Materials and components

Autor(en): **Happold, E.**

Objekttyp: **Article**

Zeitschrift: **IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen**

Band (Jahr): **36 (1981)**

PDF erstellt am: **13.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-28277

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Materials and components

Matériaux et éléments de construction

Materialien und Teilkomponenten

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SUMMARY
There have been immense advantages in the last few years in the engineering materials available which have given new design possibilities. Yet all structures are formed of a system of components. It is from the choice and combination of components with different characteristics together with the performance of the connections, which determines the efficiency of the structure.

RESUME
D'immenses progrès ont été réalisés ces dernières années dans les matériaux de construction, qui ont ouvert de nouvelles possibilités dans la conception et le projet. Toute structure est formée d'un système d'éléments de construction. Le choix et la combinaison des éléments de caractéristiques différentes, combinés avec la résistance des assemblages, déterminent l'efficacité de la structure.

ZUSAMMENFASSUNG
Dank der grossen Fortschritte der letzten Jahre auf dem Gebiet der Baumaterialien haben sich neue Entwurfsmöglichkeiten ergenben. Alle Tragwerke bestehen aus einem System von Bauteilen. Die Tauglichkeit eines Tragwerks wird durch die Wahl und die Kombination dieser aus verschiedenen Materialien bestehenden Bauteile sowie die Ausführung deren Verbindungen erreicht.

MATERIALS AND COMPONENTS

A structure has been defined as 'a fabric or framework of material parts put together' and structural engineering as 'the organisation of the path of physical forces in space to enable moderation of the environment'. As well as redirecting external forces, structures often themselves contain and enclose gases, solids or liquids at different pressure densities, temperature or states other than the medium in which the structure itself is located. Such structures are made up of components, defined as 'constituent parts', connected by joints which are defined as 'whereby two members or parts of an artificial structure are joined or fitted together either so as to be rigidly fixed or in a hinge or pivot or swivel' (1).

Broadly the requirements on the designer of the materials and joints of a structure are that they should not allow excessive deformation, have a reasonable maintenance free life, retain adequate strength in a fire, provide adequate imperviousness, insulation, transparency and so on as required and are also cheap to manufacture, assemble and erect.

