Wide-Span Cable Structures

by

Katherina Santoso

B.A., Architecture (2003)
University of California, Berkeley

Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Civil and Environmental Engineering
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ABSTRACT

In recent years, the application of cable structures in buildings has gained huge popularities. Although cable technology has been established since the 1950s, there is suddenly a surge in the number of its building application starting in the late 90s. This phenomenon is attributed to the recent advances in computational form finding, analysis and construction simulation, which make the design and construction of cable structures simpler and more economical.

Although cable structures have been employed for different building applications, this thesis will concentrate only on the use of cable structures in wide span system. Five cable systems: simply suspended cables, pretensioned cable beams, pretensioned cable nets, tensioned straight cable nets and tensegric shells are studied for their mechanical properties and suitability for wide span uses. A case study is presented at the end of each system's description to illustrate its possible application. The paper will then conclude with a presentation of a general design methodology of a cable structure.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil Engineering

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Rene for being there whenever I need you.

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1. Introduction

Wide span structures can be loosely defined as buildings which enclose large areas without any intermediate support. Its application is very desirable in specific architectural programs such as convention halls and sports arenas, where large spaces uninterrupted by structural members are needed to accommodate for certain activities. Wide span is also suitable for use in concert halls and religious facilities, where it is important for visual connection to be established within the space with minimum distractions.

For such structures, traditional beam-column system is not very effective. The bending moment in beams increases quadratically with the beam's span, thus requiring the beam's cross section to increase in the same order of magnitude. This can be easily illustrated mathematically through this following rectangular beam[1] (Fig. 1):

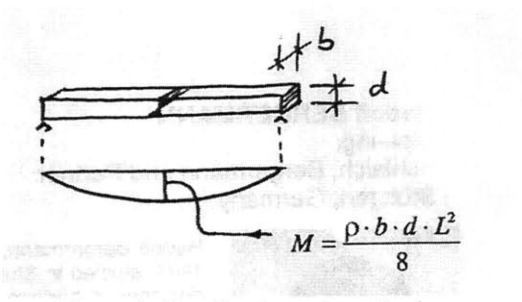

Figure 1: Bending in rectangular beam

$$M = \frac{\rho b d L^2}{8} \tag{1}$$

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[1] Schlaich, Jorg and Bergermann, Rudolf. "Conceptual Design of Long Span Roofs." IABSE Symposium Birmingham, 1994. p14.

$$\sigma_{\max} = \frac{My}{I} \quad \text{where } y = \frac{d}{2}, I = \frac{bd^3}{12}$$

$$\sigma_{\max} = \frac{\rho bdL^3}{8} \times \frac{d}{2} \times \frac{12}{bd^3} \tag{2}$$

$$= \frac{6\rho L^2}{8d}$$

For design,

$$\beta = \sigma_{\max} \tag{3}$$

$$d = \frac{6\rho L^2}{8\beta} \tag{4}$$

where ρ: density of the material

β: strength of top and bottom fiber in tension and compression

L: length of beam span

Equation (4) shows that the depth of the beam, d varies with the square of the span length, L. With this increase in depth, the dead load of the beam increases accordingly, applying on itself a proportional increase in bending moment, thus requiring an even deeper beam to resist the moment. This illustrates that with increasing span, solid beams become more and more clumsy, with their dead load eating away their strength, making it unsuitable to span a great length.

The failure of the beam for wide span use demonstrates the ineffectiveness of flexure to resist load in this particular application. Therefore, many of the solutions devised for wide-span system explore the different ways of supporting loads without the need of bending. Some of these solutions include the truss system, whose elements are only subjected to axial stresses, shell structure, which if designed well could carry forces by pure compression and cable system, that resists load only through tension. In addition to the absence of bending, cables are light and have a high strength to weight ratio. Small members could therefore be used even in very large span. This property gives cable an edge over the other wide-span system.

Cable structures are also desirable not only for their mechanical properties. From the architectural design perspective, cable system is an attractive choice. Its lightness provides an expanded impression of space and the smoothly curving cables which create structures with soft outline provide a desirable alternative to the traditional orthogonal buildings. Cable has also proven to be an economical proposition for large structures. With the continuing rise on the cost of steel, cable is becoming an even more attractive economic alternative to conventional forms of wide-span systems such as portal and space frame.

Cable roof structures can be divided into categories based on whether the roof cladding is supported by[2]:

(1) simply suspended cables
(2) pretensioned cable beams
(3) pre-tensioned cable nets
(4) tensioned straight cables
(5) tensegric shells

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[2] Buchholdt, H. A. An Introduction to Cable Roof Structures. Cambridge: Press Syndicate, 1999. p2-11.

In this thesis, the structural behavior of each of the cable systems will be explored on a conceptual basis, with a case study following each description. These case studies are aimed to illustrate practical application of each system and are chosen to provide inspirations of how a structural system can well complement an architectural design. Where there is sufficient documentation of the project, construction process will also be briefly described. Following this, a general design methodology of cable structures will be presented. This section would discuss factors to be considered when deciding on the choice of cable systems, outline form finding and analysis methods used in the design of cable nets and highlight design considerations for the various components of a cable structure.

2. Simply Suspended Cable Structures

Simply suspended cable structures refer to roofs whose cladding is supported by a single layer of non-pretensioned cables. The cables in these structures could be seen as beams on which the roof claddings, which can be perceived as girders, are resting on. It is a simple load transferring mechanism where force acting on the roof is first carried by the roof cladding, and then transferred to the cables. In a self balancing structure, that is one in which the structure supporting the cables has a geometry which permits the forces in the cables to be balanced internally, this force is passed on to a rigid frame before it continues on its way to the floor. In a non self-balancing building, where the geometry of the building supporting the roof is unable to resist the cable forces without the aid of ground anchor, the force is carried by the cables directly to the ground to which they are anchored.

2.1 Structural Behavior

Since simply suspended cable structures behave very similarly to the beam column system (with the "beam" supporting loads through tension instead of bending), architectural shape formed by this system look like conventional buildings, but with an exaggeratedly pronounced deflected roof. For roofs with rectangular or trapezoidal plan, cables hanging in vertical planes may be arranged parallel to each other (Fig. 2). In roofs which are circular or elliptical in plan, the cables may be suspended radially and attached at the perimeter to a compression ring and at the center to a tension ring (Fig. 3). For roofs of other shapes, combinations of cable arrangements may be utilized. For example, in ellipsoidal shaped plan, radial cable arrangements are used at the two half ends, while regular parallel arrangements are used for the center rectangular portion (Fig. 4).

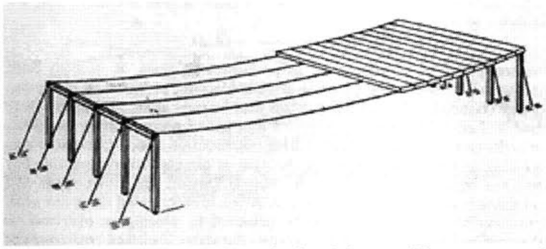

Figure 2: Simply suspended cable roof in rectangular plan

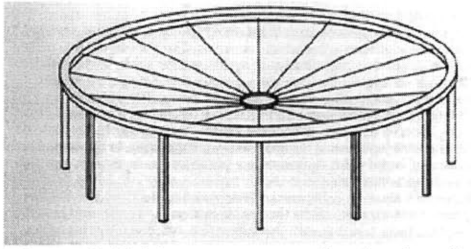

Figure 3. Cable arrangement in circular plan

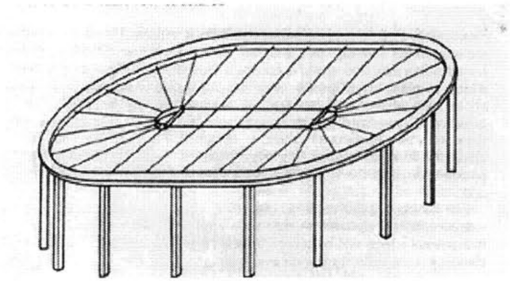

Figure 4: Cable arrangement in ellipsoidal plan

An important characteristic which set the simply suspended cable system from the other cable systems is that the cables in this system are not pretensioned. This makes the use of the system cheaper and simpler. However, since the cables are not prestressed, they do not offer any stiffness. This results in considerable deflections under loading and drainage of such roofs has to be thought of during the design process. The lack of stiffness of the cables also results in much movements of structure under wind loading. Stiffness of the system must thus be supplemented through the stiffness of the cladding material. Concrete is therefore often the material of choice for the roofing material in simply suspended cable roofs.

2.2 Applications

The simply suspended cable roof system was widely used in the 1950s, before the cost of cable pre-tensioning fell, making the pre-tensioned cable systems more popular today. Examples of roofs built with the system include that of Dulles International Airport at Chatilly (Fig. 5) and the roof of Oakland-Alameda County Coliseum in Oakland California (Fig. 6), which spans over 420 ft in diameter.

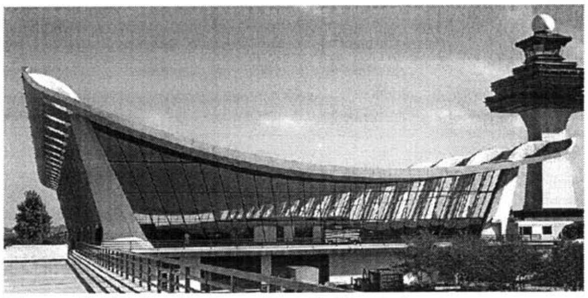

Figure 5: Dulles International Airport

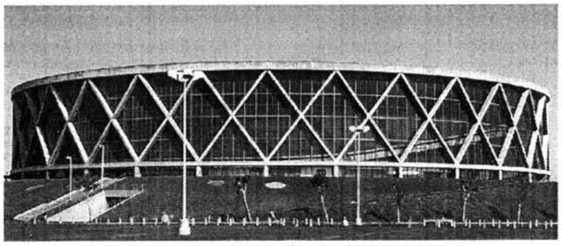

Figure 6: Oakland-Alameda Coliseum

2.3 Case Study -- Dulles International Airport, Chantilly, Virginia[3]

Dulles International Airport at Chantilly Virginia was built in the 1960s by architect Eero Saarinen. It is a structurally elegant architecture which utilizes the simply suspended cable roof system to form a signature sweeping curved roof. The building has a rectangular floor plan measuring 590 feet by 164 feet. Steel suspension cables span across the 164 feet width and are anchored to slanted reinforced concrete piers which are spaced at 10 feet interval. Precast concrete slabs are used to form the cladding for the roof. Due to the catenary shape of the canopy, an ocarina-shaped drain is incorporated in the center of the span, running longitudinally along the roof, to prevent water from collecting on the structure.

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[3] "Dulles International Airport" Architectural record. 1963 July, v. 134, p. 101-110

Structurally, vertical forces acting on the roof is supported by the cables in tension. As the cables are stressed, they exert vertical and horizontal forces on the concrete columns to which they are connected. These columns, which are standing at an angle, balance the moment created by the horizontal pull of the cables through its dead load, while vertical forces from the cables are transferred to the ground through compression in the piers. Since bending moment acting on these columns increases with distance away from the cable connection, the piers are designed to have a thicker base (Fig. 7). While vertical loads are carried by the cable-column system, horizontal forces are resisted by the stiff concrete cladding. Stiffness of the concrete slabs prevents horizontal deflection of the structure.

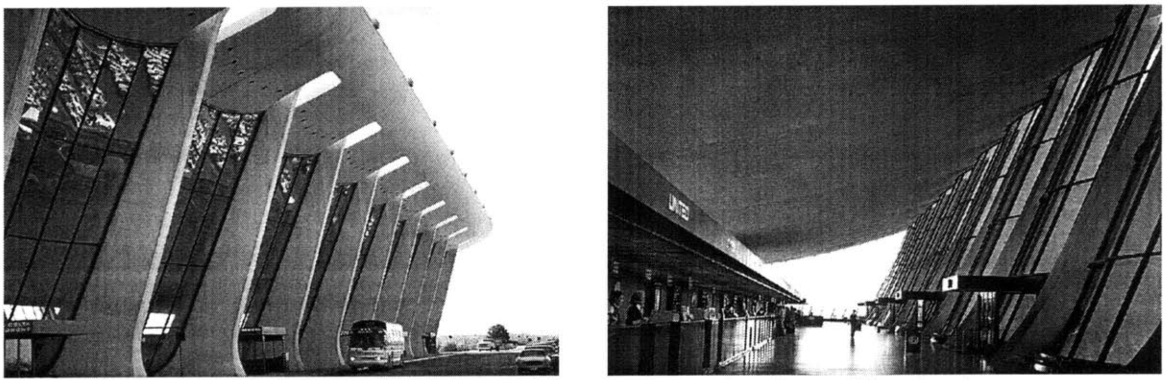

Figure 7: Columns which act as cable anchors, exterior view and interior view

In this project, the cable roof system has proven to be extremely appropriate. The catenaries-cum-slanted concrete column system leaves the inside space of the terminal free of columns to accommodate the program of the structure. The cable system also projects an aesthetically pleasing form which suggests flight and lightness, appropriate for an airport terminal.

3. Pretensioned Cable Beams

Cable beam is an 'improvisation' of the simply suspended cable system. It is formed by adding a second set of cables with reverse curvature, to the existing suspension cables. This second set of cables can be added in various manners forming three possible combinations – convex, concave and convex-concave beams, shown in Figs 8(a), (b) and (c) respectively. This double cable arrangement works more efficiently as a load bearing system, resulting in an overall lighter structure. Pre-tensioning of the cables also makes the structure stiffer (vertically, lateral stiffness is still provided by the cladding material), if cables are correctly tensioned such that they remain stretched under any combination of applied loading.

