Connections and Hardware for Lightweight Structures

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INTRODUCTION

Before the rapid growth of lightweight structures utility and economy dominated connection design. Economy in material and labour were the imperatives in designing framed structures in industry and public domains. Aesthetics was rarely a priority. Collections of these spartan looking details were published by steel promotion organisations ready for immediate use.

As the use of lightweight structures increased and the connection details became more visible they had to be brought in line with overall concepts employed in modelling of the structure. As connection details became more visible to the public, the architect's vision became a driving force in shaping the major details.

Computer modelling and scale models have been employed to help with visualisation. The engineer's job is to find a way to achieve a satisfactory performance and strength – often a very difficult task. But assisted with suitable computer programs and laboratory testing for verification of strength, the engineer ensures adequate performance of the details proposed.

Connection details used in lightweight construction can be categorised as either *integral* or *premanufactured*. The integral connections are accomplished without auxiliary pieces, is the case as for welded tubular connections. The premanufactured connection hardware may be in form of cable accessories (fork ends, rigging screws), node connectors, pins, spherical bearings and the like.

Economy has not ceased to be a worthwhile goal in this striving for aesthetic appeal. Economy can be achieved with ingenious use of materials and manufacturing techniques. Steel castings and forgings and modern welding technology are now achieving previously impossible feats. CAD-CAM technology has made it possible to cope with most convolute designs and geometries.

However, it remains to educate the engineer and the drafters becoming proficient in this new approach to connection detailing.

LIGHTWEIGHT STRUCTURES AND THEIR CONNECTIONS

Characteristic forms of lightweight structures and their connections are discussed below. Clearly the structural form and the connections are strongly related. This is in contrast to the practice in conventional steel-framed structures when standardised connections are devised to suit most structures.

Latticed steel structures

Latticed structures have a long history of use in roofs and other structures. Neatly detailed, filigree latticed steel structures had long been used for roofs and glass facade work. Well-proportioned trusses with streamlined connections are much appreciated by the project architects. Tubular trusses are also capable of achieving highly transparent structures. Their member connections are commonly of integral type, ie. directly welded connections not using any gussets. Web members of these trusses can be in form of crossed rods and cables. Figure 1 shows some examples.

The pre-manufactured connection hardware for these structures include rod end terminations, pin connections and factory made welded nodes.

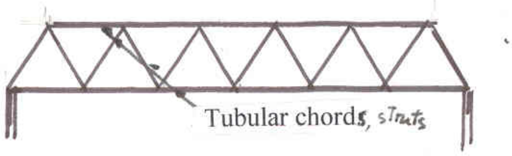

Figure 1a - Howe

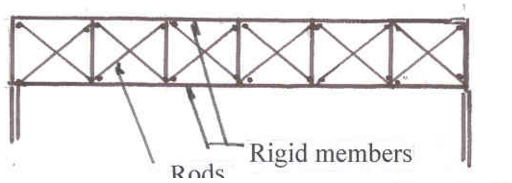

Figure 1b - Waren

Figure 1 – Truss Types

Cable Trusses

Cable trusses use cables for chords in lieu of rigid members. This is made possible by prestressing the cables to prevent compression forces being introduced into them. Their web members comprise rigid struts and post-stressed rod diagonals. The basic principle is that the residual forces in cables remain in tension under all conditions of service and wind loading. These types of structures are also known as tensegric structures.

The downside to this very economical system is that buttresses are required to resist the horizontal component of the cable forces at the supports. Thus the savings achieved by use of cable trusses are partly absorbed in constructing the buttress structures. Nevertheless, these are very elegant structures. Fig. 2 shows a typical cable truss.

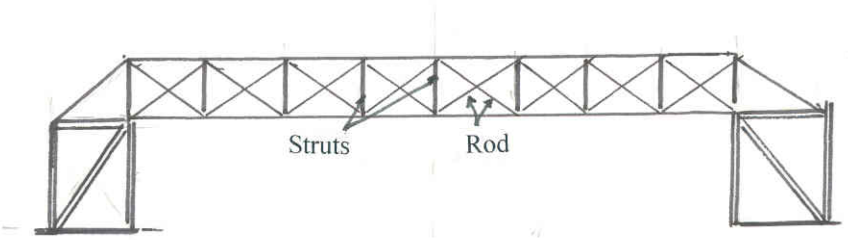

Figure 2 – Cable Truss

Special connection hardware for these structures comprise cable end terminations, rigging screws and cable deflector pieces.