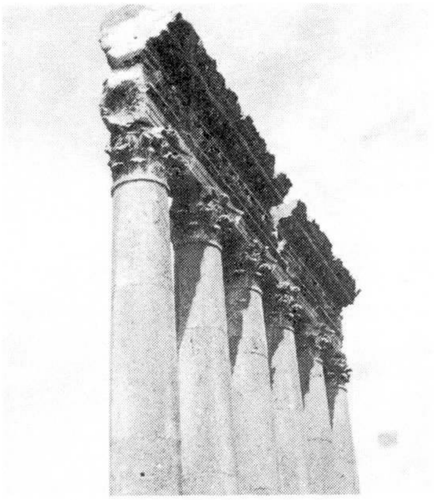

Fig 1 Beam and Post Baalbeck

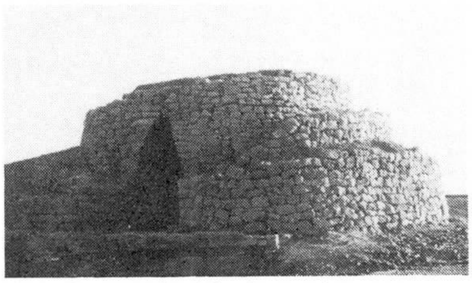

Fig 2 Corbelled arch

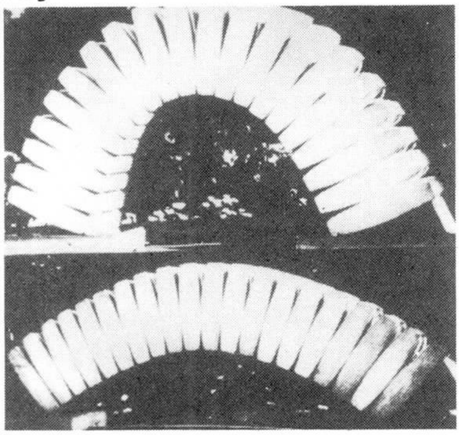

Fig 3 Voussoir arch

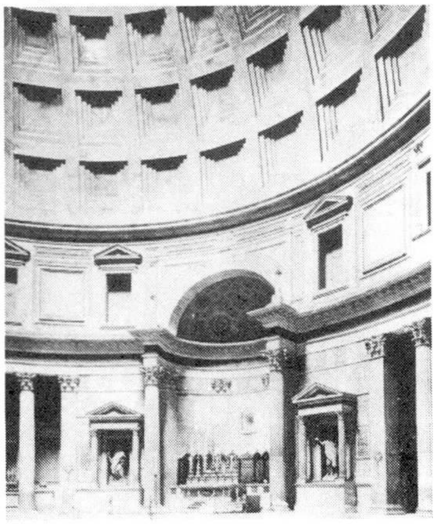

Fig 4 The Pantheon

HISTORY:

The traditional range of structures grew up because people had to build with available materials; stone, timber, bricks etc. What was successful became documented in codes of practice and continued to be repeated.

Reliable tension materials did not last so all major structures were compression structures. The earliest beam and post solutions were in stone or timber, the size determined by what people could work with handtools or lift with their techniques. But the joints cracked, even the stone often cracked, and often enough courses in any wall had to be provided so that arch action could be sustained anyway. Long spans were achieved by arches, either the corbelled arch - building out stepwise from either side - or in the arch made of 'voussoirs'. The advantage of the voussoir arch especially was that it could be made using relatively small stones or bricks and the joints really only needed these gaps filling since the structure was purely in compression. However for large spans the weight of the arch became important so such structures as the Pantheon, built by Hadrian in AD120, was coffered and that of Hagia Sophia, built about AD532, was made of pumice to save weight.

In mediaeval times there was the same limited range of materials: stone and brick, strong in compression but limited in size and difficult to joint in tension. It is not surprising that the timber frame, with wattle or brick infill, dominated the domestic scale of building and the arch and dome the design of large buildings. The geometrical difficulty of bringing the round dome or arch to a rectangular plan became the problem which produced a whole series of architectural styles.

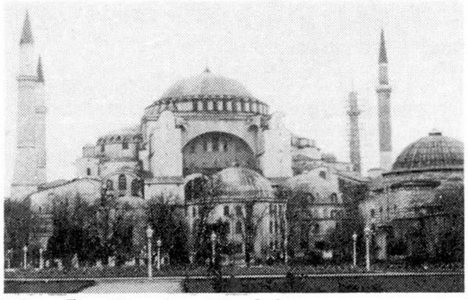
Fig 5 Hagia Sophia

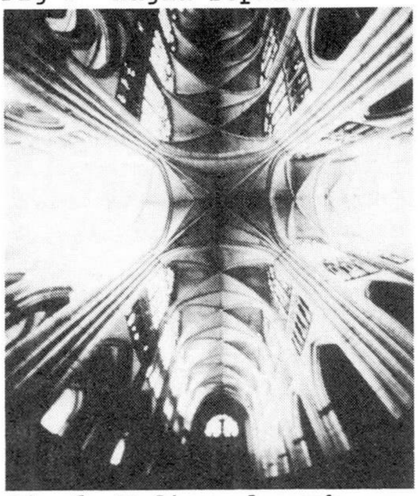
Fig 6 Mediaeval arch

The advances in the eighteenth century in iron and steel production led to the great innovation in structures. The first iron bridge was erected at Coalbrookdale in 1779 and within a very few years larger beam spans and suspension bridge structures were being built. Because the components were factory made, wrought or cast iron members pinned or bolted together, repitition was desirable, quality control became important and the systemisation of the building process developed. Thus for the Crystal Palace in Hyde Park for the Great Exhibition of 1851 the iron columns and beams were cast in Smethwick, transported to Euston Station by railway and from there to the site by pair horse wagons. Each beam, as it was removed by crane from the cart, was placed first on a weighing machine to check the class of load it was to take and then moved to an arrangement of Bramah hydraulic rams for strength testing before being erected. It was not uncommon for an entirely stable 'square' of columns and beams to be erected and bolted in twenty minutes. The glazing, guttering and woodwork was all mass produced. Even the vertical posts and horizontal planks of the hoarding round the site were chosen so that they could later be used to make the joists and floorboards of the finished building. In twenty two weeks a building of enclosed volume 33,000,000 cu ft was erected, in another sixteen it was fitted out and painted (2).

