Lightweight Glazing Systems and Applications

T.G.A. Carfrae MA MIEAust MIStructE
Director, Ove Arup and Partners

1. SUMMARY

This paper addresses some of the issues associated with lightweight glazing support structures. It starts by considering glass as a material and then possible methods of supporting it. Two aspects of supporting structures are reviewed: the use of glazing adapters; and cable trusses.

These initial remarks are then illustrated with four recent examples of glazed structures designed by Ove Arup & Partners:

- Cite des Sciences et de L'industrie, La Villette, Paris.
  Three giant glazed conservatories using patch fittings and horizontal cable trusses. The patch fittings include spherical bearings and there is no vertical support other than the glass itself.
- Foyer Roof, Governor Phillip Tower, Sydney.
  Stainless steel cable trusses supporting sealed double glazed units via aluminium extrusions that give four–sided support to the glass
- Western Morning News, Plymouth.
  Large doubly curved glass wall using a stiff structure supporting glass with conventional patch fittings
- Munich Airport Centre, Munich.
  Enormous glass and fabric roof using two side supported glass spanning between glazing adapters continuously attached to supporting steelwork. Large units are pre– glazed before lifting into place.

2. MATERIAL

Glass is a strong but not a tough material. That is, while having a high tensile strength it has no effective plasticity. A consequence of this is that any design that wishes to make effective use of its great strength must be very determinate. That is the glass stresses must be accurately known or predicted as an overstress will be disastrous. This is in stark contrast to our more commonly used materials steel and reinforced concrete.

A further issue is the problem of notches and stress concentrations. As the material is brittle, any connection to the glazing support structure must be very soft to prevent a stress concentration that will result in shattered panes of glass.

We commonly use three different strengths of glass: annealed, heat strengthened and toughened. These may either be as single panes or laminated in any combination into composite panes. Further they may be sealed together to form double glazed units. Unfortunately, toughened glass (the strongest variety) has a question mark against it now due to the possibility of nickel sulfide inclusions which lead to spontaneous shattering after a time. Laminated glass, which is normally specified for overhead glazing, also suffers owing to a lack of knowledge of the way the two layers interact through the laminate. This interaction is both time and temperature dependant. Currently the best reference document is the Canadian Code of Practice.

3. GLASS SUPPORT

Glass is usually supported on either two or four sides. It may also be supported by point or patch supports in the four corners with or without additional support points along the sides. The support may be provided either by a mechanical system or the use of some kind of glue such as silicone rubber. Structural Glazing is the term commonly used where silicone is the sole means of support.

Structural glazing is a questionable practice. There are normally many interfaces between the glass and the supporting structure that require full adhesion over the life of the glazing. These may include aluminium to powder coating, powder coating to silicone, silicone to glass treatment layer and glass treatment layer to glass. Obviously the silicone layer will perform better if applied in the shop; indeed it is not uncommon for it to be omitted entirely if applied in the field.

Because glass has a low modulus of elasticity compared with its tensile strength, thin glass panes deflect a lot. This leads to a distinct advantage of four–sided support over two–sided support. The support on all four sides allows the pane to deflect into a dome like shape. Membrane action then comes into play with tensile stresses in a radial direction and compressive ones in the hoop direction. This action can only by properly predicted using nonlinear structural analysis incorporating the stiffness of the supporting members as well as the glass itself. However, the benefits are quite substantial, four–sided support glass is typically half the thickness of two–sided support.

Obviously, the worst case is glass supported in the corners only. This is exasperated if the patch fittings restrain the glass from rotating and put the corners into reverse curvature under wind load. There is then a strong tendency to snap the corners off, especially when the glass deformations are added to those of the supporting structure. The supporting structure must be very stiff for this kind of fitting to perform satisfactorily.

4. STRUCTURAL SUPPORT

The methods of providing structural support to glazing are legion. However there are two aspects of structural supporting systems that I wish to address here.

4.1. Aluminium Glazing Adapters

Considerable economy can be achieved if instead of using aluminium mullions, small aluminium extrusions are fixed continuously to steel sections that are not only mullions but also act as part of the main structural system. This kind of arrangement is used in the MAC roof design described in section 5.4.