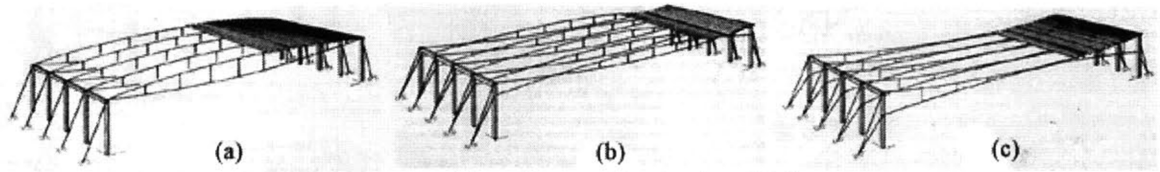

Figure 8: Possible cable combination in cable beams.

3.1 Structural Behavior

With two sets of cables having opposite curvature to each other, cable beam is able to carry vertical load in both upward and downward direction with equal effectiveness. Each set of cable is essentially "in charge" of carrying vertical load in one particular direction. The set of cable with convex curvature carries the downward force while that with concave curvature resists uplift. Figure 9 shows diagrammatically how a prestressed cable beam works. When a downward force acts on the structure, the pre-tensioned force in cable A is increased while the tension in cable B is reduced. Force is therefore in effect resisted by cable A. When the structure is subjected to an upward force, this force increases the tension in cable B and reduces the prestressing force in cable A, with cable B resisting the bulk of the uplift. As a convention, the set of cables whose pretension is increased by the load is known as the pretension cables while the other set is termed suspension cables.

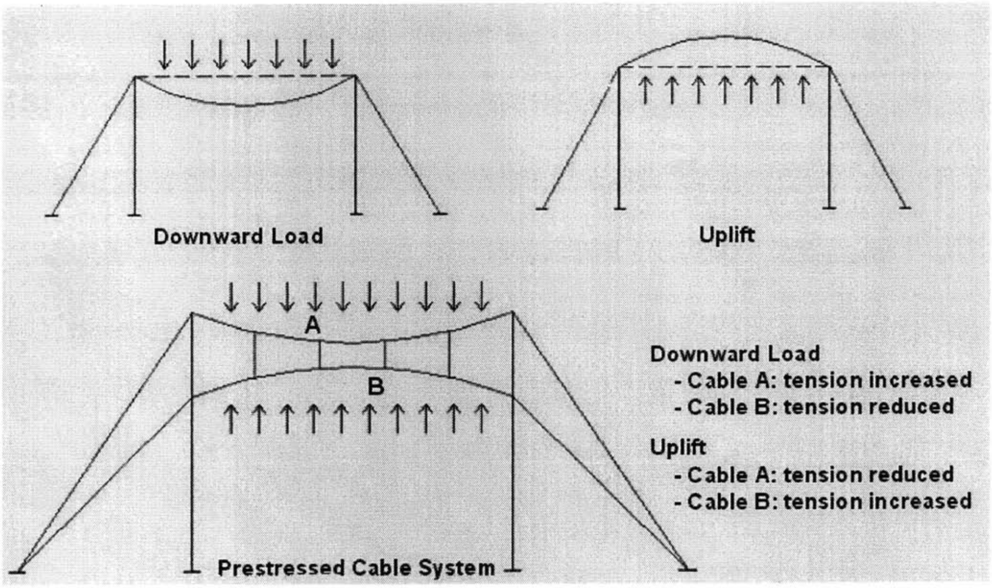

Figure 9: Structural behavior of a prestressed cable beam

Cable truss is a special form of cable beam that is developed by a Swedish Engineer, David Jawerth[4] in the 1960s (Fig. 10). While the ties connecting the two oppositely curved cables in cable beams have little structural significance, those in a cable truss act as load bearing elements. In cable trusses, the ties are inclined and connected in such a way that they, together with the suspension and pretensioning cables, form pretensioned triangles. As such, this system works exactly like the space truss system, only that the cables act purely in tension. For economic reason, in the design practice, the level of pretensioning are set such that the ties remain in tension when subjected to dead load

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[4] Buchholdt, H. A. An Introduction to Cable Roof Structures. Cambridge: Press Syndicate, 1999 p4

only. With the application of an increasing live load, some of the diagonals will become slack, resulting in only part of the ties remaining in tension. At the instant when one of the ties goes slack, the truss changes its structural mechanism to a cable beam.

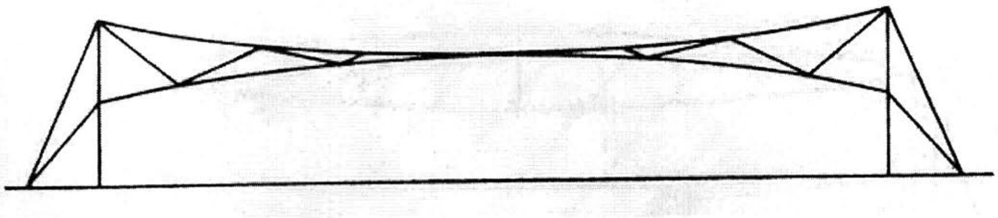
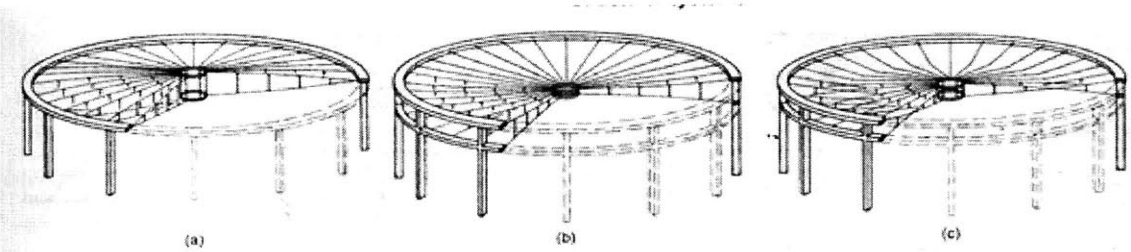


Figure 10: Cable truss developed by David Jawerth

3.2 Applications

Cable beams are most popular among the different cable systems, because they are efficient, easy to erect and can be employed to cover plans of different shapes conveniently. For roofs which are circular or elliptical in plan, cable beams may be arranged in geometrical patterns similar to those described for simply suspended cable structures. Examples of such arrangements can be seen in Figs. 11(a), (b) and (c). Among the numerous structures employing the cable beam system are David L. Lawrence Convention Center (Fig12) in Pittsburgh, PA, the 260m x 160m roof of the 2002 Chonju World Cup Stadium in Korea (Fig 13) and an exhibition hall for the Hanover Fair (Fig 14).



(a) (b) (c)

Figure 11: Cable beam arrangement in a circular plan.

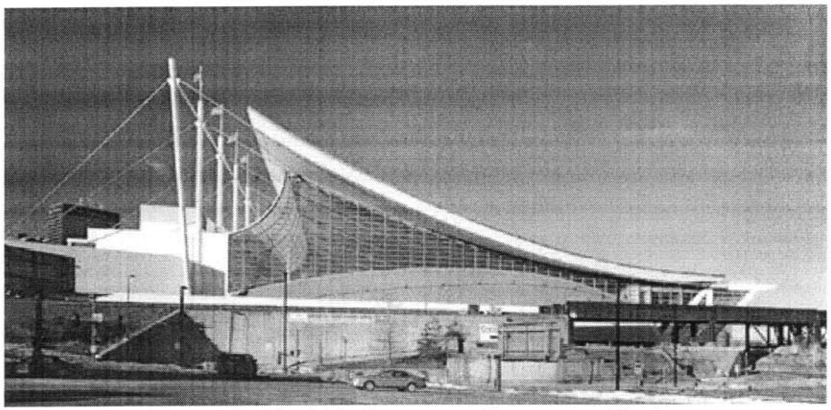


Figure 12: David L. Lawrence Convention Center

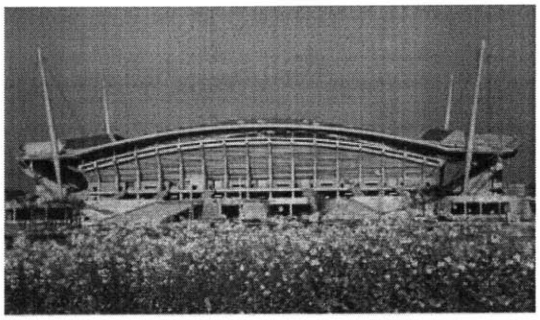


Figure 13: Chonju World Cup Stadium

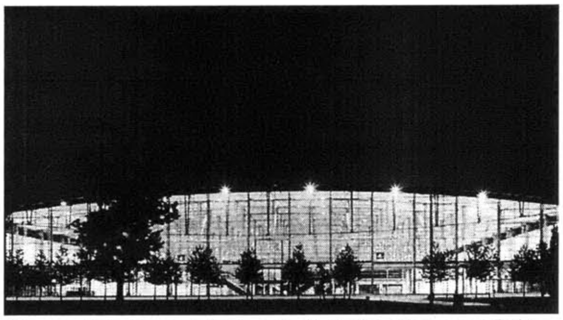


Figure 14: An exhibition hall at the Hanover Fair

3.3 Case Study --David L. Lawrence Convention Center, Pittsburg, PA[5]

David L. Lawrence Convention Center is the largest column-free space in the United States. The newly completed center encloses 1.5 million sq ft of area, which includes an exhibit hall, meeting rooms, lecture halls, a ballroom and a garage. Design inspiration for the convention center is obtained from the Sixth Street, Seventh Street and Ninth Street suspension bridges in Pittsburg which are located at closed proximity to the site. The three bridges are the only example in the world where three suspension bridges are positioned side by side along a river. Drawing inspirations from the bridges, the architects, Rafael Vinoly Architects, envision a cable structure for the convention center, to reflect the advancement of today's engineering technology.

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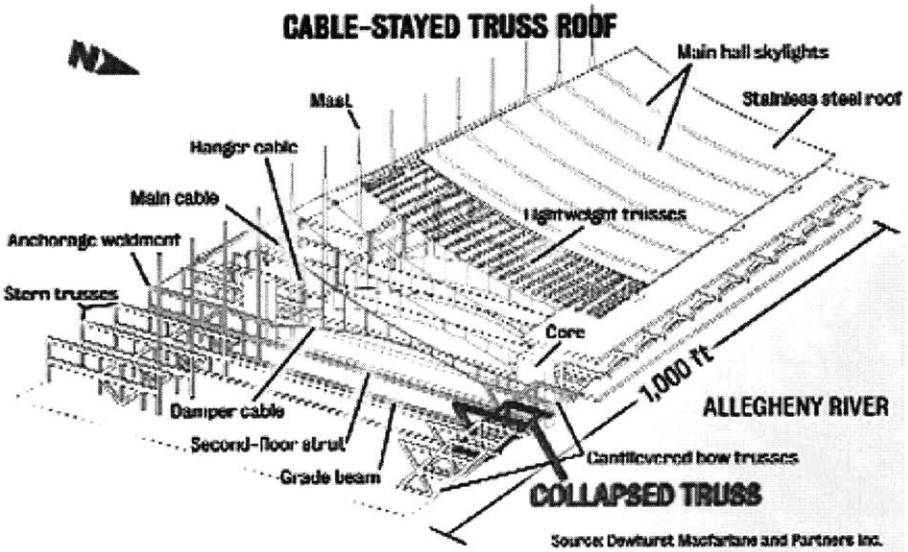
[5] O'Callaghan, James. "An Unconventional Approach" Civil Engineering Magazine. November 2003. <http://www.pubs.asce.org/ceonline/ceonline03/1103feat.html>

3.3.1 Structural System

This two-story building is made up of two main structural elements—the steel frames and the cable beam roof structure (Fig. 15). The steel frames run along the north and south end of the structure. The north and south frames are referred to respectively as bow and stern trusses – so named because of their resemblance to those parts of a ship. The configuration of the steel frame is such that it supports the main floors and serves as anchorage mechanism for one end of the cable roof (the cables in the opposite side are anchored directly to the ground). Conventional space trusses are laid between the bow and stern frames to form the floor of the second story. Cable beams span at the top of the frames to support the roof cladding.



Source: Dewhurst Macfarlane and Partners Inc.

Figure 15: Structural drawing of the exhibition hall showing the key structural elements

Cable beam system is chosen over truss structure for the clear span roof of the second floor exhibition hall because of economic reason. For this large roof span, cables proved to be more efficient and economical. That, as well as the intention to weave suspension bridge technology into the design, was a driving factor for choosing the cable beam system.

In the structure, each cable beam is slung from the anchorage weldment on the bow frame, over a central mast, and down to an anchorage weldment at the top of the stern frame[6]. This span varies between 300 and 400 feet along the length of the roof. The beam consists of a convex upper cable, which resist the downward force, and a concave lower cable that prevents uplift (Fig. 16). Each cable is comprised of 7 no 3" strands, designed to carry a maximum tension of 3600 kips. Connecting the upper cables and the lower cables are the vertical ties. Stainless steel sheet lies above the upper cables to form the cladding of the exhibition hall.