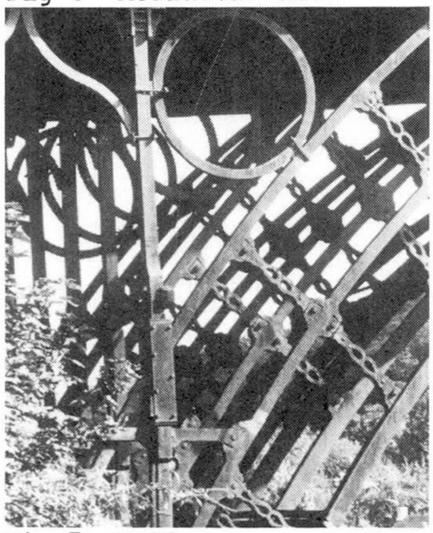
Fig 7 Bridge at Coalbrookdale

The engineers leapt to use this new material because of its strength/weight ratio, its ability to take tension and perhaps also because it was easier to predict performance. Certainly Victorian engineers arrived at minimum material structures because they saw them as having only to satisfy strength criteria .... hence the beautiful open trusses; an aesthetic which still moves us. As James Marston Fitch has said 'the three triumphs of the nineteenth century were the

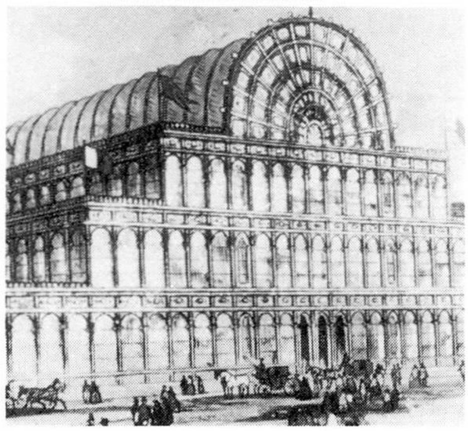
Fig 8 Crystal Palace

enclosure of great areas in the Crystal Palace, the spanning of great voids in the Brooklyn Bridge and the reaching of great heights in the Eiffel Tower' (3).

So started a concept of structure as frameworks of struts, ties and beams reflecting the forces induced by an assumed worst loading condition, usually treated as static loads. The materials characteristics looked for were strength in compression and tension and materials were regarded as Hookian with a linear stress-strain relationship. Engineers, since achievement was the measure of success, tested either physical models or the actual structures, for example William Fairbairn tested different possible sections for Robert Stephenson in the design of the Menai Tube Bridge (4). With cast and wrought iron there was a strong tendency for pinned joints. There was great sense in this approach because it caused the actual structure to 'perform' fairly closely to the 'model' which was analysed. As the use of structural steel developed, full or partial fixity at joints became assumed but inaccuracies in analysis were tolerated because joints were rivetted, over-loaded joints usually yielded plastically and erection connecting techniques such as reaming punched holes before bolting prevented crack propagation.

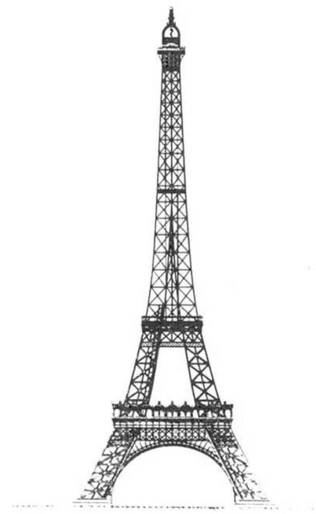

Fig 9 Eiffel Tower

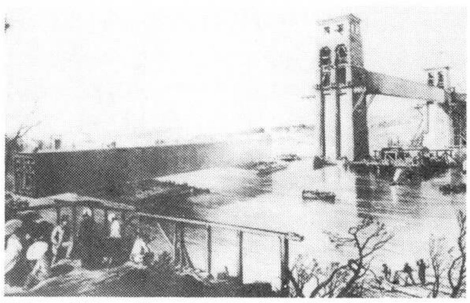

Fig 10 Menai Tube Bridge

As problems other than strength were exposed by time engineers views of how to use materials became confused. For example corrosion, especially of mild steel, became a problem and the painting of their lattice frames was difficult. So designers started to use tube members which were seen as the 'true' expression of steel in structures - but with the consequent difficulty of jointing and tolerancing.