Catenary cable systems

A typical example of these systems is shown in Fig. 3. Catenary cables are very efficient in carrying uniform loads their vertical in plane. Since wind uplift must be catered for there is a need for addition of a reverse catenary. Masts are used to transfer the vertical reactions from the catenaries into the foundations. The cables, or rods, are prestressed to a level that prevents them becoming slack by wind, live and snow actions at serviceability limit state. Some form of stiffening system is often incorporated along the span to cope with non-symmetric (patch) loads as catenaries are not very efficient in handling them. This can be in form of a latticed structure or a system of web members similar to the cable truss webbing.

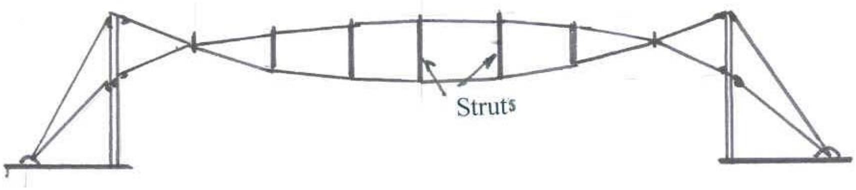

Figure 3 – Catenary Cable Truss

Catenary cables lying horizontally are also used for lateral wind bracing where two cables working in opposition are often used. Very large roof structures have been braced in this manner.

Connection hardware consists of fork ends, turnbuckles, cable deflectors and cable clamps. The masts use mast heads at top and often spherical bearings at their base.

Bow string girders

These are essentially one way structures. Roof and floor beams can be constructed using rolled or tubular members as top chords and rods or cables for the bottom chords. Counter-catenary system is often necessary where wind forces can cause a net uplift. Essentially they are a subtype of catenary cable systems. Figure 4 shows several types of these girders. The main appeal of these systems is that they look light and elegant.

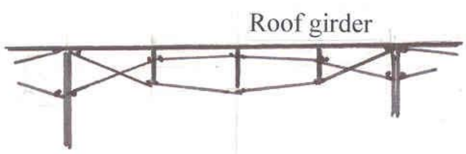

Figure 4 – Bowstring Girder

Connection hardware for bowstring girders include fork ends, cable (rod) end terminations, rigging screws and purlin cleats

Cable nets

Doubly curved (anti clastic) cable nets of the type used in Munich Olympic Stadium are examples of this type of highly specialised and truly lightweight structures. Since the nets are relatively flexible, cladding of the roof presents a challenge. Fabric membranes and polycarbonate sheets are used for the usual roof membranes.

Smaller nets of the type shown in Figure 5 are feasible solutions for glazed walls and canopies with aspect ratios ranging from 0.7 to 1.45.

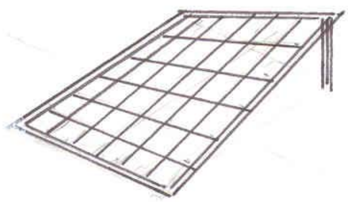

Figure 5 – Cable Net (Hypar)

Pre-manufactured connection hardware for these structures include cable or rod end terminations, turnbuckles, and cable clamps.

Taut cables

Straight rods or cables when sufficiently prestressed can provide strength and stiffness as they deflect to form equilibrium of forces. In essence they resist the imposed loads as a very flat catenary cable (see Fig. 6). The usual application is for screen walls. To comply with a serviceability criterion of H/150, the cables must be prestressed to a relatively high level. On the other hand the cables or rods must not reach their yield point up to the limit state loading or else they would become slack at some stage before reaching the limit state loads. The soffit beam and the floor structure need to resist the relatively high forces due to cable prestress, and hence, they must be designed for adequate strength and stiffness.

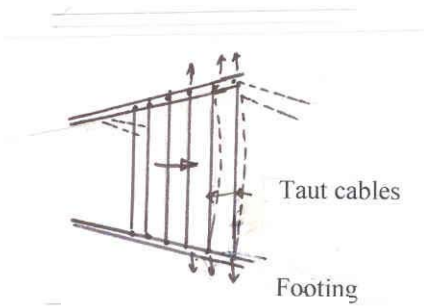

Figure 6 – Tout Wires

Connection hardware for taut cable systems include cable or rod end terminations and the clamps from which the envelope is suspended.

Diagrid shells

Diagrid shells, a subtype of reticulated barrel vaults consist of a grid of tubular members intersecting in a regular pattern. Provided there are stiffened end walls and intermediate stiffeners the vaults are very stable and can cope with non-uniform loading. Figure 7 shows the typical structure.

