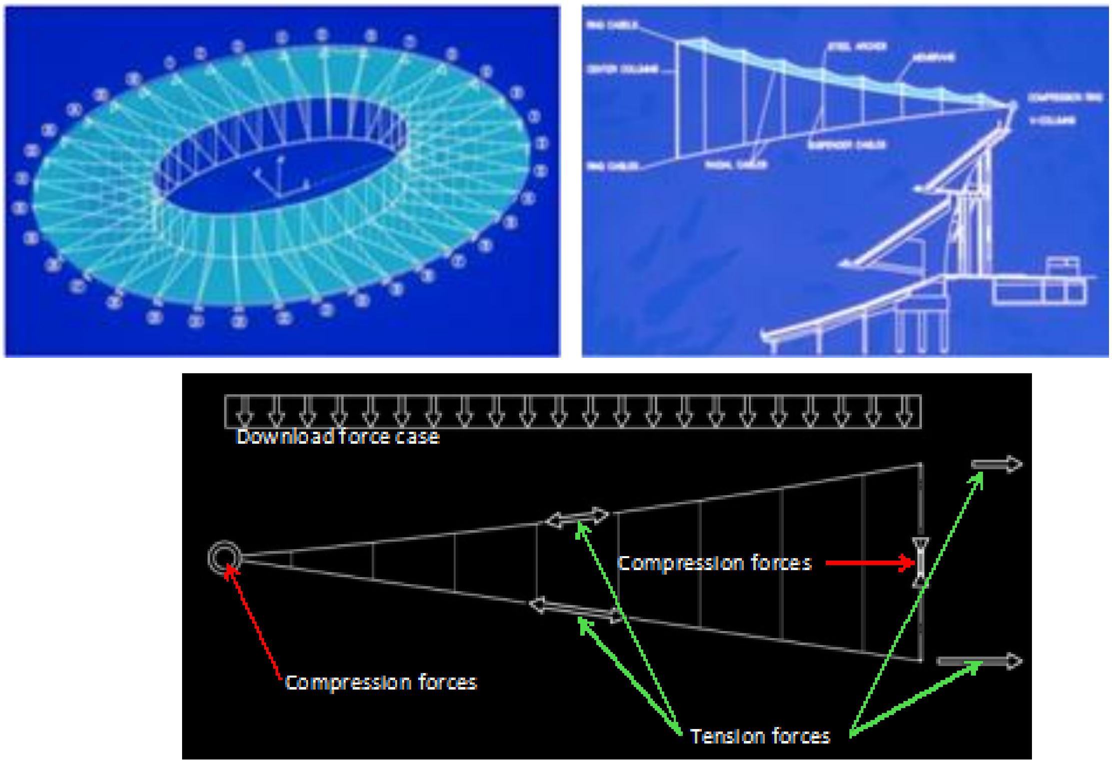

Fig. 16. Model, cross section and flow of forces in Bicycle Wheel roof system.

Fig. 17. Malaysian National Stadium, Kuala Lumpur.

The example above is one of the most efficient and most economical stadium roofs ever built. It covers the area of over 50,000m2 and a total of 1,700 tons of structural materials (steel, cables and cast steel connectors) was used to build it. The unit weight is about 34kG/m2 including the catwalks, which don’t contribute to the structure system of the roof.

There are many shapes and many examples of cable Bicycle Wheel roof structures that can attest to their superiority over any other, conventional structural systems. One of very convincing arguments is the utilization ratio of the structural materials used. This is a ratio of the applied loads vs. dead load of material carrying these loads[3]. For structural steel the ratio of 1:1 is reached for the cantilevered roofs projecting not more than 35.00m. For projection close to 70.00m (like at KL Stadium above) this ration for steel will be about 1:5, or 20% of utilization rate. For steel cables in a Bicycle Wheel system, this ratio in 5:1, or 500% of utilization. By comparison, the weight of the structural steel for the cantilever roof system of Beijing “Bird’s Nest” Olympic Stadium in China was about 45,000tonnes of steel. For a roof coverage area similar to KL Stadium, the unit rate is about 900kG/m2. The utilization rate of structural steel is about 10%. Which is more efficient, you think?

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