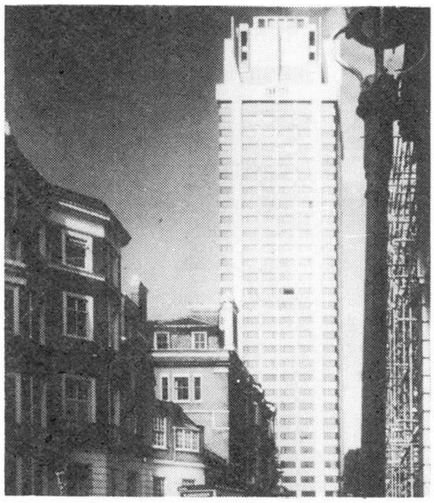

Fig 11 Knightsbridge Tower London

BENDING STRUCTURES:

Solid beams or cantilevers in terms of use of materials are ineffective but materials availability and functional reasons induce their use. Architectural planning, not pure statistical reasoning, often defines the nature of framed structures. For example a housing tower in London has its vertical support and wind resisting components, the walls which provide fire and sound insulation between the apartments constructed and reinforced concrete because of cheapness and availability. The floors can be given flat soffits because the climate only requires heating and radiant gain is never great and so a servicing void is not

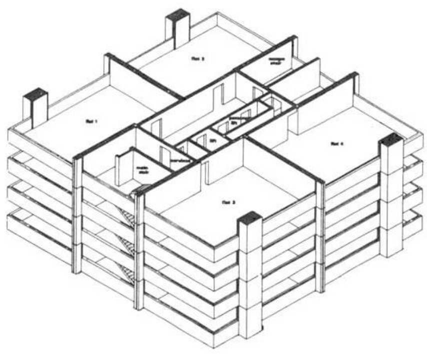

Fig 12 Knightsbridge Tower London

needed. Materials effectiveness in terms of the volume of concrete per floor (inclusive of all supports) is equivalent to a 14" thick slab overall. However reinforced concrete is slow to set and therefore to use but appropriate to the economics of the UK construction industry. In essence such a structure does not have joints as the reinforced concrete is continuous, lowly stressed and tolerant. Structural steel however has a very efficient strength to weight ratio and structures made of it ask more of their joints. Comparatively in Chicago where the climate, both literally and financially, is entirely different, the braced tubes of Skidmore, Owings and Merrill are a much more defined structural answer. Criteria for the structure is still rigidity and the joints are also relatively lowly stressed.

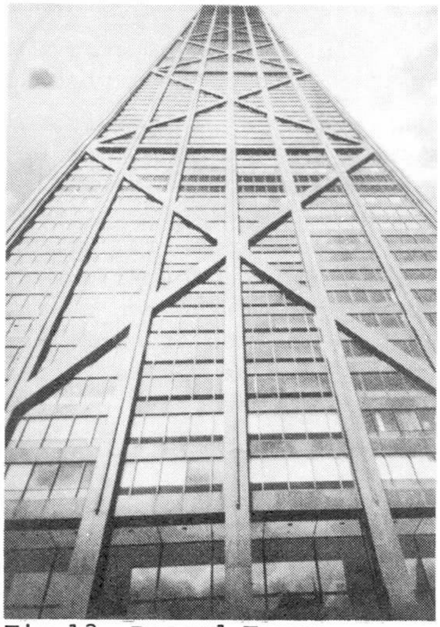

Fig 13 Braced Tower Chicago

However, whether in steel or concrete, it is the relative ease of making such joints which is the designer's constructional problem. The old rivetted joint had great structural advantages. The holes acted as crack stoppers and any tendency to stress raising was reduced by reaming. Such joints were easy to inspect and relatively easily distorted if over-stressed. However the heating, hammering and handling of rivets was expensive and time consuming and they are unlikely to be seen again.