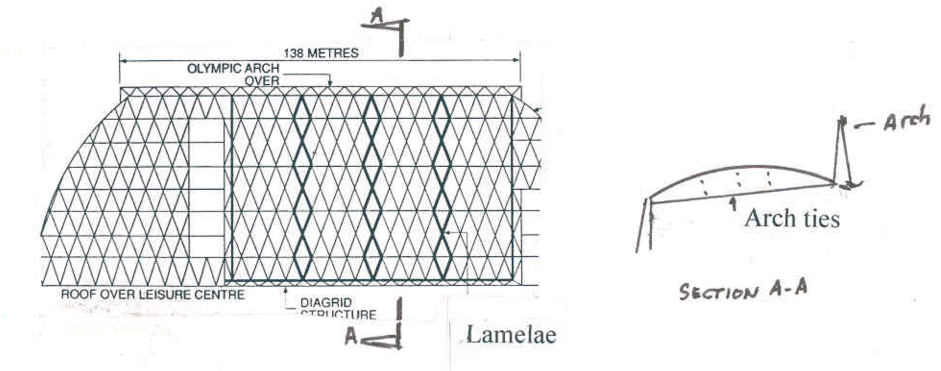

Figure 7 – Barrel Vault (diagrid)

The pre-manufactured connection hardware for diagrid shells include fabricated or cast steel nodes and bearing assemblies.

Space trusses

These structures use an orthogonal gridwork of members to create two layer, three way structure which includes diagonal web members between the upper and the lower grids. (Fig. 8) Their main drawback is in the use of large number of expensive nodes. Also, as many end terminations are involved, the reliability of the loadpath is somewhat reduced.

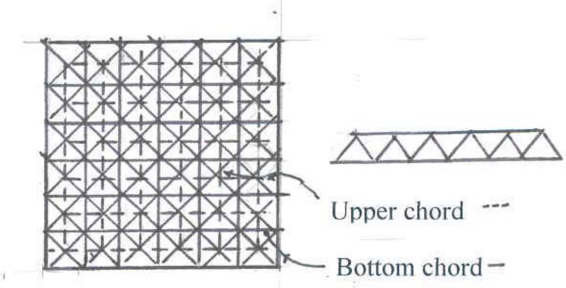

Figure 8 – Space Truss

The particular connection hardware for these systems are Universal node connectors (NODUS, MERO).

CONNECTION DETAILS AND HARDWARE FOR LIGHTWEIGHT STRUCTURES

The following is a brief catalogue of connections and connection hardware used in lightweight projects. Additionally, designers can make use of standardised connections where appropriate.

Cable and rod hardware

The most important item in this context is the cable and rod terminations. Usually these are designed, manufactured and tested by the cable suppliers. What is outstanding is that they combine the use of high strength steel, forged or cast, followed by heat treatment. Sockets or fork ends for spiral strand cables have an inverted conical hole allowing the cable to be inserted and encased using molten lead/zinc compound to achieve a reliable bond.

High strength rods are fastened to the socket drilled and tapped to receive a threaded end of the rod which may engage a minimum of 4 diameters or such other length that will transfer the axial forces without the danger of stripping the threads.

See Figure 9 for typical applications.

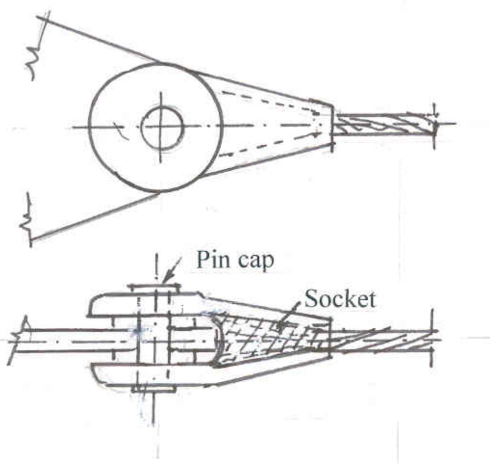

Figure 9a – Forged Socket

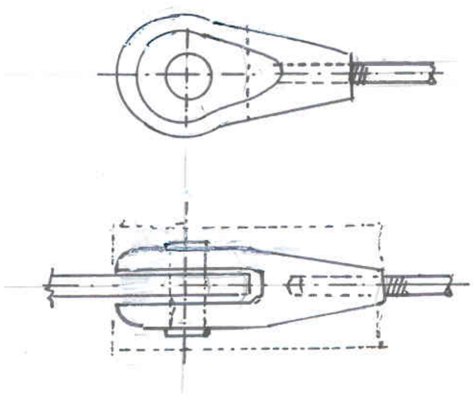

Figure 9b – Milled Socket

Figure 9 – Forked Ends (sockets)

Larger diameter cables are often made of high strength wires (strands) individually anchored into the sockets. BBR manufacturers terminate the wires (5mm dia) into a button like upset ends that react against a thick perforated high strength plate. VSL use wedges to each cable strand.