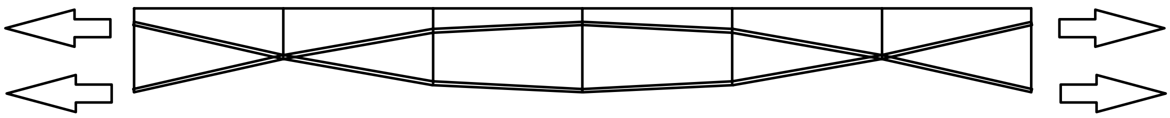
4.2. Cable Trusses

Cable trusses are very delicate and form an elegant way of spanning a hole that is to be covered with glass without unduly detracting from the translucency of the completed roof or wall. Their use is described in sections 5.1 La Villette and 5.2 GPT Foyer.

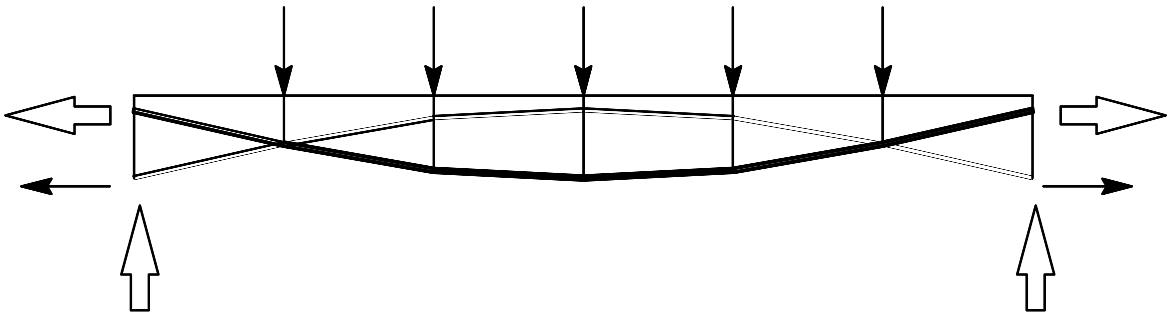
A cable truss is one where two tensile elements are formed into curves opposing one another. The plane that they support may be on one side or the other, or even between the cables or rods. The opposing cables carry the load applied to the glass according to its direction with one cable carrying suction loads and the other pressures. They do not usually have diagonal web members and can therefore only handle uniform loads with ease. A point or out of balance load requires the cables to deflect enormously before the cable shape becomes funicular to the applied load. Furthermore the truss has no resisting stiffness until it has so deflected.

By prestressing the cables, one against the other, the structural performance of a cable truss can be dramatically improved. Under uniform loads the truss now has twice the stiffness. More importantly, the deformation under out of balance loads is considerably reduced as the pretension in the cables gives instant stiffness. However, the pretension must be sufficient to create a large stress in the rod or cable. Otherwise the tension will vanish when the truss undergoes either a rise in temperature or a movement of its boundary conditions. This is why high strength cables or rods are preferred to ordinary mild steel.

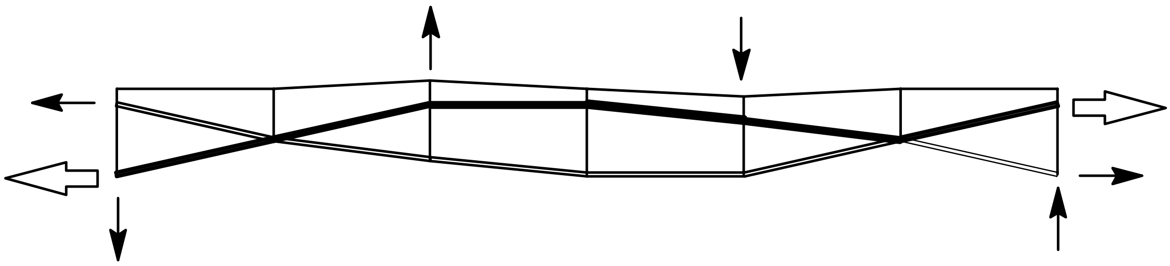
The disadvantage of a cable truss is the large pull it exerts on its anchorages. This force is typically ten times larger than the load applied to the supported glass. As described above, these anchorages must also be very stiff. There is a temptation to merely strut between the two ends of the truss apart but that would question the use of such a truss in the first place.