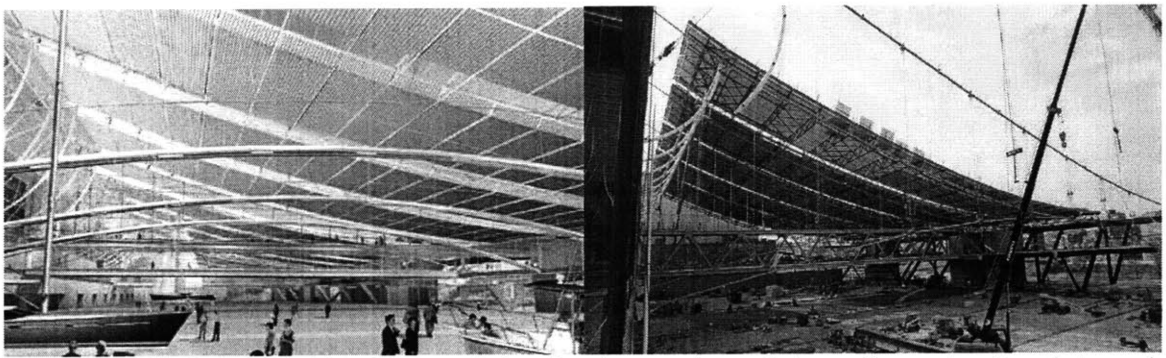


Figure 16: Cable beam and side cable stayed glass façade; an artist rendering and a construction photograph

At the gabled end of the roof is a cable stayed glass façade which is not only aesthetically appealing but also structurally significant. This glass façade is conceived, architecturally, to provide natural day lighting to the exhibition hall. The incorporation of this nice architectural feature, however, poses a difficult engineering problem. The large deflection of the roof, which is initially acceptable if there is no glass façade, is now deemed

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[6] Post, Nadine, M. "Fatal Collapse in Pittsburgh." Engineering News-Record. 18 Feb. 2002. <http://enr.construction.com/news/buildings/archives/020218.asp>

excessive and will exert strain large enough to break the glass. A stiffening system thus needs to be added to reduce the roof's deflection. To tackle this stiffness problem, Dewhurt, Macfarlene and Partners engineers develop an innovative solution — cable stayed glass façade. By dropping cables at every proposed mullion position and tensioning them between the flexible roof structure and the rigid building frames, the live load deflections of the roof structure was reduced from 3 feet to less than 6 inches. These cables do not only reduce the roof's deflection, they also act as a support for the glass panels, forming a mullion free glass wall.

3.3.2 Construction Process

The complexity in building this cable structure does not stop in the design phase. Due to the intricacy in the interaction between the cable beams and the steel frame, erection of the structure is a challenge on its own. During construction, pre-stressing of the cables will cause a considerable deflection and rotation on the frames. This deformation needs to be considered when erecting the frame, to ensure that the final configuration of the frame would only be obtained after the cables are pretensioned. To predict the effect of cable tensioning on the frame, a time history computer analysis program is used for this project. Engineers used this analysis tool to model each stage of the roof tensioning process and analyze its effect on the frame deflections. By observing the predicted deflections of the anchorage frames at various stages of cable pretensioning, it was possible to plan the frame installation such that the frame will assume its final desired configurations only after all the cables are tensioned.

The design of the David L. Lawrence Convention Center has indeed successfully integrated innovative engineering system into the architecture. The cable beam system not only performs efficiently as long span structure, it also projects an elegant roof shape which echoes the arching forms and the engineering triumphs of Pittsburgh bridges.

4. Traditional Pretensioned Cable Net Structures

4.1 Structural Behavior

Cable net is obtained when the suspension and pretension cables of the cable beams are laid in space to form a single surface. The behavior of cable net is thus similar to that of a cable beam, with one set of a curved cable resisting the downward force and another set of oppositely curving cable resisting the upward lift. Since the surface must incorporate cables of opposing curvature, it follows that the net must be anticlastic or saddle shaped. The net must not accommodate the crossing of cables of the same curvature because in such areas, a local "basket" will be formed and the cables will not be properly tensioned. As such, the roof in the region will be soft and is subjected to large movements which will damage the cladding. In large roofs, flat areas should also be avoided because such parts are not very stiff and may be subjected to flutter. While this structural requirement poses as a restriction in the architectural design of cable net structure, it has established a characteristic signature shape to cable net roofs.

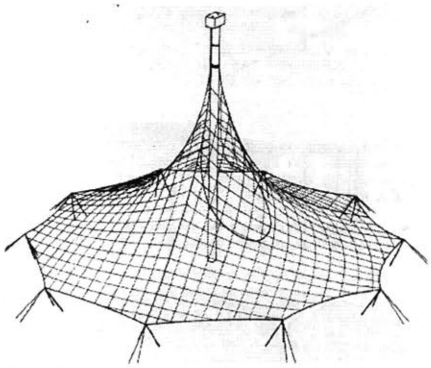

Figure 17: Cable net with edge cables and a center mast.

The supports of the cable net can be provided in the form of a central mast and edge cables, as shown in Fig. 17, or with stiff boundary members such as frames or arches as shown in Fig. 18(a) and (b). Cable net with masts and edge cables tend to be less stiff and require more complicated details than nets with stiff boundaries. It is therefore always encouraged to employ cable net with fixed boundaries for structure with very large span. The mast system, with its tent-like form, is however architecturally more appealing. This system is widely used in the Middle Eastern region for its cultural suitability. Cable net suspended from a mast is also more suitable for use in temporary structures because its members can be transported with ease.

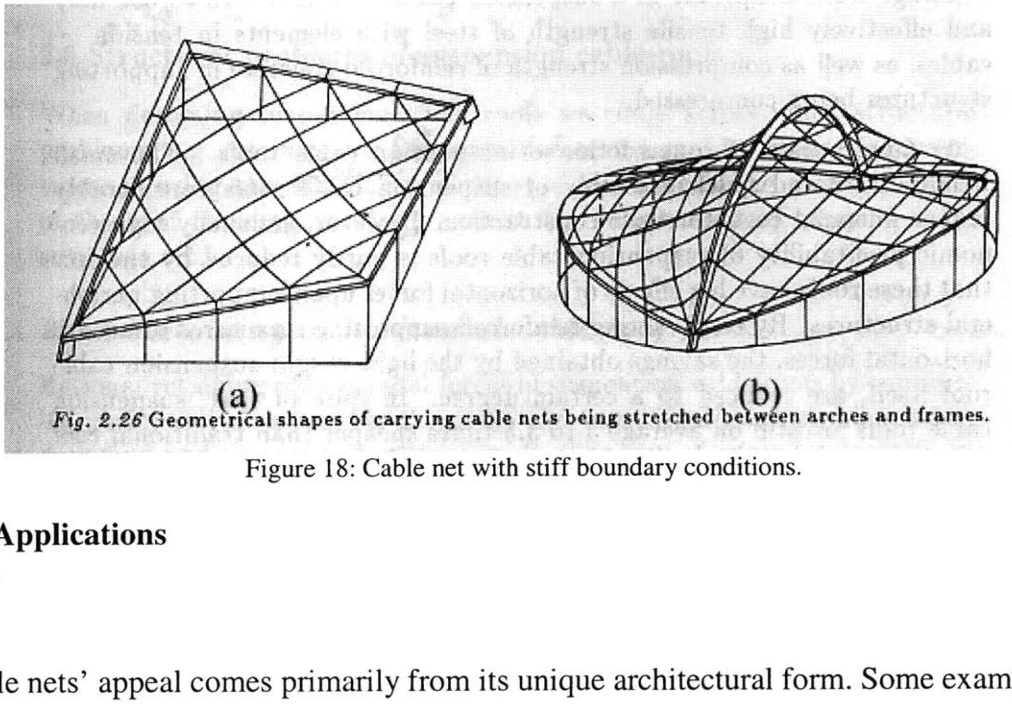

Fig. 2.26 **Geometrical shapes of carrying cable nets being stretched between arches and frames.**

Figure 18: Cable net with stiff boundary conditions.

4.2 Applications

Cable nets' appeal comes primarily from its unique architectural form. Some examples of these phenomenal structures are the Youde Aviary, a classic anticlastic cable net suspended by 3 tubular arches (Fig. 19), the cable net roof of the Munich Olympics Stadium (Fig 20), and the canopy at Sony Center in Berlin, where cable net is span between a flying buttress and a perimeter compression ring (Fig 21).

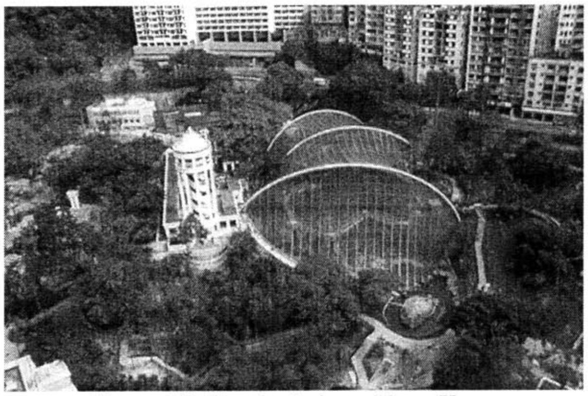

Figure 19: Youde Aviary, Hong Kong

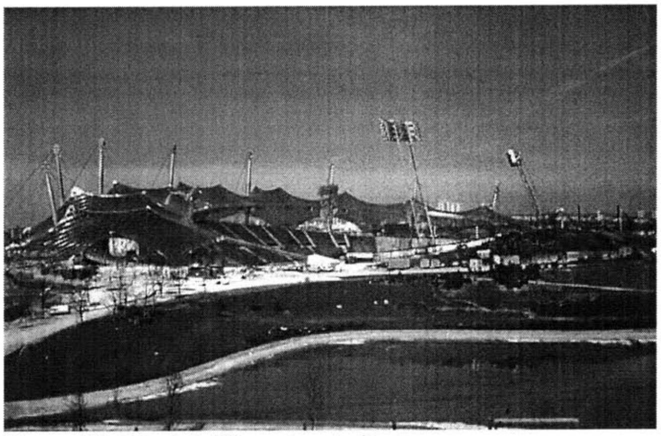

Figure 20: Munich Olympics stadium

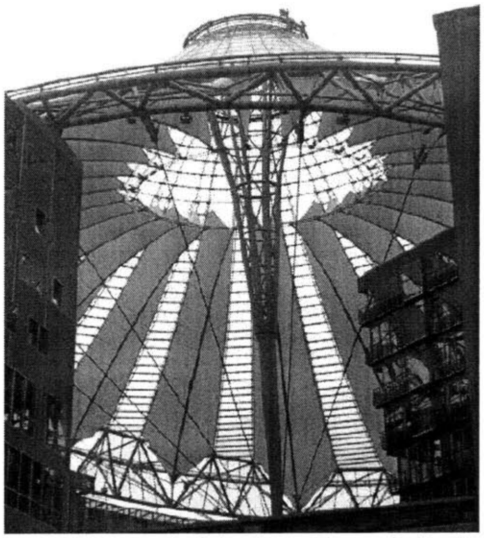

Figure 21: Roof of the Sony Center in Berlin

4.3 Cladding Material

Although most of the cladding material in a cable net does not function as a structural element, the choice of material used may affect the overall performance of the structure. And since roof cladding forms a significant part of a net structure, it is important that designers understand the intrinsic qualities of the cladding material and their implications to the structure.

4.3.1 Fabric

The most widely used cladding material for cable net structure is fabric. This is only natural as the inspiration for cable net structures first comes from traditional tents. Besides historical reasons, fabric does indeed have the material properties which are suitable for use with cable nets. Like cables, fabrics have strength when placed in tension. This additional strength is negligible and will not contribute to the strength of the cable net. This characteristic, however, ensures that the cladding will not fail when subjected to tensile action in instances of excessive deflection. Fabric is also valued because it is light, cheap and easy to install.

The choice of fabric to be used is usually driven by lifespan and cost. The least expensive fabric material for architectural applications is the woven polyolefin such as polyethylene and polypropylene. These polymers are flame retardant and UV resistant. Their lifespan however is relatively short (5 years and less). Thus, they are used only in temporary structures. The most common architectural fabric used today is the PVC coated polyester based fabrics. This fabric is more long-lasting, with the heavy-coated ones having a 15 year replacement cycle. The fabric is fire resistive and comes in numerous colors (making it very popular very architects). It is also flexible and makes an ideal material for deployable or retractable roofs. The most permanent architectural fabric is Teflon (PTFE) Coated fiberglass fabric. This fabric is non-combustible and meets the most stringent building code worldwide. Off the roll, this translucent material has an oatmeal appearance which bleaches out to white in the sun after a couple of months. PTFE fiber glass fabric is also chemically resistant and UV resistant. It is however costly, and is used only when the quality and durability of the fabric is important, such as in the case of Georgia Dome in Atlanta and the new Millennium Dome in Greenwich, England[7].

4.3.2 Glass

Another cladding material which is becoming more popular for cable structures is glass panels. Glazed cable net structure is preferred by many architects today for its transparency and modern look. Glass also has a longer life span than most fabric. Glass, however, has not been used very widely as a cladding material in cable net structure because it is very sensitive to deflection and breaks when subjected to excessive stress. To date, many of the glazed cable net structures are flat, vertical cable wall façade (Fig. 22). The only anticlastic glazed cable net structure built in the world is the canopy over Rhön Clinic in Bad Neustadt, Germany (Fig. 23).

Figure 22: Cable net wall of Columbus Circle, NY

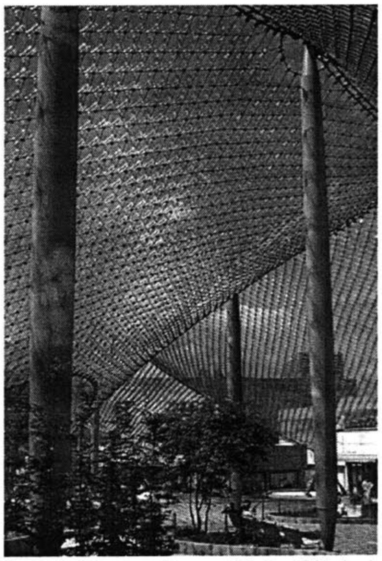

Figure 23: Roof over Rhön Clinic in Bad Neustadt

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[7] Goldsmith, Nick. "Material for the New millennium". Widespan Roof Structures. London : T. Telford ; Reston, VA : Distributors for USA, ASCE Press, 2000. p213-217.