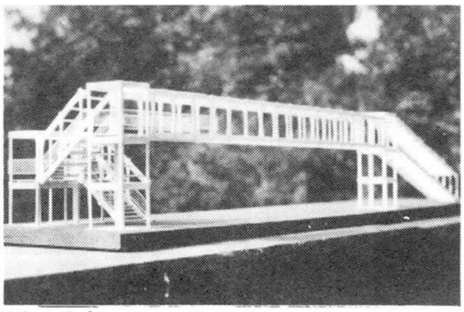

Fig 14 Footbridge in West Germany

The welded joint has now largely taken over and is relatively easily checked for adequacies though its requirements for precise dimensioning, lack of forgiveness to constructional errors, susceptibility to crack propagation and the risk of crystalline embrittlement due to metallic changes resulting from greater energy imput than assumed in the specified design, are all to offset greater joint efficiency. Site connections on framed structures can now be carried out with friction grip bolts which hold the two members together in such a way that it is the friction between them which provides the moment or shear resistance required. One of the advantages of this type of joint is that if overloaded it can be allowed to slip thereby shedding load and reducing the stress and then regaining its load capacity. Such joints can not only be used for traditional beam connections but also to standardise connections between members joining at different angles, such as in a design for a steel footbridge for West Germany or double lattice shell for the Mannheim Bundesgartenschau to allow movement during erection before being clamped tight in the constructed state (5). The author has been involved in studies of structures in brittle materials such as glass in which risk of catastrophic failure was eliminated by the

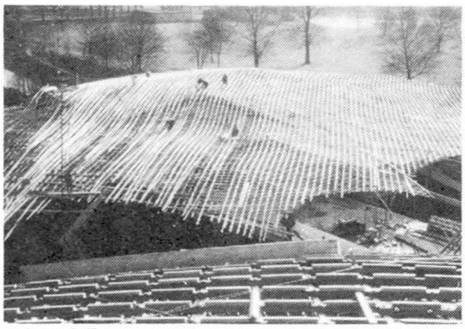

Fig 15 Mannheim Lattice shell

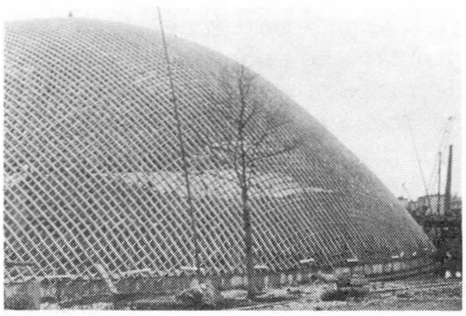

Fig 16 Mannheim Lattice Shell

provision of plasticity by the use of friction grip joints which could reduce load by angular rotation should the members become overloaded.

As the scale of construction increases, such as in bridges, when thermal and rotational movements are considerable and jointing is complex and expensive, the provision of joints with a predictable performance has increasing attraction for the engineers. In the building field the joints are more lightly loaded and the use of inexpensive bearings such as neoprene pads allow attractive expression of forces and resolution of thermal movement problems.

SKELETAL STRUCTURES IN COMPRESSION AND TENSION:

The discussion so far has concentrated on the constructional aspects of framed members and joints. However there is a tendency, probably an increasing one, in a world of diminishing resources, that the cost of any structure is reflected by its own weight so that of two structures, both equally adequate and efficient, the lighter one is the cheaper and therefore preferable.

This is a field which has attracted several workers. I owe to Professor James Gordon (6) my introduction to H L Cox's (7) arithmetical treatment on the design of structures of least weight. Professor Frei Otto (8) is working in the same field in which he is physically measuring the form, the force, the path and the mass of a wide range of structures both manmade and in nature. The relative effectiveness of structures in these terms is well known to most engineers - a bending element is noticeably less efficient than a compression one which, in turn, is less efficient than a tension member. This is of course why a truss uses much less material than a beam, a fact which the Victorian engineers, in the days of expensive materials, well understood.

It was the realisation of solutions for secondary problems - such as corrosion (especially with the development of the use of mild steel) which led to the introduction of plate or tube members which were easier to paint - or for fire protection which stimulated the use of reinforced concrete. These changed the aesthetic of structures.

Yet developments in 'rusting steels', reintroduction of cast iron as a structural