Cable truss showing prestress



Cable truss with uniform load



Cable truss with out of balance load

5. APPLICATIONS

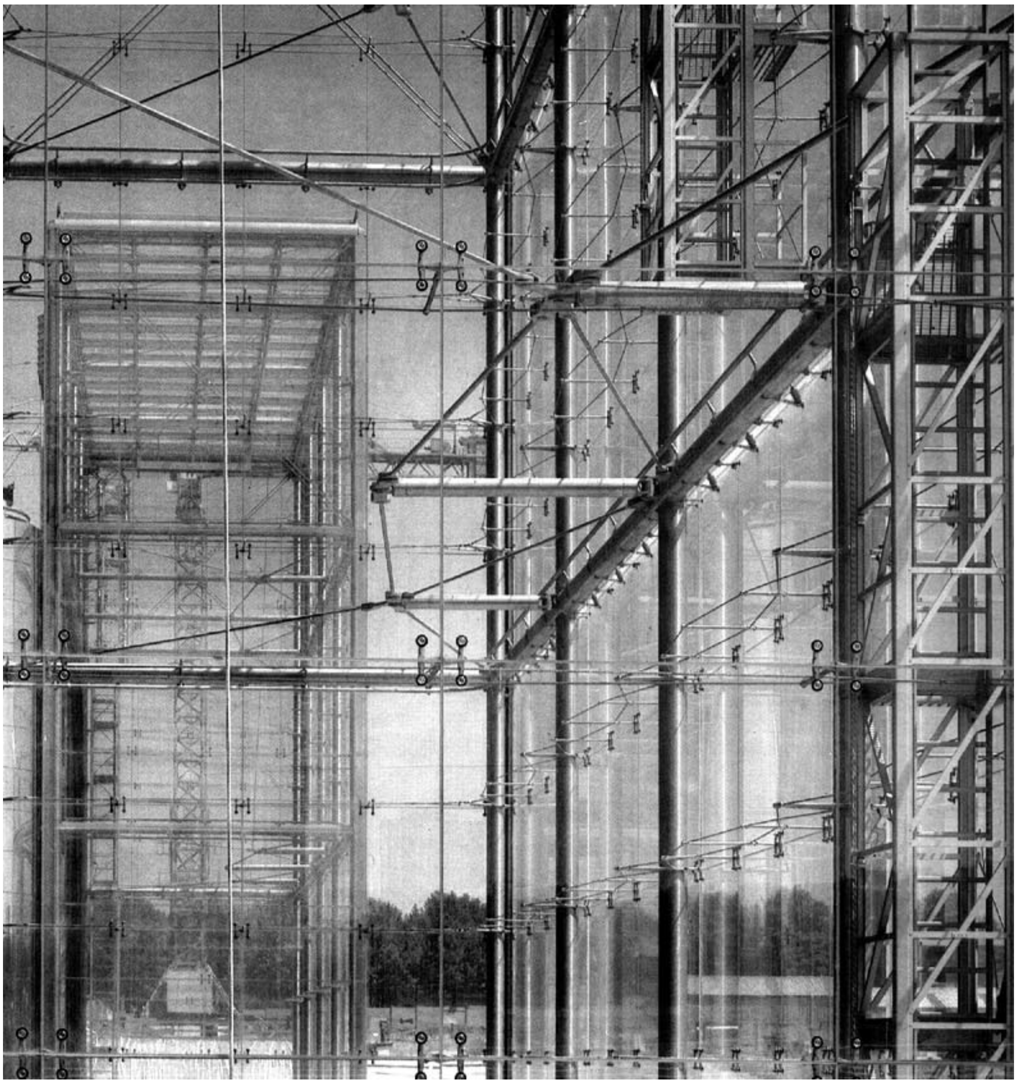
5.1. Cite des Sciences et de L'industrie, La Villette, Paris

The glass boxes at La Villette are like three giant conservatories each measuring 32m high by 32m wide by 8m deep. Each box is made up of 32 panels of glazing measuring 8m by 8m each comprising 16 panes of 2m square glass. The panes are of 12mm thick clear toughened float glass and are interconnected by patch fittings at each corner. There are no glazing bars and the panes are sealed using silicone that is not required to act structurally. Lateral support is provided by three horizontal cable trusses and there is no vertical structure within a panel other than the glass itself.