Glass has a theoretical tensile strength of 10,000 N/mm², but experience shows that the effective tensile strength reaches a maximum of only 80N/mm². This steep reduction is due to the fact that glass is not a homogeneous material, but instead contains flaw and weak points. Glass is also brittle, such that when it is stressed beyond its elastic limit, it will suddenly break. This poses as a potential hazard, especially if glass is used as a roofing material. With recent technology, tensile strength of glass can be improved up to 120N/mm² through appropriate treatment such as thermal or chemical toughening. Thermally toughened plane of glass also, on breakage, disintegrates into many small pieces with no sharp edges, making it a safer roofing material[8].

Beside improvement in glass' material strength, recent formulation of effective connection between glass panels and cables also contribute to the increased used of glass as a cladding material. The increased use of glass can also be attributed to a new form-finding method with which cables in nets can be arranged such that flat glasses can be used for cladding. The use of flat glasses, instead of the currently used curved glasses, would substantially decrease the cost, making glass a more popular choice.

4.4 Case Study -- Rhön Clinic, Bad Neustadt, Germany [9]

The world's first glazed cable net structure was designed by Werner Sobek Ingenieure, a Stuttgart based structural engineering company, in 1997. The structure was created to provide a covered link between medical clinic buildings in Bad Neustadt, Germany.

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[8] Campagno, Andrea. Intelligent Glass Facades Basel ; Boston : Birkhäuser, 1999. p14-15.

[9] Rhon Clinic. Werner Sobek Ingenieure company website. 28 April 2004. <http://www.wernersobek.com/englishweb/frameset.html>

Architecturally, the goal was to create a spacious, light filled space which is unobtrusive to the existing buildings and surrounding areas. Cable nets hung from wooden masts and glazed with silicate glass was an ideal solution. This structure is almost transparent with only 5 structural supports spaced distance apart.

The galvanized steel cable net is edged with ring cables which are connected to a wooden compression at the center (Fig 24) and guy cables, which are anchored to the ground, at the periphery. This curved shape of the net is defined using CAD-based form-finding methods to ensure that every parts of the cable member is in tension under loading.

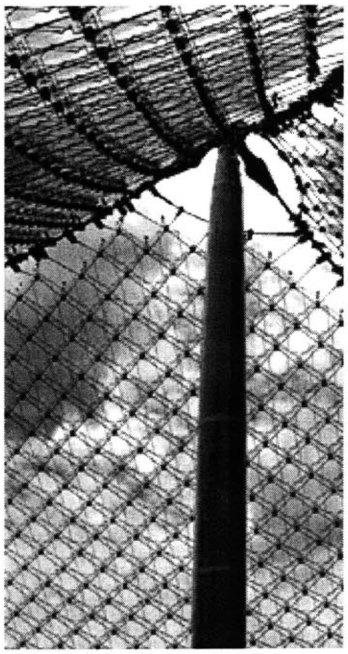

Figure 24: Connection between net and truss

Figure 25: overlapping of glass panels

The cable net is clad with glass panels. The use of glass in this structure was made feasible by a newly developed system in which overlapped glass panels of uniform size are fixed to a cable net of varying mesh geometry using standardized stainless steel clips (Fig. 25). This innovative system does not only make the use of glass possible, but also economical as flat glasses of standard sizes are used. This connection method also eases the green-house effect associated with glass enclosures. The overlapping of glass leaves openings small enough for an exchange of fresh air and yet still effective in providing protection against the rain. This structure is sufficiently stiff and stable, with the glass plates strong enough, such that they may be walked on for cleaning. The roof is also well designed to carry the huge loads of snow which envelops this mountainous region in the winter.

Although this structure may not be the best case study for long span cable nets (as each net spans only a diameter of 100 feet), it is however sited for the innovative use of glass as a cladding system, which I foresee to be the next trend in cable net architecture.

5. Tensioned Straight Cables

In 1994, Buro Happold presented an idea which defied the now traditional cable net concept where anticlastic shape employing two sets of oppositely curved cable is essential. Buro Happold suggested the use of straight cables with flat fabrics as a new net system for wide span. They pointed out that there are considerable advantages in using straight tensioned cables which can carry both the downward force and upward lift in one set of cables. They cited the advantages of this new system as[10]:

(1) The elimination of one set of cables brings with it the removal of cross clamps and some anchorages.

(2) Whether the load is acting downwards or upwards, the cable is tensioned in the same direction, which can be a great advantage if this tension is taken by a funicular arch or ring beam.

(3) With just one set of cable, connections between the fabric cladding and cable can be greatly simplified. This results in easier roof installation.

5.1 Structural Behavior

Straight cable net system works by having a very high pre-tensioning on the cables to stiffen it sufficiently against any deflection. The flexible fabric which acts as cladding material also needs to be pre-tensioned in the same direction of the cables. Despite the high cost of pre-tensioning, Buro Happold claimed that with the benefit from removing

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[10] Gill, Colin, Lidell, Ian and Schwitter, Craig. "Straight Tensioned Cable Roof Structures" IABSE Symposium Birmingham, 1994. p221-226.

one set of cables, this system would still result in a more economical large span roof structures (as compared to traditional anticlastic cable roof).

Buro Happold also indicated the advantage that this system has in the structural analysis and form-finding aspect. The structural behavior of a straight cable system is very much simpler than that of two-way cable nets. While the calculation of forces and deflection of an anticlastic net need the aid of a computer analysis software, that of a single cable system can be calculated manually using the nonlinear cable equation. In form finding aspect, the iterative process to develop an optimum shape for single net system is also much quicker.

There is however a possible downside of this system. The pre-stressed fabric in between the cable elements does not carry concentrated load as well as the cables. Under local loading, large deflection may be developed in the fabric, which may in turn cause the failure of the structure. When adopting this concept, it is therefore important to provide adequate drainage for rain and snow. Possible large deflection in the fabric must also be anticipated and considered in the overall design of the structure.

5.2 Applications

Since 1994, when this idea was first presented, there have been three structures designed with the pre-tensioned straight cable net system. They are the Eastleigh tennis center which covers 6000 square meters of space (Fig. 26), a very large demountable tent of

20,000 square meters for a religious community, RSSB, in Bedfordshire (Fig. 27) and the famous millennium dome in Greenwich (Fig. 28). All structures are located in the United Kingdom.

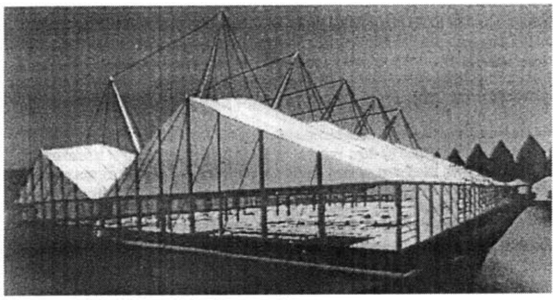

Figure 26: Eastleigh tennis center

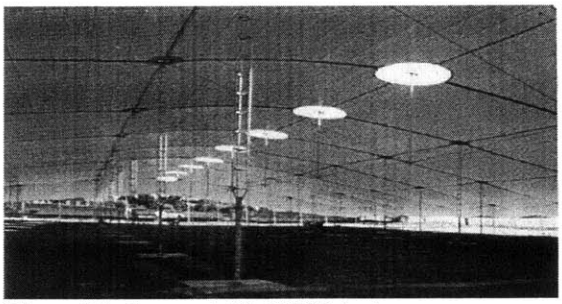

Figure 27: demountable RSSB tent

Figure 28: Millennium Dome, Greenwich

5.3 Case Study -- Millennium Dome

The Millennium Dome is a fabric clad tensioned cable structure which acts as a giant umbrella providing a protected environment for exhibition pavilions and a central show areas. The dome has a diameter of 320 m and a central height of 48m. It encloses an area of 80,000 square meters (20 acres) and has a capacity of 40,000 people.

5.3.1 Structural System

The roof of the Millennium Dome utilizes the pre-tensioned straight cable system. In this system, 72 tensioned steel stringer cables are arranged radially on the dome surface, stretching between a central cable ring and edge cables which are anchored to the ground. These stringers are supported at a radial spacing of between 25 and 30 m by circumferential cables, which are in turn supported by an arrangement of upper hanger and lower tie-down cables which are attached to the steel masts.[11]

The cables and the mast work very effectively as a self-balancing structure. Forces acting on the roof are carried by radial stringer cables, and transferred to the circumferential cables. These forces exert tensional stress on the circumferential cables, which in turn pull the lower tie down cables to which they are connected. The tension in the lower tie down cables equilibrates each other and ensures that the mast, to which they are connected, stays upright. This upright mast in turn ensures that the tension in every upper hanger cable is maintained, so that they can hold the circumferential cables in position (Fig. 29).

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[11] Liddell, Ian. "Large Environmental Enclosures, the Roof of the Millennium Dome" Widespan Roof Structure: London : T. Telford ; Reston, VA : Distributors for USA, ASCE Press, 2000. p149-158.

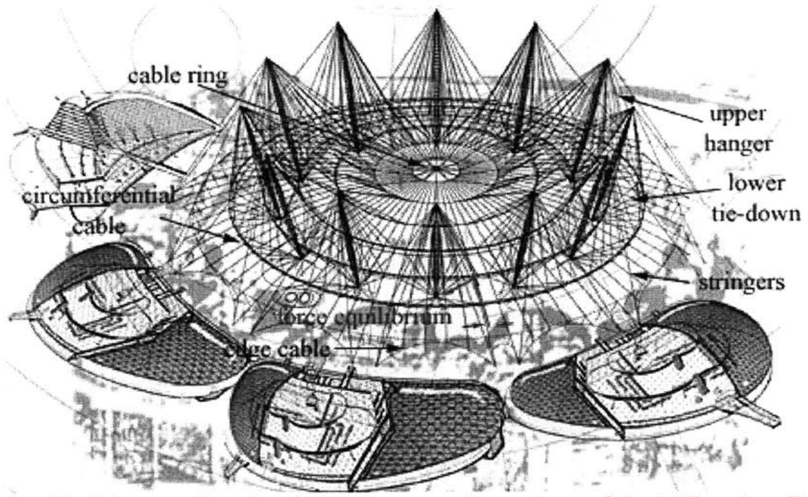

Figure 29: Diagram showing the key structural members of the Millennium Dome.

The stiffness in the cables is provided by highly pre-tensioning these cables. In fact, the pretension of each radial cable is about 400kN, which is 2/3 of the tension capacity of the material. This incredibly high tension is needed due to the long span of the radial cable (150m). It is also a result of the load carrying mechanism of the pre-tensioned straight cable system, in which one set of cable carry both downward loading and upward force.

Between the cables, tensioned fabric is used as cladding. As mentioned earlier, the reduced stiffness in the cladding makes this system prone to dangers associated with excessive deflection under rain and snow loads. This possibility must therefore be carefully studied and prevented. The roof of the Millennium Dome, with its tapering segments, is less prone to this problem because its slope increases with the span of the fabric panels. As such, water will be able to flow off the dome and is less likely to accumulate. However, circumferential cables, if placed on top of the fabric, as originally designed, would catch water on its upper part and would cause a dam above each circumferential line. The circumferential lines therefore need to be lifted off the fabric, and this is done using rigid steel members, termed as the wishbones (Fig. 30)[12].

5.3.2 Cladding Material

The fabric used for the cladding of the roof is PTFE coated glass fiber. PTFE is selected primarily for its durability as the new government especially specified in their review of the project that all options should be kept open regarding the long term usage of the Dome. PTFE is also chosen for all its desirable properties mentioned earlier – flame resistant, unaffected by UV light, water proof and dirt resistant. This fabric is attached to the radial cables through a carefully detailed connection. Each fabric's is lined with a 12mm edge cable, which would hook into special clamps fixed to the radial cables. For a clean look, fabric sealing flaps were closed over the top of the joints and sealed together using hot iron at 380˚C (Fig. 31).

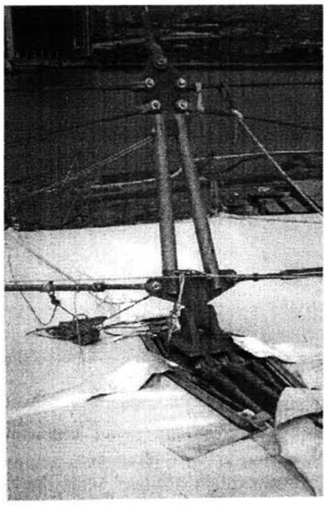

Figure 30: Wishbones to raise circumference cables.

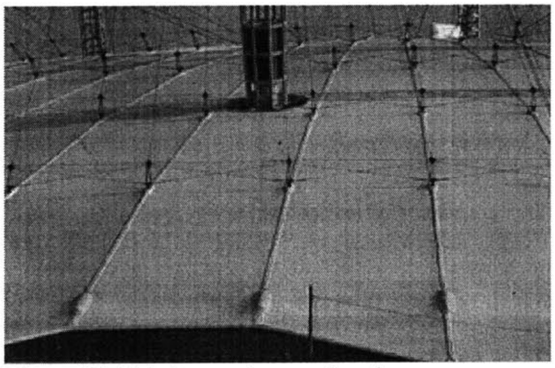

Figure 31: Fabric attachment detail.