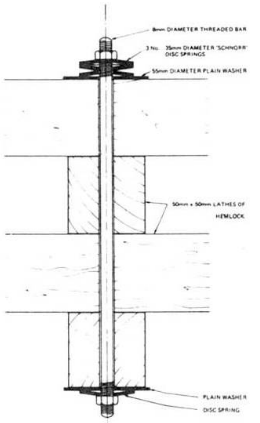

Fig 17 Mannheim Lattice Shell

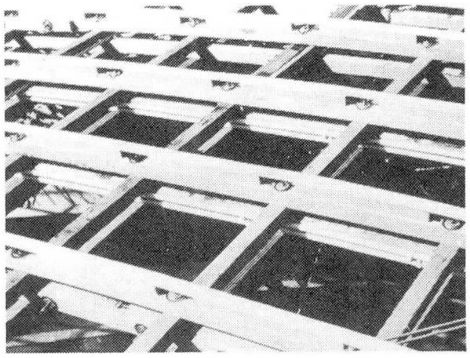

Fig 18 Mannheim Lattice Shell

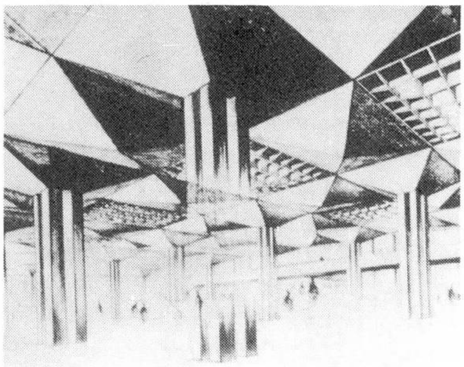

Fig 19 Articulation for thermal movement Conference Centre Riyadh

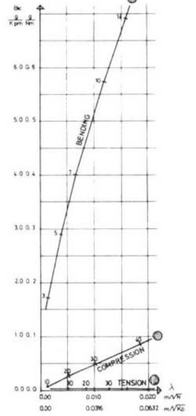

Fig 20 Curve of Efficiency Frei Otto

material, the invention of water filled tube members or intumescent paints as fire protection which have revived the possibilities of earlier structural aesthetics. The sophisticated steel joint, economic because of its repetitious nature, is now coming more into use due to these developments. Centre Pompidou was a conscious exercise in reviving such aesthetic.

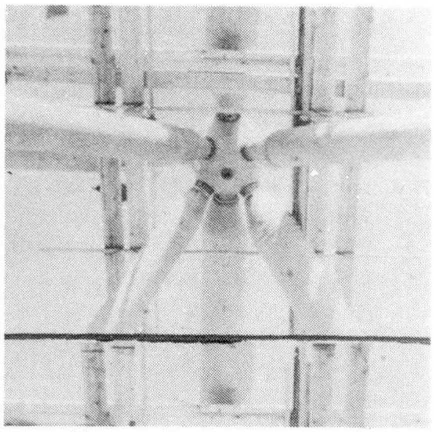
Fig 21 Joint at Expo '70 Osaka

End fittings are not required on columns, you can just put a strut on the ground and sit on it. The problem of the compression carrying gap filler was solved a long time ago. So struts can be cheaper in carrying load over short distances than ties. But for larger distances the buckling mode dominates and for a simple strut is $\frac{\pi^2 EI}{\ell^2}$.

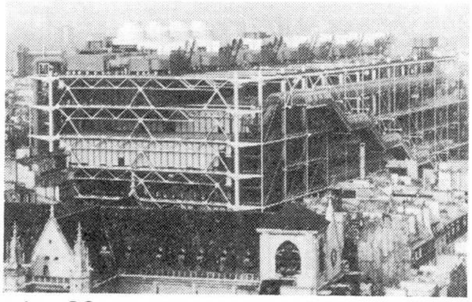
Fig 22 Centre Pompidou

Which means that the compression strength diminishes as the length increases and because of the geometrical properties of I dividing the load into several members increases their total weights. So it is not surprising that for a compression structure frames are provided for the structure even if cladding is required to enclose space. In a panelled geodesic dome the panels buckle and, by and large, all forces are carried at the junctions where stiffness occurs. Incidentially this division of structure from cladding has also suited the organisation of site works whereby separate trades have built the two elements and the present economics of the construction industry certainly now favour this solution.

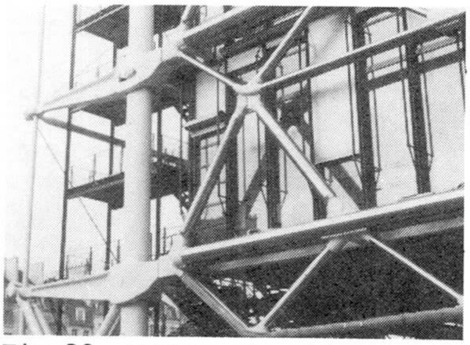
Fig 23 Centre Pompidou

However for larger lengths the tensile member becomes increasingly more economic. As it is not limited by problems of instability the weight of the element itself is proportional to the length, while the weight of the end fitting is the same for a given load whether the length of the tension member is long or short. As an additional determinant of economy for a given load the weight of the end fittings of several tension bars are less than that of a single larger tension rod. So for a long cable for a suspension bridge the cost of end fittings will be very low proportional to its length but for short lengths (like a cable roof) it is cheaper to have several members rather than one because of the cost of end fittings. A statement which is obvious to those who work in prestressed concrete. So where an enclosure is also required fabrics should provide the cheapest structure of all.