The connection between four panes of glass and the supporting cable truss comprises a stainless steel H bracket with four patch fittings. These fittings were developed specifically for the project and incorporate a spherical bearing within the thickness of the glass. This prevents the corner of the glass from being bent back and also allows the whole panel to deform significantly under wind load thus allowing the use of a flexible support structure.

One problem with manufacture of the glass was the shape of the countersunk holes. The two parts of the hole which had to be drilled from each side of the glass were invariably slightly misaligned. The result was a slight lip around the inside of the hole at mid–thickness. As the upper panes were supporting three panes below the force transmitted to the inserted fitting was quite high. A piece of annealed aluminium was chosen as a lining material which was sufficiently strong to transmit the force while being soft enough to prevent a stress concentration within the glass.

The weight of each pane is hung directly from the one above via the H bracket. At the top of a column of four panes, the glass is supported by the steel superstructure. This connection includes a spring that prevents a shock load that might otherwise occur should a pane be accidentally broken. If the spring were not present, the breakage of one pane might result in the progressive collapse of a whole panel.



View through conservatory

The resulting system achieves a quite unparalleled degree of transparency which is wholly appropriate to the facade of a museum of science and technology. Indeed the components of the glazing system are on display within the museum itself.

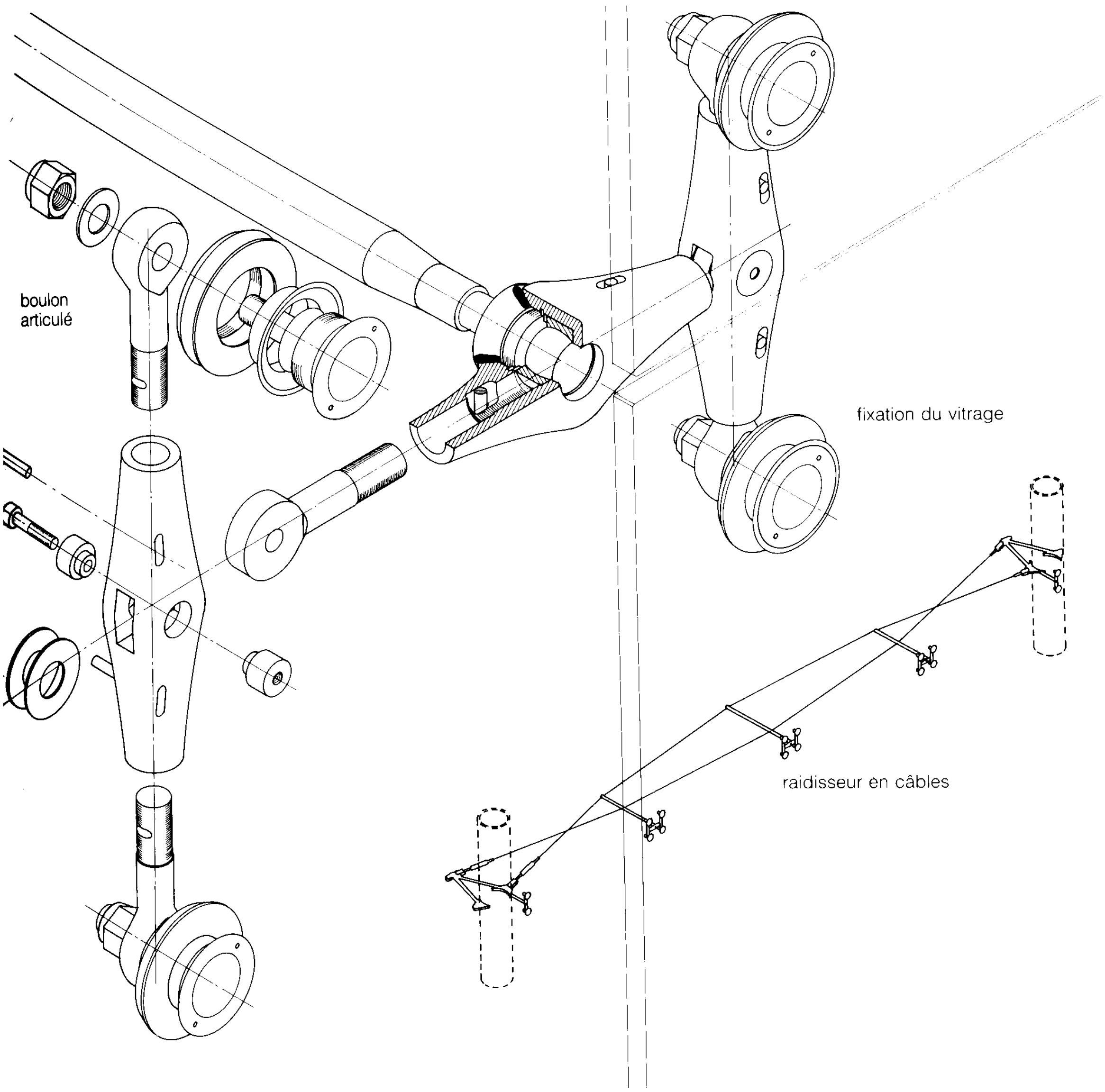


Diagram of H bracket and patch fixing

5.2. Foyer Roof, Governor Phillip Tower, Sydney

The roof over the foyer at Governor Phillip Tower (architect Denton Corker Marshall) also comprises cable trusses. These were an economical way of spanning the 12m wide space as massive anchoring structures were available on both sides of the foyer. On one side was the 750mm thick reinforced concrete core wall and on the other was a 600mm square steel box section stabilising the main columns.

The cable trusses are made of grade 450 duplex stainless steel rods connected by stainless steel investment castings into which each rod is threaded. Stainless steel tubes space the rods apart and support the glazing above via another investment casting.

The glazing panes are 2m square and are sealed double glazed units. These units allowed us to design a compact aluminium extrusion that mechanically captures the unit on all four sides. This provides positive four–sided support and leaves the top surface completely smooth for good drainage. The glass is therefore used very efficiently and is more cost effective than a patch supported single sheet of glass. Furthermore the extrusion conceals the sprinkler pipes that would otherwise be larger than the supporting structure.

Each of the three 12m by 12m roof panels was preassembled and glazed at ground level on a specially designed lifting jig. The roof was then winched into position and the cable trusses stressed back to their anchorages before allowing the jig to be lowered to the floor for reuse.