Engineers have succeeded to make the sockets out of fabricated high strength steel plates by use of welding. This was achieved with varying degree of success as far as appearance is concerned.

Rigging screws

Rigging screws, are in fact cylindrical/prismatic tubes with internal threads of opposing directions. The rod/cable tendons are terminated with rolled threads at either end of the turnbuckle to be screwed. Turning the rigging screw brings the rods into tension, see Fig. 10. It needs to be remembered that rigging screws can not always be used to achieve the desired level of prestress in the cable due to the very high torque required. In such situations other means often involving hydraulic jacks need to be employed to tension cables.

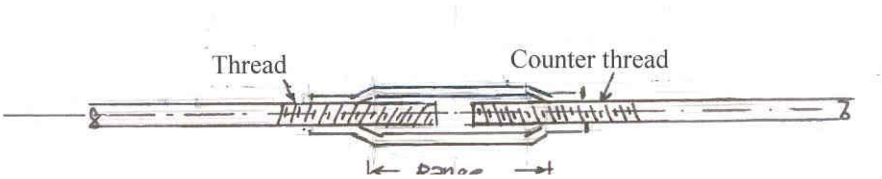

Figure 10 – Rigging Screw

Cable *clamps*

Cable clamps are used when a transfer of force need to occur between two intersecting cables or between the main catenary and the secondary cables (Fig. 11). Cable clamps work on the principle of friction grip bolts.

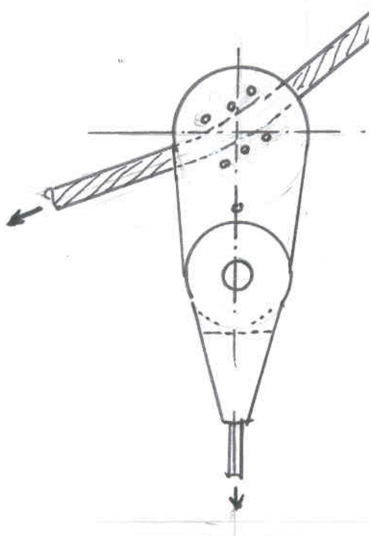
Figure 11a – Cable Clamp

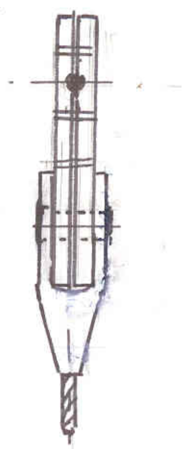
Figure 11b – Section A

Cable deflectors

The main use of cable deflectors is to support the cable over the curved length. To minimise local bending the radius of curvature of cables are often limited to 10 diameters or more. Thus the deflectors can be quite long, (see Fig 12).

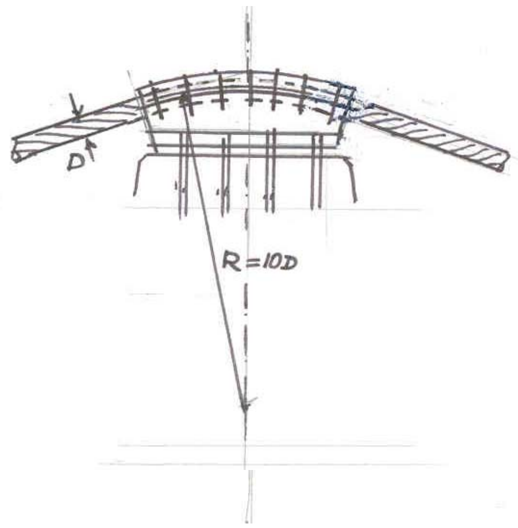

Figure 12 – Cable Deflector

Pin connections

The principal use of pin connections occurs in members that are intended to undergo occasional rotations at their ends. Pin connections are found in bow string girders, mast stays, mast hangers and a wide variety of other applications. The simplest form of pin connectors is where rotation occurs in the principal plane that is in a plane at the right angle to the pin axis (one degree of freedom).