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[12] Liddell, Ian. "Creating the Dome" The 1997 Royal Academy of Engineering, Hinton Lecture. 29 April 2004. < http://www-g.eng.cam.ac.uk/mmg/newsandfeatures/liddell/dome_lecture.html>

5.3.3 Construction Process

Although the construction of straight cable domes is hailed to be simpler than other cable domes, for a large structure such as Millennium Dome, it still involves a certain degree of complication and needs to be very carefully planned. An outline of the construction process is roughly described here. It need to be stressed that however vivid the description is, it hardly paints the complexity in the coordination involved during the real erection.

First, each of the 12 masts and the pyramids that support the masts were assembled and welded in an area adjacent to the permanent site. The assembled pyramid were then carried to the site and placed on the concrete piled foundation with a crawler crane. The masts were also carried using the same crane and placed adjacent to its final position (Fig. 32). The masts were then guyed off with four restraining cables before the crane was released. The front two cables were temporary but the other two were permanent back-stay cables. In order to restrict the movement of the masthead under wind loads, the four restraining cables were post tensioned before the crane was released.

Once all the masts are placed in their respective positions, the cable net is next to be erected. The net, which consisted of over 2600 cables were assembled on the ground and lifted in four main sections. Each section formed a large concentric circle which when pulled simultaneously at 36 positions was elevated to its final height (Fig. 33). The missing infill cables between the circular sections were installed individually using a combination of abseiling techniques for the higher locations and powered access equipment where practical. When all cables had been installed, they were tensioned to their final design stress by progressively jacking the anchor points of the radial cables. The stressing operation was carried out progressively around the dome in three stages.

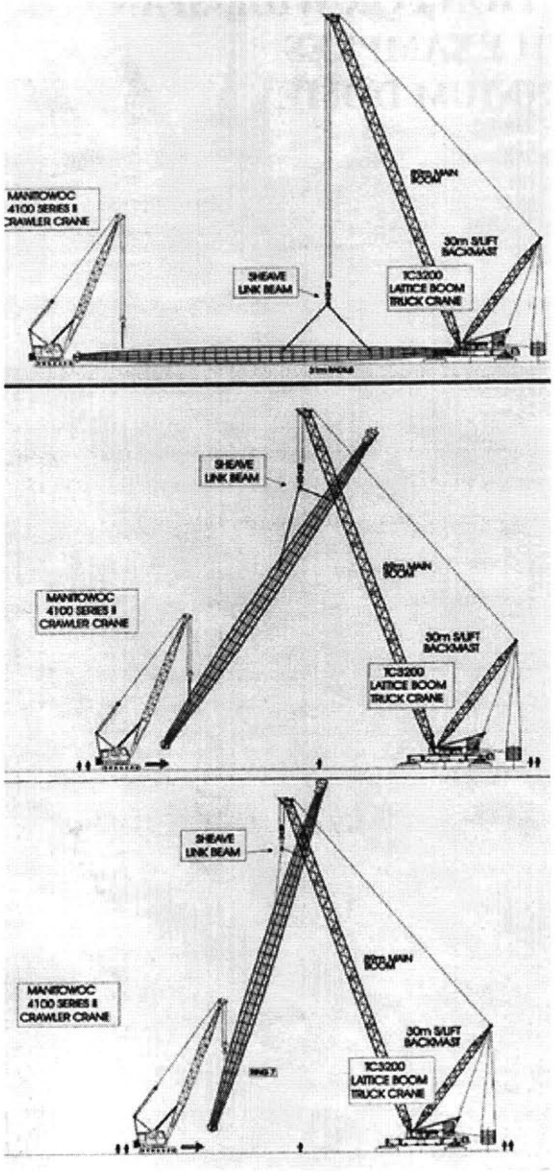

Figure 32: Erection process of a mast

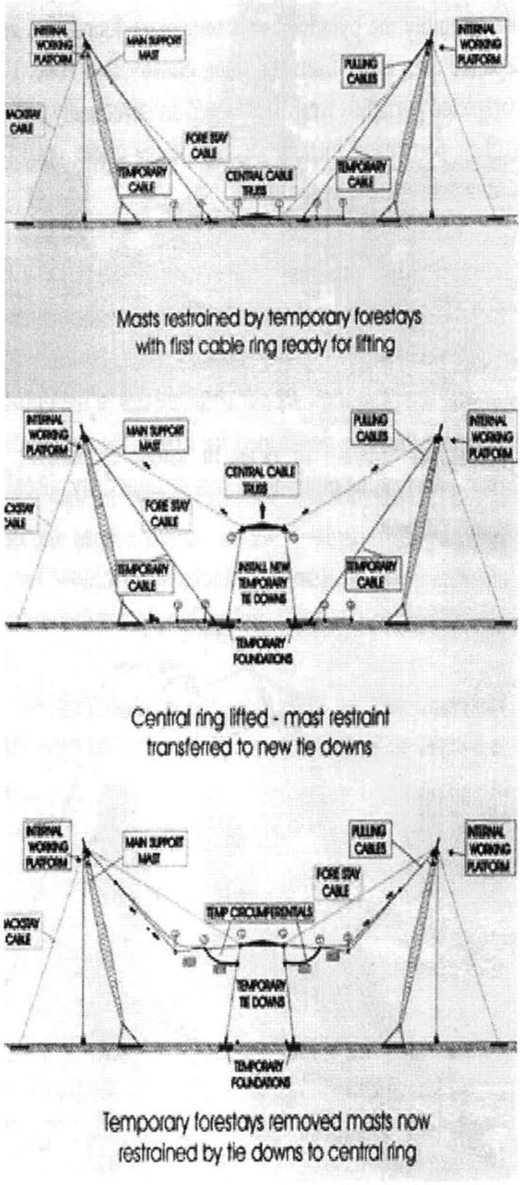

Figure 33: Erection of a section of the cable net.

6. Tensegric Shell

6.1 Structural Behavior

A tensegric shell is a hybrid shell which is made up of cable net and compression bars (Fig. 34). The structure of the tensegric net is derived from the tensegrity system, which was first discovered by Buckminister Fuller in the 1962. This system is defined as a state when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space.[13] In a tensegeric system, the structure is self equilibrating, with the "pull" in the compressive structures balancing the "push" from the tensile elements. Although the system is stable on its own, to support loads, the members of a tensegeric shell needs to be pre-stressed against each other. Pre-stressing can take place by lengthening some of the compression bars or by shortening some of the cables.

In tensegeric shells, the bars are arranged such that they join the cables at the nodes and that they are not connected to each other. Typical bar arrangement in various configurations of cable nets can be seen in Fig. 35[14]. The exact placement of the bars could be generated through computer form finding methods which ensures that the forces in the structure is equilibrated internally. For easy construction, forms can also be designed such that all the struts and cable elements have identical length.

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[13] Burkhardt, Robert. "A Technology for Designing Tensegrity Domes and Spheres" 29 April 2004. <http://www.channel1.com/users/bobwb/prospect/prospect.htm#sec:intro>

[14] Vilnay, Oren. Cable Nets and Tensegric Shells, Analysis and Applications. New York : Ellis Horwood, 1990. p12-19.

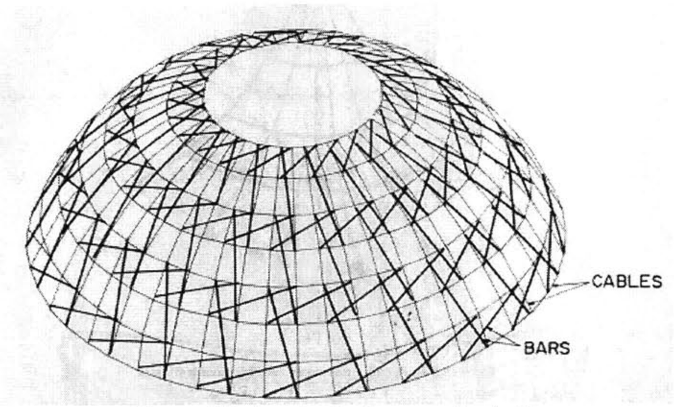

Figure 34: A spherical tensegric shell.

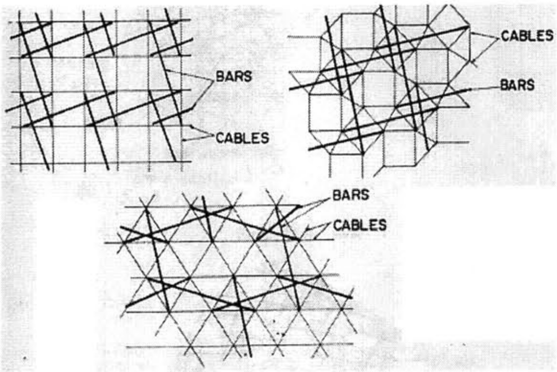

Figure 35: Various tensegric net arrangmenets.

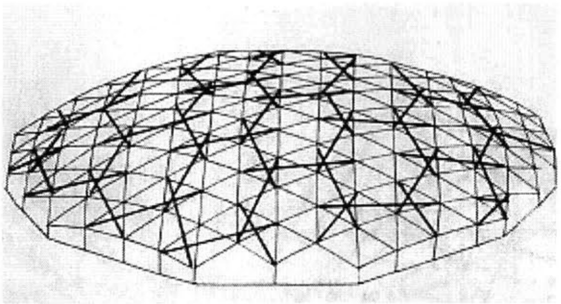

Figure 36: A shallow tensegric shell.

6.2 Advantages and Disadvantages of Tensegric Shell Structure

Tensegric shell, which works through both tension and compression, is a very effective system for wide span. In fact, tensegric shell has some advantageous properties, which are not found in any other cable net structures. The incorporation of rigid compression bars has made tensegric dome much stiffer than if it were to consist of only cables. This system is therefore less susceptible to large deflection problems which are commonly found in other net structures. Since tensegric net is self equilibrating, the design of the boundary condition at the base of the dome can be relatively simple. The stability of the tensegric dome also enables it to have low-profile curve, resulting in a shallower dome (Fig. 36). Space confined by shallow tensegric shell is more suitable for practical usage than that confined by conventional cable nets, in which much awkward space is wasted along the edges. Shallower dome also brings with it the advantages of lower wind lift and less drifting snow, resulting in the use of smaller structural members. Being shallow, the canopy also has a smaller surface area, thus reducing fabric cost.

Design and construction of tensegric shell is however more complicated than typical cable net structures. The structural concept of tensegric shell, which is based on equilibrium of forces, is simple. However, to comprehend it mathematically is not easy. The presence of both compressive and tensile force in the system also makes the diagrammatic visualization of force flow in the structure non instinctive. The construction of tensegric shell is more messy than ordinary cable nets because the compression bars need to be fitted into the system individually. The connection of the bar to the cables also needs to be detailed with care.

6.3 Applications

Despite the potential of tensegric dome as a wide span structure, there are only a handful of built structures which employ this structural system. The first tensegric structure every built in the world is the Gymnastic Arena for the 1988 Korean Olympic (Fig. 37). Another structure which uses the trangerity system is the The Amagi Dome in Suzenzji, Japan which encloses a relatively small area of 3000 square meters (Fig. 38).

Figure 37: Gymnastic Arena for the Korean Olympic

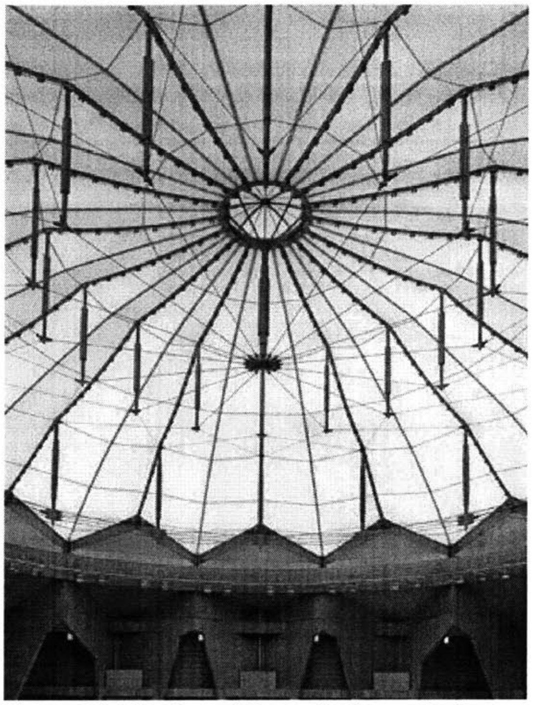

Figure 38: The Amagi Dome in Suzenzji, Japan

6.4 Case Study -- The Gymnastic Arena for the Korean Olympics[15]

The Gymnastic Arenas for the Korean Olympics is a circular tensegric dome of radius 393 feet. The tensegric system of this arena roof is a simplification of Fuller's tensegrity dome. David Geiger, a Pennsylavania based engineer simplified Fuller's dome by getting rid of the redundancies inherent in Fuller's triangulated configuration (Fig. 39). By doing this, he is able to make the adopted dome system statically determinant, and much simpler for structural analysis and construction.

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[15] "Dome Case Studies" Columbia University, 30 April 2004. <http://www.columbia.edu/cu/gsapp/BT/DOMES/SEOUL/seoul.html>

6.4.1 Structural System

This arena cable dome roof is formed by continuous tension cables and discontinuous compression posts. Forces on the roof are carried by radial ridge cables (which span between the central tension ring and the perimeter compression ring), hoop cables, intermediate cables and the compression struts (Fig. 40). The cables and the struts behave very much like cantiliver trusses, which converge but not quite touch at the center tension ring.