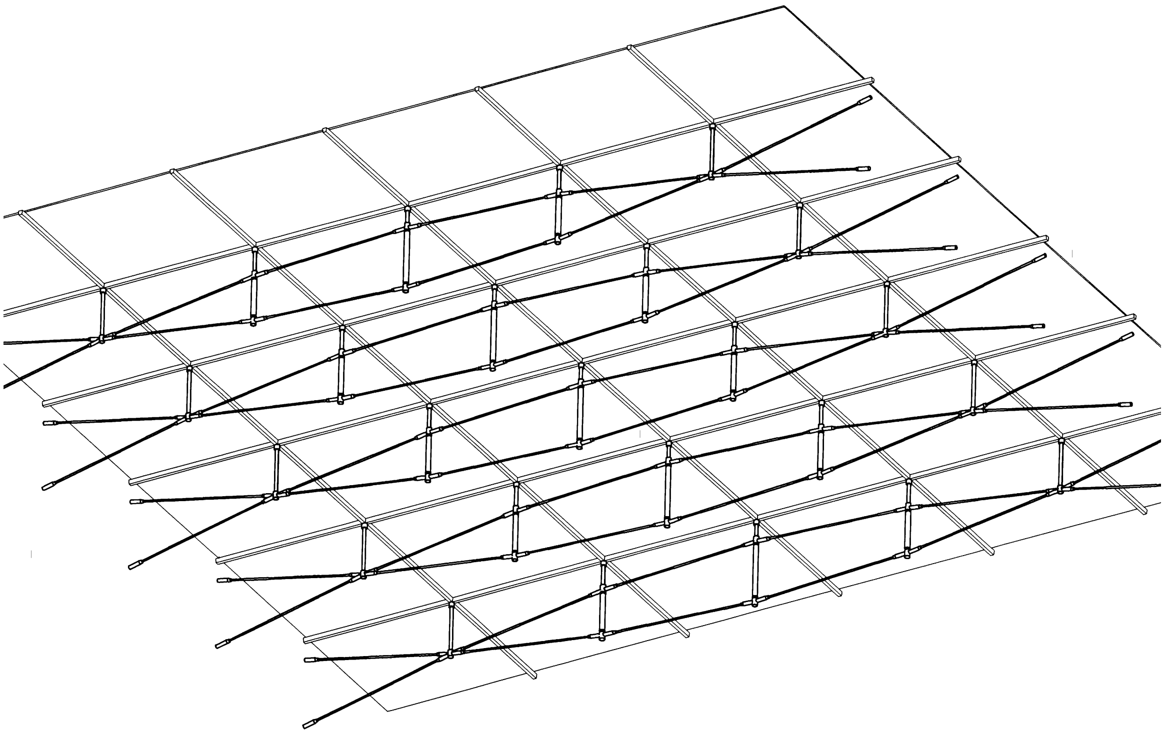


Diagram of one roof panel

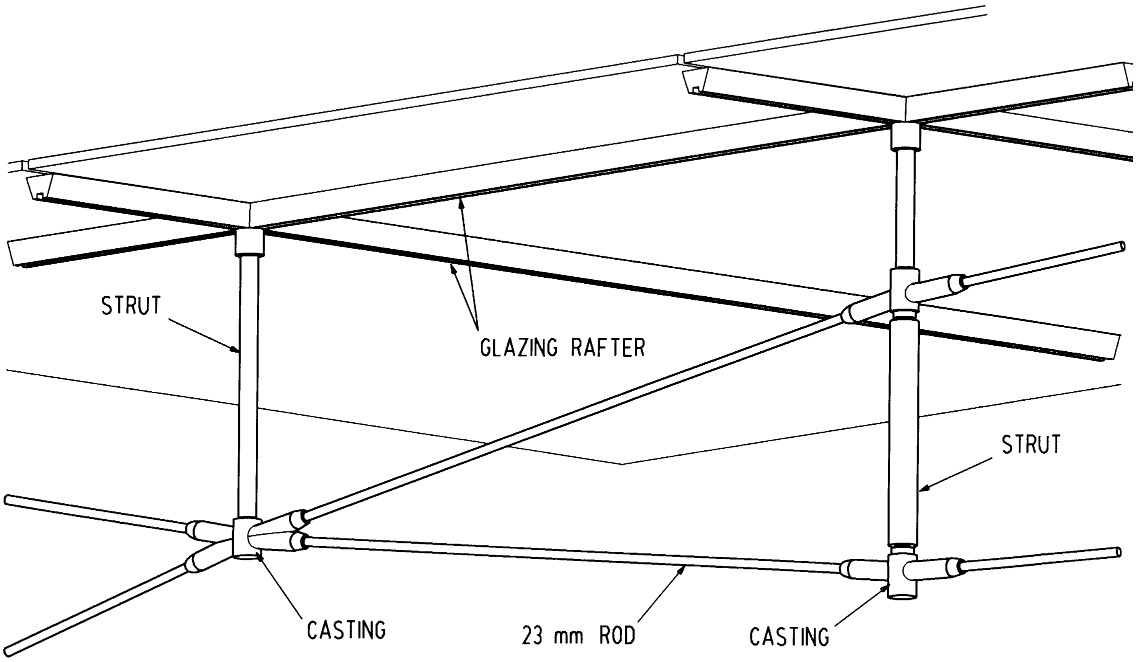


Illustration of glazing components

5.3. Western Morning News, Plymouth

The Boat as it is affectionately called, houses a printing press and was designed by architect Nicholas Grimshaw. The skin of the building comprises over 650 panes of about 2m square glass set in a toroidal geometry that gives each pane at a given level identical dimensions (except at the prow). The panes are supported using Pilkington Planar patch fittings in each corner.

The patch fittings are gathered together by a lost wax cast, stainless steel, cruciform bracket. Vertical support to the bracket is provided by stainless steel rods that carry the dead load of the glass. Lateral support is provided by cast ductile iron trusses which cantilever from the massive steel tusks that line the outside of the building. The hollow tusks also support the roof of the building and eventually the stainless rods from which the glazing is hung. This supporting structure is sufficiently stiff to allow the use of a simple patch fitting without requiring an embedded bearing.

The concave wall shape allows people to look into the building with the minimum of distracting reflections and to marvel at the giant press inside.