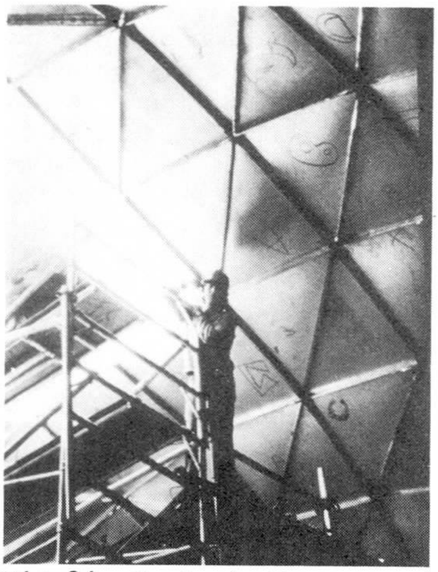
Fig 24 Geodesic Dome Beaulieu

SURFACE STRESSED TENSION STRUCTURES:

For enclosed structures such as buildings the use of surface stressed tension structures are likely to develop for economic reasons. For such structures concentrated loads are distributed over large areas by gross deformation and these areas are provided by plates or nets usually, though not always, composites or laminates. Since the performance of the surface biaxially is non-linear the material, its form or its fabrication must allow for these movements if overstressing is to be avoided. An orthogonal grid of cables either coated or supporting a membrane is such a surface. The joints of the cables usually have the advantage that they 'slip' under overload allowing stress relief and this is now an accepted element in the design of such structures.

The problem with such tent structures is to take the distributed load from the tension members into the supporting mast(s). The earliest cable roofs, such as the Raleigh Livestock Terminal, took the cables to stiff edge beams arches which had to be of considerable size to take the forces. In contrast cable net roofs, such as the pavilions for the Lausanne Exhibition, took the forces from the mesh to the mast top by main cables and, for the first really large flexible roof the German Federal Pavilion for Expo 67 in Montreal cable loops from the mast tops relaxed the surface forces. Obviously the provision of reinforcing main cables is an additional expenditure of material yet a continuum membrane cannot readily accept stress concentrations at mast heads without reinforcement. A traditional answer is by bearing over a large area as for the tent at Dyce. The design of the Munich Aviary is a prime example of the principle of minimising material for end connections. Stainless steel wire grid was used as a fabric with each wire supported at the mast zone by a system of small beams linked together and taken by a series of 12mm cables to the mast top. The design of the Gatlinberg Centre develops this further in that the individual wires of an area of grid are individually taken to the mast top and locked off.

One might say that the use of the structure of a building as defined by the first paragraph of this paper reaches its extreme in air supported structures where the structural component is also the climatic moderator. In theory the use of a single skin requires joints only at the edges though, since the material