Another type of pin connector offers two degrees of freedom, that is the ends of the member can rotate both in the principal plane and in a plane perpendicular to it. The second direction of rotation is usually restricted to about 2 degree. This is achieved by introduction of a radial / spherical bearing slipped over the pin. Figure 13 shows both types. The proportioning of the pin plates (eye plates) for connections subject to tensile forces is strictly governed by the steel design standards.

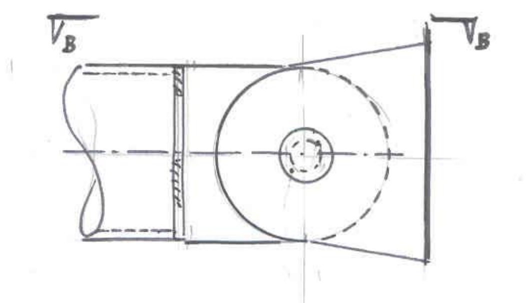

Figure 13a – Double Eye Plate

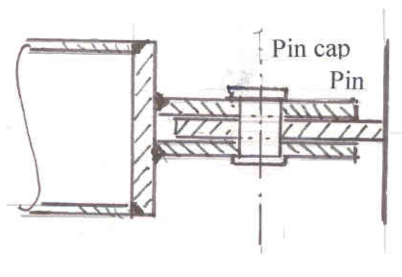

Figure 13b – Section B-B

Many pin connections are used to transmit end reaction of the member; thus they are working in shear. This means that the edge distances are not only needed at the ends of pin plates but also at right angles. Figures 14 shows an arrangement where the eye plate is circular rather than elongated as in the standard pin connection. For simplicity, all eye plates can be made three quarter round to achieve some standardisation. The governing dimensions are given in Fig.14.

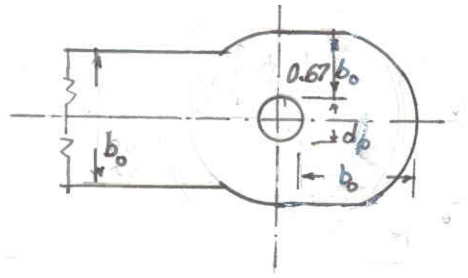

Figure 14a - Configuration when axial load is applied

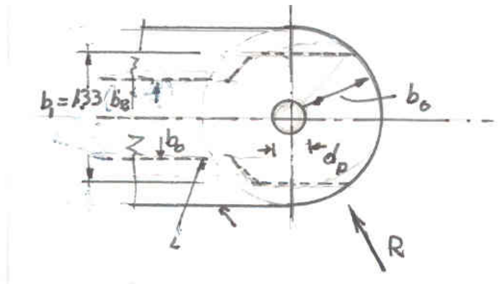

Figure 14 b -Configuration when shear is applied

Figure 14 – Pin Plates

Where two degrees of freedom of rotation must be catered for use, can be made of a Radial/spherical bearing, often employed in mechanical engineering. Fig. 15 shows the pin connection for two-way rotation.

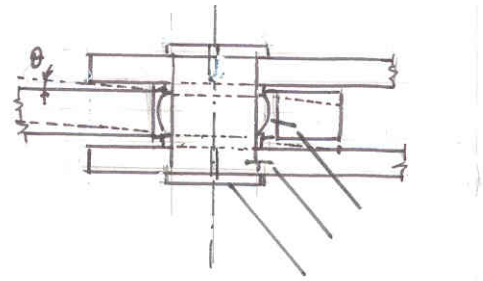

Figure 15 – Radial/spherical Bearing

Lubrication and corrosion protection of pin hardware is of particular importance. In the ideal world the pins should be lubricated periodically but this rarely happens in practice. The best one can hope is to apply the initial lubrication with good quality of very viscous grease. To avoid excessive abrasion, the bearing stresses on pin should be limited to 0.75 f_y, which will prevent “cold welding”.

Spherical bearings are also used to support guyed masts that by necessity rotate in two directions depending on the elongation of the cables under changing loads. Large radial spherical bearings can be used although full spherical bearings are commonly used.

Space Truss Nodes

Multi directional nodes are required to connect three way trusses and their web members. The nodes are usually universal to fit anywhere in a whole roof so they can be mass-produced and fully tested. MERO nodes (Fig. 16) are the most appealing of the systems because of their aesthetic design.