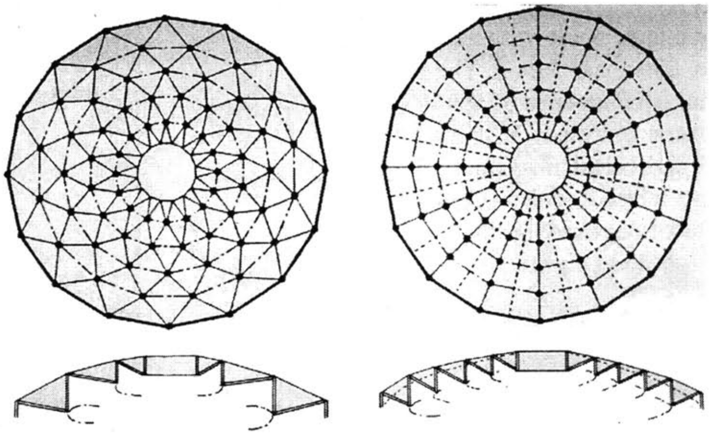


Figure 39: Fuller's tensegric system vs Geiger's tensegric dome

6.4.2 Cladding Material

The dome is clad using four layers of fabric. The outermost layer is a high-strength fiberglass fabric with a silicone coating on both sides. Beneath it is an insulating layer of silky fiber glass, followed by a Mylar insulation barrier and a silicone coated ascoustic liner. This cladding is designed to provide adequate thermal resistance for Korea's winter and yet transulecent enough to allow light transmission to meet most daytime needs. The fabric is not tensioned and are simply connected to the radial ridge cables.

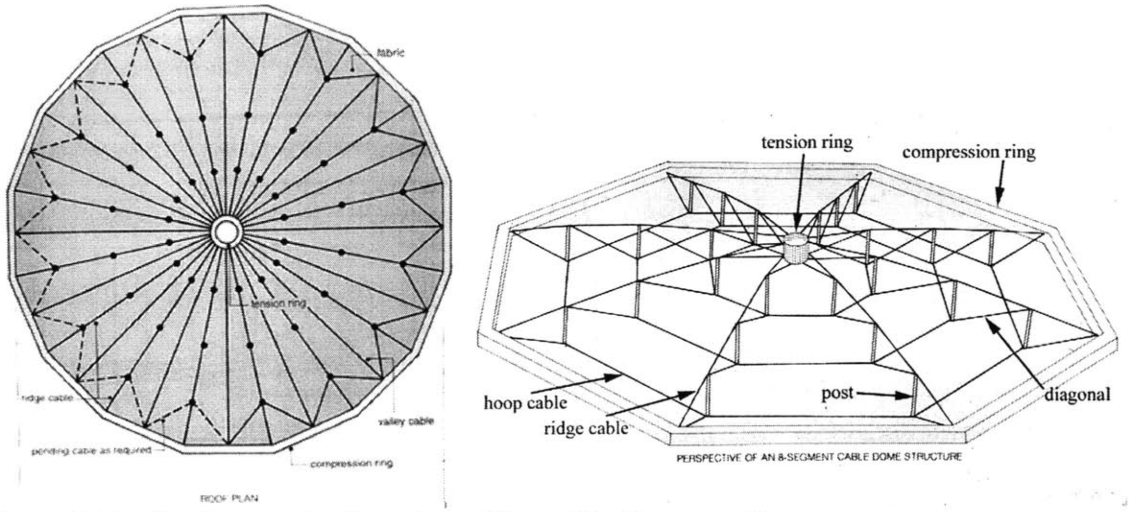
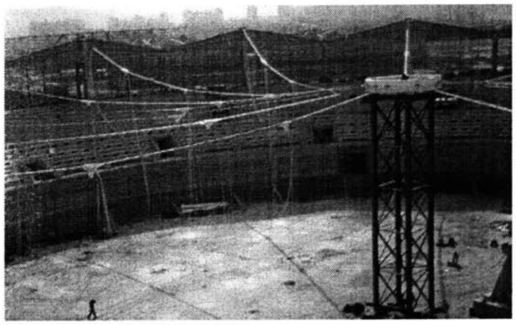


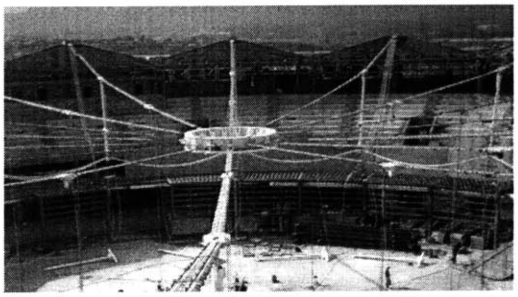
Figure 40: Details of the structural members of the roof for the gymnastic arena.

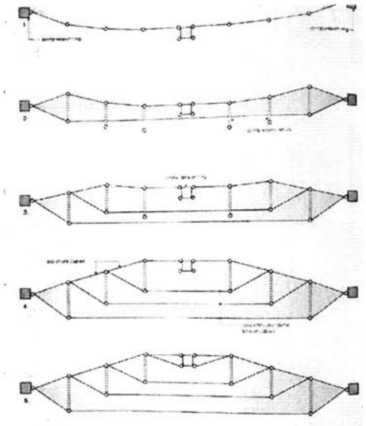
6.4.3 Construction Process

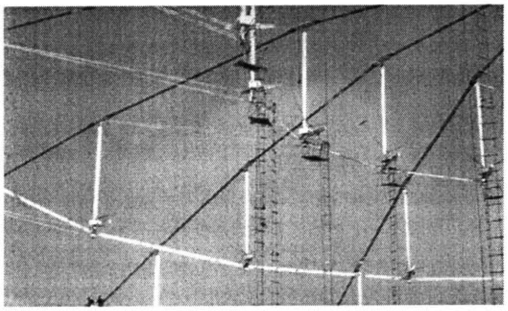
The construction of the dome starts after the walls of the arena are completed. 16 radial ridge cables are threaded to the steel central ring on the ground, before they are hoisted up by a temporary crane to their position (Fig 41(a)). The other ends of the ridge cables are then threaded to the reinforced concrete compression ring. As the ridge cables are being erected, tension hoop cables are laid on the ground with the compression posts attached in position. The hoop and posts were then lifted and attached to the connection castings which are already in the erected ridge cables (Fig. 41(b)). Diagonal cables which run from the top of the compression ring to the bottom of the compression struts were then tensioned, pulling the hoop into the final position. This process is repeated for all four sets of hoops and struts (Fig. 41 (c)). This pre-tensioning of diagonal cables is a complex process in which sixteen group of workers were stationed in baskets at the bottom of the compression posts to jack each of the diagonal cable simulataneously (Fig.

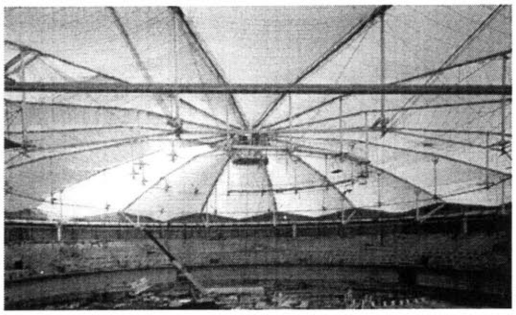
41(d)). After the cables are all pre-tensioned to a desired force, the fabric are laid and bolted to the castings on the ridge cables with stainless-steel nut (Fig. 41(e)).


(a): Support tower placing tension ring into place.


(b): Hoop cables and struts attached to ridge cable.


(c) Steps of the erection process.


(d) Workers suspended in baskets pretensioning cables.



(e) Fabric laid on the completed cable dome.

Figure 41: Erection process os a tensegric dome.

7. Design of a Wide-Span Cable Structure

The design of a wide span cable structure is a complex process. It requires, not only a good understanding of the behavior of cable systems, familiarity with computer programs is also essential. Due to the non-linearity of the cable behavior, classical methods of design and analysis cannot be employed. In this section, a design methodology specific to cable net structures is decribed.

The design of a wide span cable structures can be typically divided into the following stages:

(1) Deciding on wide-span system used
(2) Form Finding
(3) Analysis
(4) Design of element sizes and connections
(5) Construction

7.1 Choice of Cable System

Although cables are generally efficient for long-span roof structures, some systems are more suitable than others when used for particular architectural programs or requirements. In deciding which cable system is to be employed for a particular structure, the following factors have to be considered:

7.1.1 Physical form

Each cable system carries with it a characteristic profile. Simply suspended cable system assumes the natural catenary shape, cable beams form gently curved roof, cable net has its signature anticlastic double curvature and tensioned straight cables form a stretched flat roof. Tensegric shells can take on different forms, but is generally dome-like. Due to this reason, the structural system of a building is indirectly controlled by the architectural design. As a general guide, if a prominent canopy is desired, cable net systems which include traditional net, tension straight cables and tensegric shell, may be considered. When a simple gesture is preferred, simply suspended cables and cable beams are more suitable.

The shape of the area to be enclosed may also affect the choice of the system. If a rectangular area is to be covered at minimum cost, as in case of large exhibition halls, unidirectional cable girders or hanging roofs suit better than doubly-curved cable net system. While cable beams and singly suspended cables are suitable for orthogonal sites, cable nets are appropriate for circular or curvilinear layout.

Associated to the issue of physical form, the need for anchorage in certain cable systems must also be considered. When spatial conditions do not permit, only systems which need no anchor support such as simply suspended cables, tensegric shell and nets with fixed frames can be considered.

7.1.2 Span

All of the above mentioned systems are structurally efficient for long span. However, there is a limit to the maximum span that each system can support effectively. In general, cable nets are able to span a greater width than single cable systems. With stiffness acting in both directions (as opposed to one in single cable systems), cable nets form stiffer structure and thus able to span to a greater width with relatively smaller deflection. Between the two single cable systems, cable beam is able to span a greater width because the pre-tensioned cables help arrests excessive deflection. Simply suspended cable systems fail beyond a certain span as deflection in the non-tensioned cables grow exponentially with span. Among the cable nets, tensegric shell is most effective, followed by nets with anticlastic double curvature and the straight cable system.

In tensegric domes, where forces are balanced internally, an increase in the dome's diameter involve the replication of the existing system with little increase in expense or weight per square foot. In other cable net systems, where stiffness is provided primarily by the pretensioning in the cables, an increase in span requires a greater increase in the pretension force, resulting in a huge rise in the cost.

7.1.3 Availability of Skilled Labor

The construction of cable structures is a complex process and requires a specialized group of skilled labor. In places where skilled labor is not available, simply suspended cable structures are recommended. In simply suspended cable structures, the cables are simply supported and require no pre-tensioning Most of the skills needed in the construction of these structures are in the casting of concrete for cladding. This is a pretty ordinary process which can be done by regular construction workers. Cable beam construction is also relatively simple and may be considered if the service for simple cable pre-tensioning is available. Cable net construction, however, should only be considered if skilled workers experienced in erecting cable structures can be employed. The erection of cable net requires good coordination among workers during cable pre-tensioning, and mistakes made during the process may affect the stability of existing frames and cause fatal accidents.

7.1.4 Cost

In building a cable structure, most of the cost goes into design and construction. Material cost is not significant. Thus, the simpler the cable system, the cheaper it is. For regular span, simply suspended cables would be the cheapest to employ, followed by cable beams and the nets.

7.2 Design

Once a specific system has been decided, design of the structure commences. Due to non-linear behavior of cables, classical methods of design and analysis are not applicable to cable structures. There is also no available building code to aid in the design process. The process of obtaining the most optimum cable structure therefore involves analyzing a structural form using basic analysis method and updating the shape of the structure to improve structural performance. The general methodology pursued in the design and construction of a cable structure is illustrated in the attached flowchart[16] (Fig. 42). Due to the complexity of the process, many procedures are done with the aid of computers. Processes which are typically automated are highlighted in the chart. This design process, as with most design methodologies, is iterative, with the results of the analysis examined and used to redesign the shape of the cable structure. With computers, this iterative process can be done very effectively. Although there are many algorithms presently used with success for each of the computer process, the general methodology illustrated is appropriate for a wide variety of prestressed tensile system.

7.3 Form Finding

The form finding process that is about to be described are applicable only for cable net systems. There is little form-finding involved in the design of simply suspended cable structures and cable beams because the arrangement of cables in these single cable systems are governed primarily by the shape of the area to be enclosed. The ways in these can be done have been discussed in earlier sections.