View of building

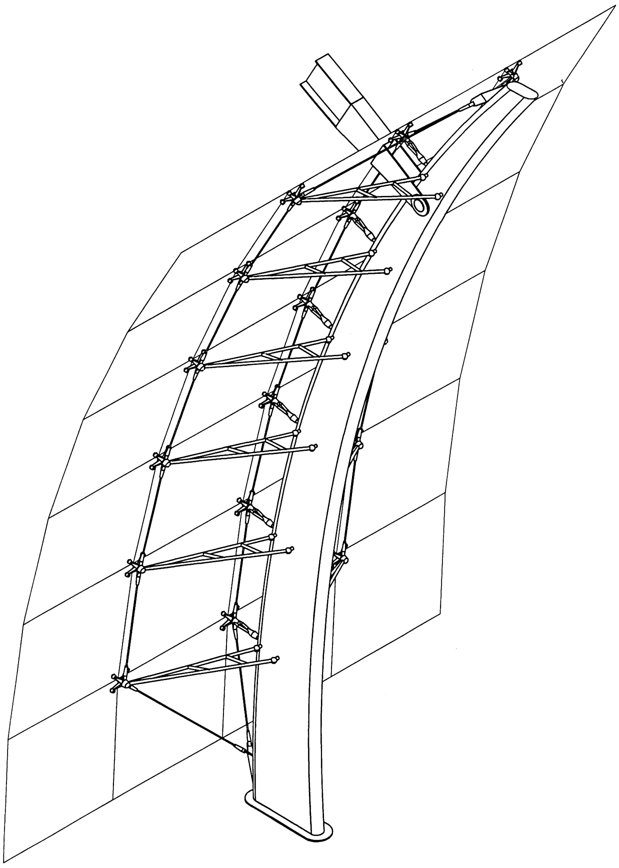


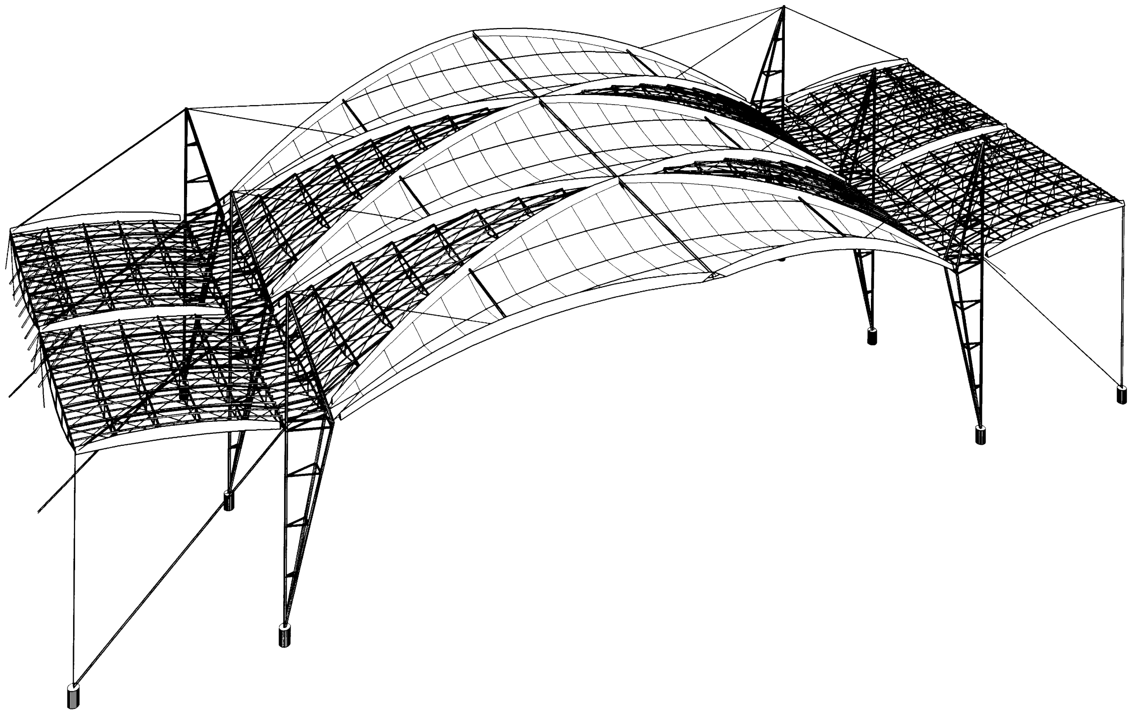
Diagram of one tusk and associated glazing