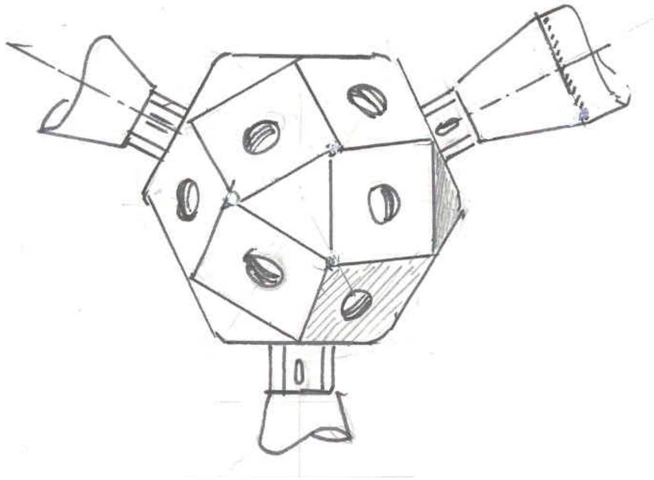

Figure 16 – Nodes for Space Trusses – MERO Type

Prefabricated nodes for diagrid structures

These nodes permit field joining the tubular diagrid members. Up to six members are connected to one node. The nodes can be prefabricated by welding or they can be cast in high strength steel. Field joining may be by welding or by bolting using hidden bolts to avoid criticism of industrial looking joints. Figure 17 shows typical diagrid connections.

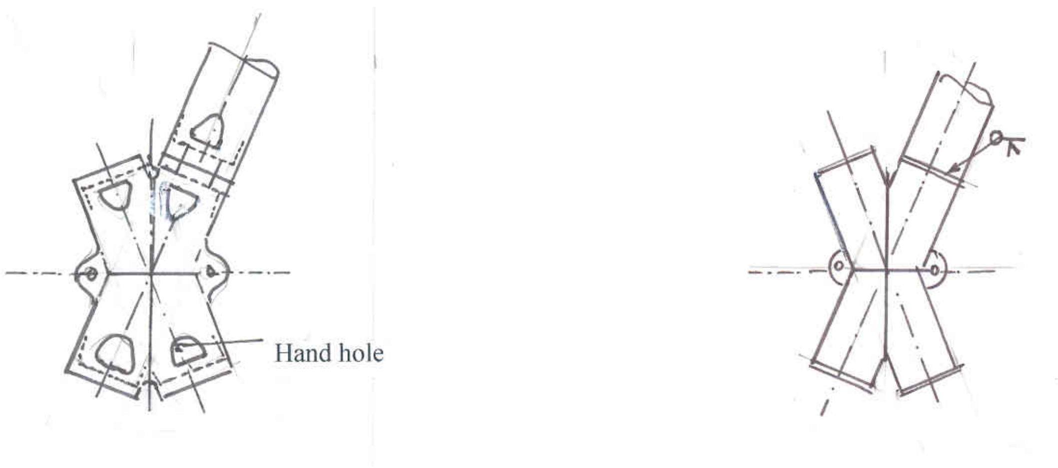

Figure 17 – Barrel Vault Nodes

Gussets and mastheads

Even the humble gusset does not escape the scrutiny by the architectural team. Gussets are also subject to connections verification by the engineer to achieve enhanced reliability. Mastheads are just another variant of large gussets that are highly stressed by large forces from incoming cables.

Stress analysis and testing of connections

Connection details are often left to be done last. This results in an insufficient time available for full analysis and verification of the connections. In the authors' opinion most collapses and service troubles stem from poor connection design and detailing and fabrication.

Verification of connection performance is in form of stress analyses ranging from hand routines all the way to finite element modelling procedures (Fig. 18).

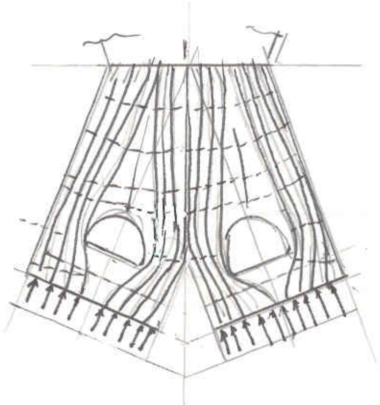

Figure 18 – Stress Trajectories

Testing of highly repetitive connections and highly stressed connections is often a necessity. Otherwise these parts may have to be overdesigned leading to unattractive designs.

CONCLUSION

In designing connection details and connection hardware needs a form and the effort from architect and the engineer. The final result will be a proof of how successful this effort has been. A lot of training goes into this effort but it is all worthwhile in achievement of an outstanding project.