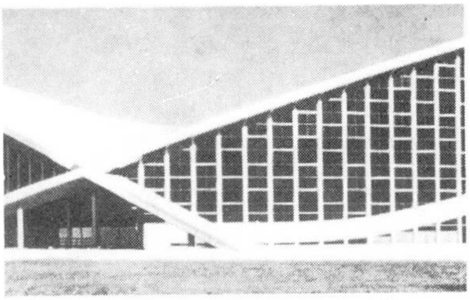

Fig 25 Raleigh Livestock Terminal

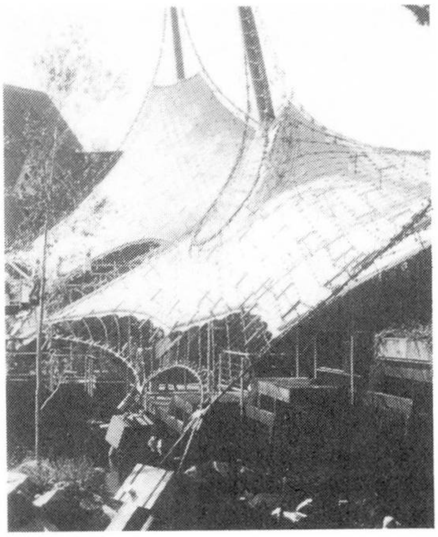

Fig 26 West German Pavilion - Expo 67

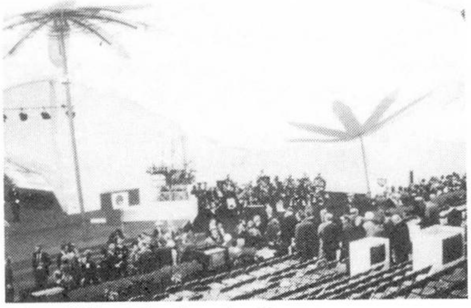

Fig 27 Tent at Dyce Scotland

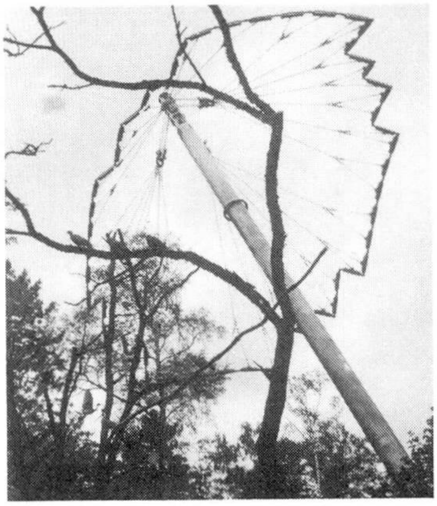

Fig 28 Munich Aviary

always comes on rolls, there are a considerable length of joints. They are all lowly stressed and welding is now commonplace. It is interesting that as the dominant mode of failure is by puncturing, the joints exist as crack stoppers.

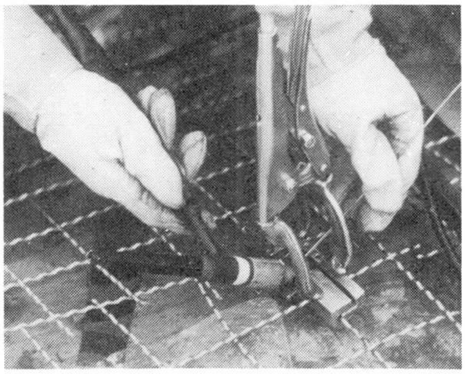

Fig 29 Jointing Munich Aviary

Summarising we can generally say that it is tension rather than compression which gives problems in joint design. We can also probably say that where structures are required for rigidity rather than strength the component sizes are generally so stiff that the joints are relatively lowly stressed and inaccuracies of analysis of behaviour and construction tolerances are usually fairly easily allowed for.

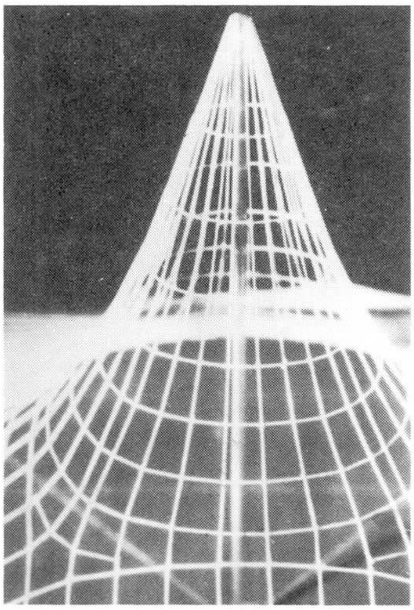

Fig 30 Mast top for Gatlinburg

The tendency back towards framework structures in which tension joints are highly stressed is more of a problem and joints with an increase of flexibility to allow load shedding or to reduce the risks of stress concentration are desirable.

The increasing use of composities and adhesives, or at least adhesion, raises problems for which the structural engineering world has more limited experience. The preference is not to use them because they often give little if any warning of failure. The objective is to avoid stress concentration and if a joint such as the scarfed joint in timber can be developed the engineer feels secure. But certainly there is a need for more return to the old engineering technique of physical testing rather than the current expectation that everything should be able to be done by scholarship and mathematics.

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