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[16] Campbell, David M. "The Unique Role of Computing in the Design and Construction of Tensile Membrane Structures" American Society of Civil Engineers, New York.1 May 2004 <http://www.geigerengineers.com/techpaper.cfm?RecordID=2>

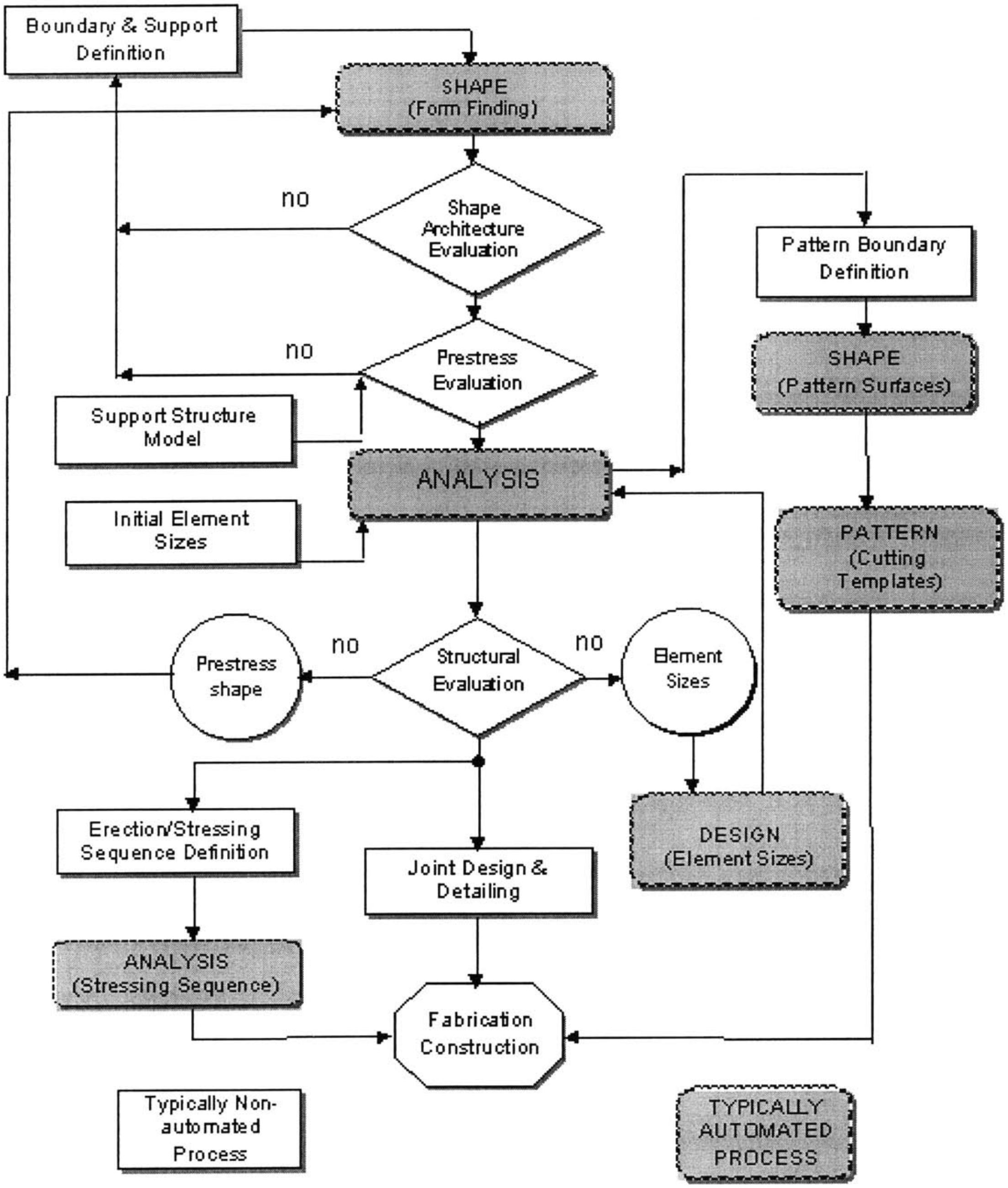

Figure 42: Flowchart illustrating general approach to cable structure design and engineering.

The objective in form finding method is to create a model of the intended structure from which a geometry that satisfies the requirements of form and equilibrium can be found. This is an inherently non-linear problem since form and equilibrium are inextricably linked and adjustment made to either one will affect the other. Thus, as mentioned earlier, an iterative process is acquired to obtain a general solution to this problem. A variety of algorithms can be used to determine suitable forms, ranging from purely geometric approaches to the force-density method. A few of the methods discussed in this section include[17]:

(a) Force-density method

(b) Natural shape finding method based on Newton-Raphson non-linear analysis iteration

(c) Dynamic Relaxation Method

7.3.1 Force-Density Method

The idea of force-density method is to obtain a unique shape of equilibrium state given a prescribed selection of force density in each net element. Force-density refers to the force to length ratio of an element. An element is defined as the cable member between two nodes while a node is the connection at which two cables intersect (Fig. 43).

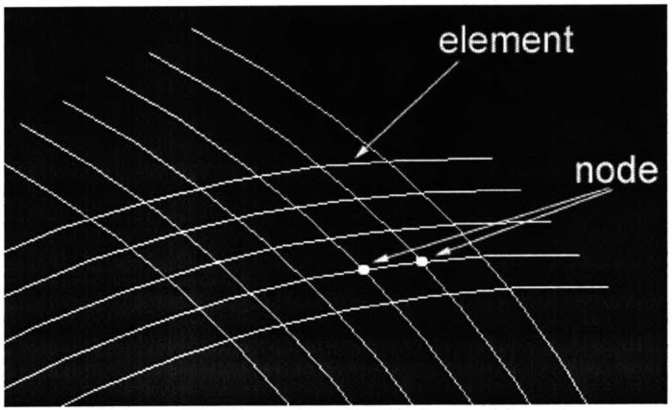

Figure 43: Element and node in a cable net.

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[17] Meek, John L. and Xia Xiaoyan. "Computer Shape Finding of Form Structures" International Journal of Space Structures Vol. 14. No. 1, 1999. p35-54.

In force-density method, an initial geometry of the cable net is obtained from sketches (as visualized by the architects). This geometry is then defined in a computer program by prescribing coordinate values to the positions of free nodes and fixed nodes of the cable. Loading conditions and a desired force-density distribution is then input into the computer. With the given loading vector and force-density distribution, the computer program will determine new co-ordinates for the free nodes using linear equilibrium equation.

An extension of this simple linear shape finding method is developed for conditions where certain restrictions result in the force density equation to be non-linear. This extended force density method would have to use non-linear equilibrium equation to calculate the new nodal coordinate systems. An example of such condition is a prestressed net where the lengths of the cables in the restrained net are defined to be constant and yet uniform pre-stressed forces in all the cables are desired. Since restrictions are placed in both force and length of the cable element, the force-density equation is non-linear.

7.3.2 Natural Shape Finding Method

Natural shape finding method is a shape finding method used specifically in modeling cable network, as proposed by Argyris, Angelopoulus and Bichat[18]. This method is

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[18] Argyris, J., Angelopoulos, J. and Bichat, B. "A General method for the shape finding of lightweight tension structures." Computer Methods in Applied Mechanics and Engineering, 3: 1974. p135-149.

programmed to find the length of the unstressed cables for a pre-determined applied load, target net shape and pre-stressing cable forces.

In this method, a flat net is first established within the projected plan boundary of the structure. Prescribed displacements, at selected nodes which correspond to known structural support points, are then given in small increments until these nodal points reach their target coordinates. Non-linear finite element analysis using Newton-Raphson iteration is performed at each incremental displacement, to obtain a new equilibrium configuration. For each iteration, the stiffness matrix of the structure and the load is updated with results from the previous analysis. When the selected nodal points reach their predetermined position, large elastic strains would have been accumulated in displacing the net from the flat configuration, resulting in high stresses in the structure. From this analysis, the unstressed length of the individual cable element, Lo, can be obtained as:

$$L_o = \frac{L + \Delta L}{\frac{1}{P_d} + EA}$$

Where L the original unstressed length, ΔL is the increased in length from the original unstressed length (strain at final configuration x Lo) and Pd is the desired prestressing force in the cable.

7.3.3 Dynamic Relaxation Method

Dynamic Relaxation method is a pseudo-dynamic analysis which allows a static problem to be solved by a simulation of a pseudo-dynamic process. Under this method, an initial shape of the structure is approximated, as well as its mass and stiffness. A prescribed loading and pre-stress in all the cables must also be determined. Through a pseudo-dynamic method, a final configuration will be established, in which equilibrium of the structure is satisfied for the given pre-stress and loading condition.

In this method, the net membrane is first discretised by finite elements and the element's mass is lumped at its node. Prescribed external load, P is then applied, which excites a movement on the structure manifested by the oscillations of the nodes. If a structure is stable and forces within the structure equilibrate themselves, under this free vibration, the oscillations will die down due to viscous damping induced by the stiffness. In this method however, initially, the nodal points of the structure oscillate with increasing velocity and accumulating displacements. This phenomenon is a result of the presence of residual forces. Residual force is calculated as the difference between the applied external load, P, and the internal forces in the structure. This force arises because in the crudely chosen initial geometry, static equilibrium of the surface under the assumed value of pre-stress forces cannot be satisfied.

During this dynamic process, the kinetic energy of the system is monitored. When the peak energy is detected, the process is interrupted. The computation is again restarted from a rested configuration using the updated geometry (which incorporates the accumulated displacements). This process is reiterated until the residual forces are reduced to a minimum. At that, a new configured shape is obtained such that oscillations of the structure under free vibration will eventually die down.

A final shape, which satisfies static equilibrium given a prescribed loading and prestressing force, can be obtained using any of the above algorithms. In general, however, the force density approach is becoming the most accepted method in the industry. Its popularity stems from the flexibility of the method in accommodating additional conditions such as the restriction of having uniform length for every element.

7.4 Analysis

The key advantage of using computer shape finding program is that the shape results can be utilized directly for analysis. General analysis of cable net structure requires geometric nonlinear techniques. A typical analysis is usually done by using matrix analysis employing non-linear finite element methods with Newton-Raphson iterative procedure. This analysis is similar to the analysis method employed in some of the form-finding techniques.

In this analysis process, it is important that the structure is tested under the different possible loading combinations. Analysis of the structure under dynamic loading should also be performed. Dynamic impact of wind (earthquake is usually not an issue in cable system because of the light weight of the structure) on cable stresses, fatigue and deflections of the individual cable and the entire structure shall be studied and considered in design.

7.5 Design of Element Size and Connections

7.5.1 Element Size

Cable size is chosen to satisfy the mass and stiffness requirement that is prescribed during form finding and analysis of a structure. Check must also be done to ensure that the cable is able to resist the maximum axial stress developed in the structure under the most severe loading condition. It also needs to be decided whether different cables sizes shall be used for the different cables according to the maximum stresses experienced, or one maximum size shall be employed for all cables. Very often, the cost saved in varying the element sizes is not worth the added complication experienced during the construction process.

7.5.2 Connection

Three types of connections are to be discussed in this section[19]. They are cable-to-cable connection, cable-to-frame connection and cable-to-ground connection (tension anchors).

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[19] Buchholdt, H. A. An Introduction to Cable Roof Structures. Cambridge: Press Syndicate, 1999. p269-272.

7.5.2.1 Cable-to-cable connection (clamps)

Cable-to-cable connections are used to hold two criss-crossing cables so that they do not slide against each other. This connection simulates a pin joint which prevent relative vertical and horizontal displacement between two cables, but does not provide any rotational restrain.

In order to design roofs with minimum cable dimensions and clamps that are simple to fit, nets have often been designed with two small-size cables in place of a larger one, as indicated in Fig. 44. Clamps can generally be classified into two types, one which can be fitted on site (Fig. 45), and the other which has to be fitted to the cable strands in the factory (Fig. 46). The prefabricated system is suitable in nets where the lengths of the individual cable links are fixed. This system has the advantage of being relatively easy to assemble and erect. An error in the manufacture or assembly of the connections, however, cannot be remedied on site and will result in difficult pre-tensioning of the structure. This problem can be avoided by including a number of turnbuckles in the design to enable the length of the cables to be adjusted. With the addition of turnbuckles into the design, prefabricated connections tend to be more expensive than connections that are fitted on site. In cable net where cables are free to assume their positions under the prestressing force, cable to cable connections need to be fitted on site, after all the cables have been pretensioned.

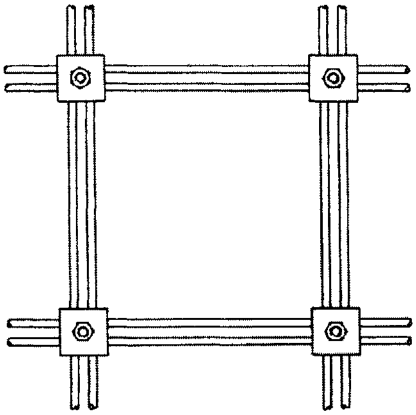

Figure 44: Detail of cable nets with dual-strand cable system

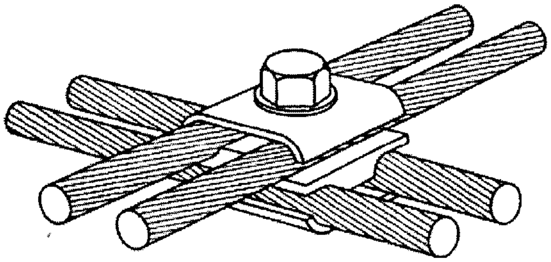

Figure 45: Fit-on-site cable clamp connection.

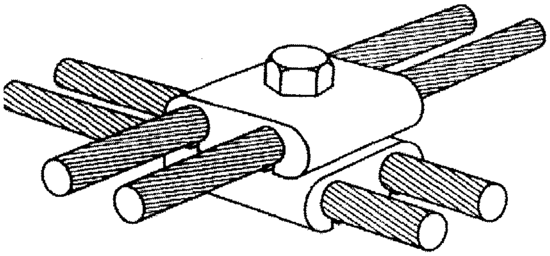

Figure 46: Prefabricated and factory installed clamp.

For nets in which only two cables intersect at each joint, clamps of the types shown in Fig. 47 and Fig. 48 can be used. Where the cables are attached to edge cables, special clamps are required. An example of such clamp is shown in Fig. 49.