5.4. Munich Airport Centre, Munich

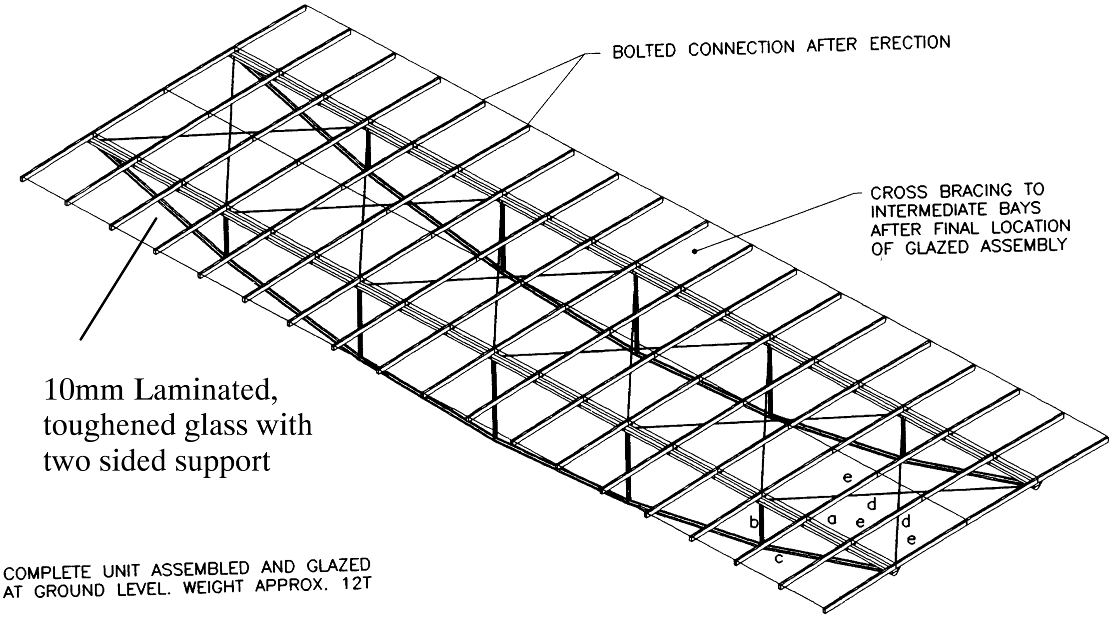
This enormous glass and fabric roof over a courtyard between commercial office buildings in Munich is currently out to tender. The phase one roof measures 130m wide by 150m long with a further 100m in length planned for phase two. The architect is Helmut Jahn, Chicago but the engineering has been carried out by Arup in Sydney.

The glazed part of the roof comprises two different circular vaults that descend into a common 4m wide glazed gutter. The panes are 1.35m wide by 2m long, 12mm thick toughened laminated glass, and span laterally between glazing adapters on two sides. The aluminium glazing adapters are continuously supported by steel rectangular hollow sections which from part of the roof bracing system as well as stabilising the plane trusses below.

The plane bowstring trusses span up to 25m between triangular box sections. When the bottom chord is in compression due to uplift, the vertical web members cantilever down from the steel mullions and prevent the chord from buckling. This allows a deceptively light member to be used as the bottom chord. As with a cable truss, these trusses live without the benefit of diagonal web members. However in this case it is the top chord member in bending which copes with the out of balance loads. The top chord being next to the glass plane can afford to be a bit bigger visually. It also acts as a principal strut within the roof bracing system. The overall effect is to produce a deceptively light looking support structure.



View of two bays of roof



One glazing panel

The bowstring trusses are to be assembled in pairs on the ground with the steel mullions spanning between them and cantilevering halfway towards the adjacent trusses. This unit is then cross braced and pre–glazed before being lifted as a complete 25m by 8m glazed panel up to the supporting structure where only four simple pin connections need to be made. Afterwards the tips of the mullions are interconnected at mid span and the remainder of the rod bracing installed from below.

This roof forms part of a commercial development and would only be successful if its cost was minimised. The items that most affect the cost of large areas of glazing, are the size and thickness of the glass panes and the labour content of installation.