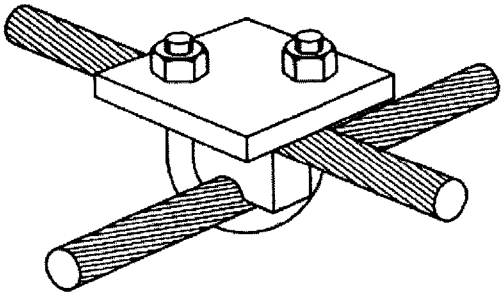

Figure 47: Single U bolt connection for cable net

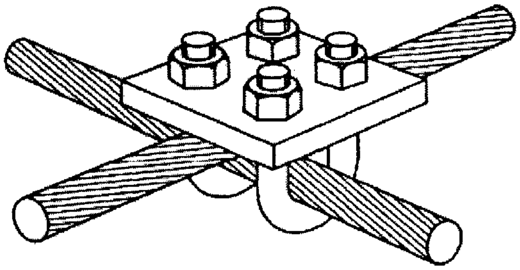

Figure 48: Double U bolt connection for cable net

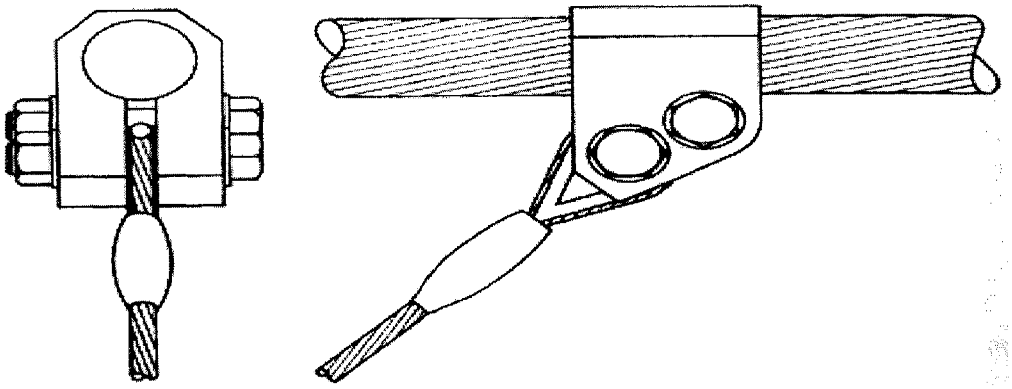

Figure 49: Detail showing clamp for connection of interior net cable to edge cable

7.5.2.2 Cable-to-frame connection

Cable-to-frame connection is employed in cable beams and cable nets with self-balancing structures. As the name suggests, it forms the connection between a cable and a rigid structural frame, which could be steel or concrete. In the design of cable-to-frame connections, both cable termination sockets and connection between the cable and the frame need to be considered.

Cable termination sockets are steel casting fitted near the end of a cable to hold the strands in a cable together (Fig. 50). The external shape of sockets can be varied to suit individual design requirement, but for each shape variation, the basic dimensions of the socket cone or basket will remain the same for a given size cable. Generally, the length of the conical basket is approximately 5.5 to 6 times the cable diameter and the diameter of the cone is approximately 2 to 3 times the cable diameter.

The clamp connections between cables and frames need to be well designed to ensure that the value of the pretension in the cables is maintained. These clamps may come in many forms, but irregardless of their physical look, they must satisfy the following requirements. The clamps must provide sufficient frictional resistance to ensure that the cables will not slide out. Any slight sliding of the cable will result in the loss of pretension and lead to floppy structures. If the cables are protected by sleeving, the connection should be designed so as to prevent moisture from penetrating into the cable should the sleeve be damaged by the clamping. In cases where the cladding is supported directly on the cables, connections should also be designed in a manner as not to interfere with the cladding. Figure 51 shows a typical clamp connection between cable and steel frame while Figure 52 shows that between cable and a concrete column.

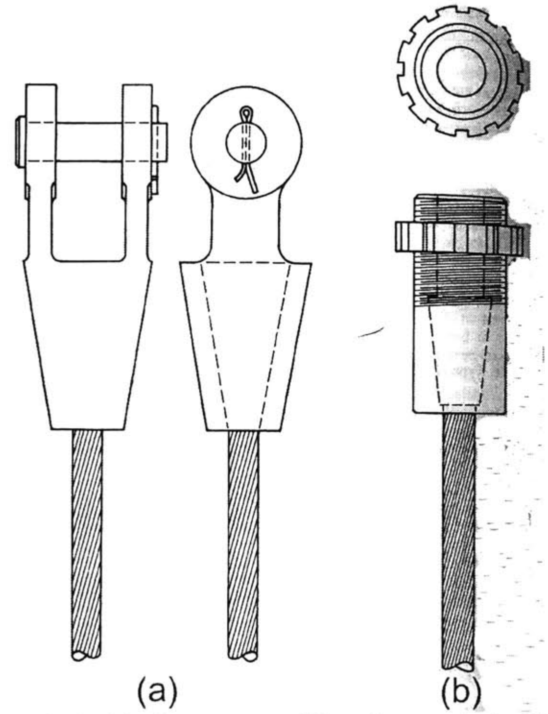

Figure 50: (a) Socket terminal with pin connector (b) socket terminal with screw terminal.

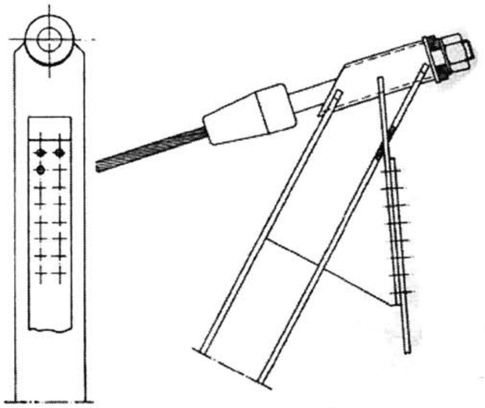

Figure 51: Attachment of cable with socket terminal to top of steel column.

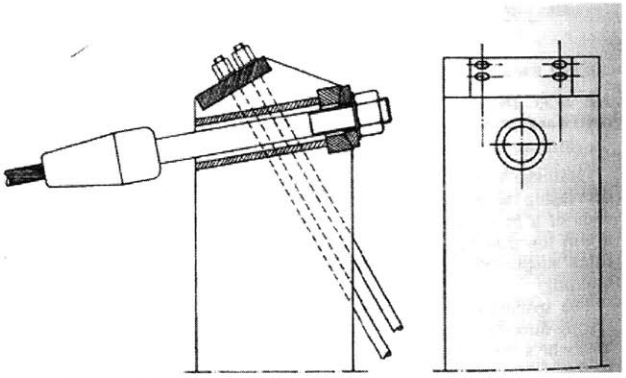

Figure 52: Attachment of cable with socket terminal to top of concrete column.

7.5.2.3 Cable-to-ground connection (tension anchors)

Tension anchors are used to hold cables to the floor when forces from the cables need to be transmitted directly to the ground. Anchors may be adopted in both cable beams and nets.

There are many different types of tension anchors, each of which is suitable for a given ground condition. The commonly used anchors are gravity anchors, plate and mushroom anchors, ground anchors and tension piles. Gravity anchors work by using the dead weight of the anchor to balance the vertical component of the cable forces while the ground balances the horizontal components (Fig. 53a). Gravity anchors are therefore bulky, but they may be used in soil with poor force resisting properties such as gravel and sand or fine sand. Plate, mushroom and other footings rely primarily on the weight of the soil to resist the force from the cable (Fig. 53 (b), (c) and (d)). Compact soil condition, such as that in clay, is thus necessary to provide the necessary weight. Ground anchors equilibrate the upward thrust from the cable through shear frictional forces between the anchor and the soil while the horizontal pull is resisted by the weight of the soil (Fig. 53 (e)). This anchor is thus suitable for use in soil which provide good amount of frictional resistance such as earth which contains much granular material or clay soil. Tension pile resists vertical force in the same way as ground anchors. However, the horizontal thrust in this system is resisted by the friction between soil and another tensile pile which is angled in the opposite direction to that of the cable (Fig. 53(f)).

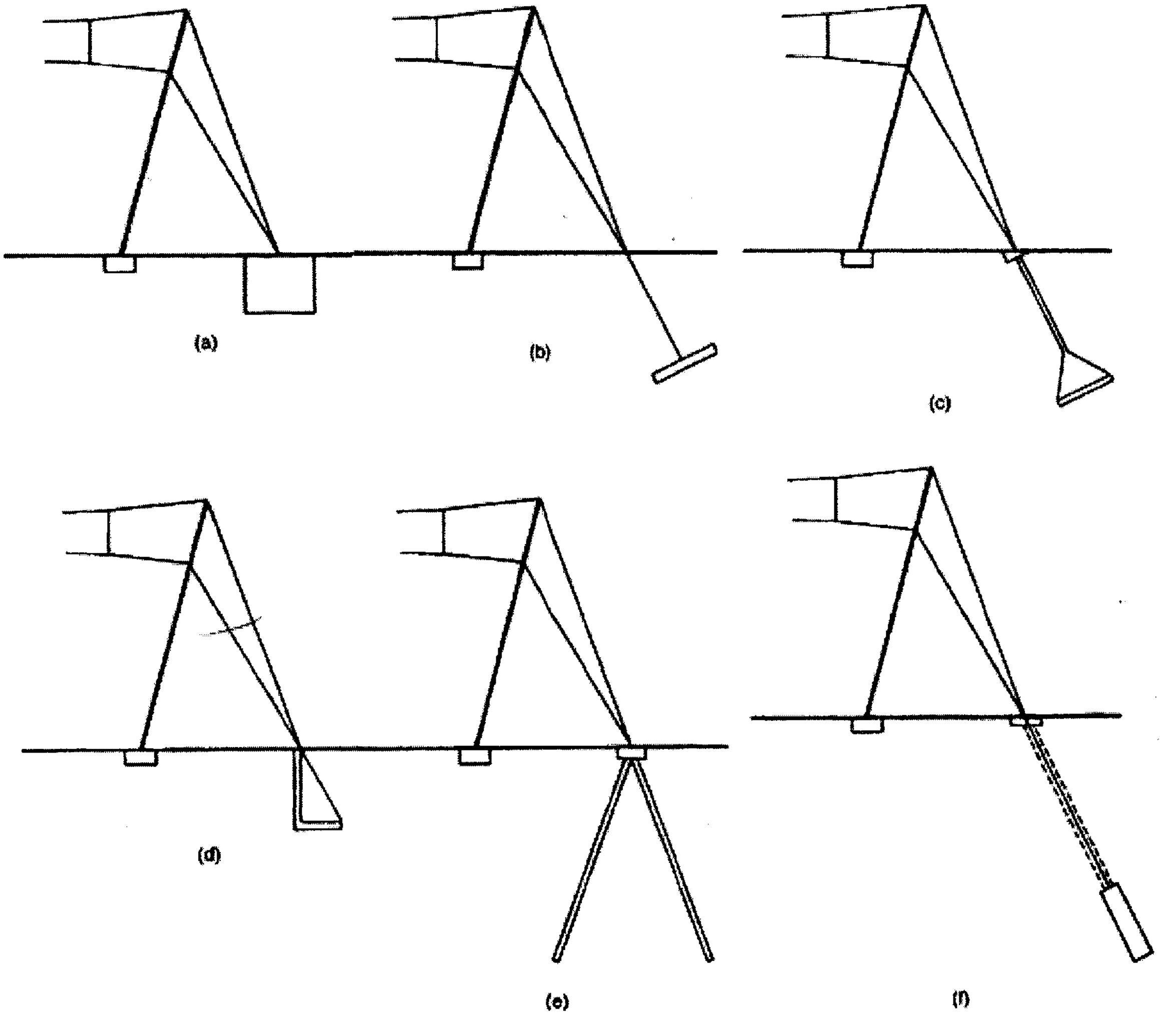

Figure 53: (a) Gravity anchor, (b) Plate anchor, (c) Mushroom anchor, (d) Retaining wall anchor, (e) Tension piles and (f) Ground anchor.

7.6 Construction

Construction is viewed as the most difficult process in the building of a cable structure. Since detailed construction process of each cable system has been described earlier, this section shall highlight the reason behind the complexity in the construction process -- the intricate prestressing procedure of the cables. This intricacy does not lie in the physical prestressing of the cable but in figuring out the prestressing sequence of the structure. In fact, the pretensioning of a single cable can be simply done by pulling its ends using a special jack. Figuring out which cables to be prestressed first is not so easy. The prestressing of one cable may affect the tension in another cable. It is thus important that the correct sequence of stressing is carried out if the structure were to have the desired prestressed state. In a complex cable net system, analysis of stressing sequence using computer software needs to be carried out, to assure that various components of the systems will not be overstressed during pretensioning.

8. Conclusion

Cable indeed makes for an effective wide span system. Not only does it carry loads through axial stresses, which utilizes all of the cable's cross section, the high strength to weight ratio of cable also means that its strength is fully utilized to carry applied loading rather than its own dead weight. Beside its mechanical properties, cable is equally desired for its aesthetic appeal. The lightness of the cable gives an expanded impression of space and its characteristic curvilinear form provides a fresh alternative from the orthogonal box buildings.

Although all cable systems are effective for wide span, each system has its own distinct characteristic which may make it attractive for certain conditions or more suitable for particular architectural applications. Simply suspended cables, though rarely used today, may still be employed if budget is tight and the restriction on the roof deflection is not stringent. Cable beams are attractive for its simplicity, low cost and ease of construction. It is also best suited to sites which are orthogonal in plan. Pre-tensioned cable net is loved for its anticlastic shape. Net hung from masts is also especially popular in Middle Eastern countries because of its similarity in form to the native vernacular tent structures. Straight cable net system, which has the same spanning capability as traditional cable nets, may be favored for its relatively simple erection. And tensegric shell is the best system to be adopted when a very large span need to be enclosed.

The method for designing each of these cable systems is different, but the approach is very similar. A general procedure in the design of a cable structure would be to first decide on which cable system to be used, followed by form-finding and analysis. If desired results are obtained from the analysis process, elements and connections of the cables can then be designed and constructed as suggested by the analysis results.

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