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Short communication

Frei Otto and the development of gridshells

Ian Liddell

The Old Vicarage, Sudbury, Suffolk, United Kingdom

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ABSTRACT

The innovative architect, Frei Otto, developed the concept of gridshells which could be designed by a funicular modelling method and constructed from an equal mesh net of timber laths bent into the planned shape. In 1970 this technique was used to construct a 9000 m^2 curved roof structure from 5 cm square timber laths. This paper summarises the design and engineering work that went into the construction of this remarkable building.
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Mannheim Gridshell

1. Introduction

Frei Otto, who was born in Berlin on 31.05.1925 and died on the 09.03. 2015, was one of the most innovative people working in architecture from 1950 to 1990. He was the son and grandson of stonemasons and sculptors but spent most of his free hours in his youth building model planes and gliders. He was drafted into the German air force towards the end of the second world war and ended up in a prisoner of war camp at Chartres where he was in charge of repairing bridges and buildings without much materials. He returned to Berlin in 1947 and started to study architecture at the technical university.

E-mail address: ilidde@btinternet.com

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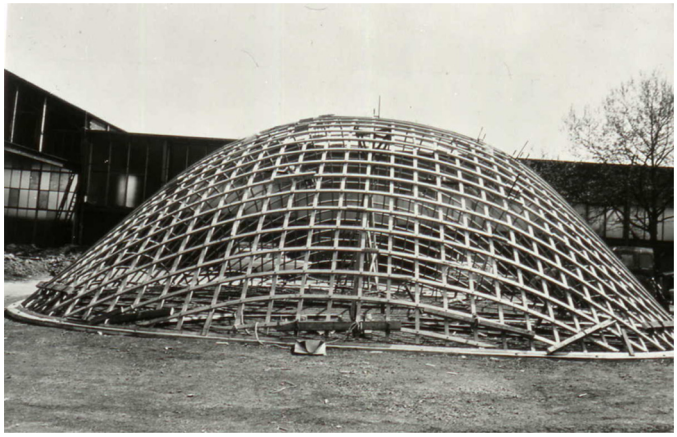


Fig. 1. Trial gridshell structure at Essen.

On an exchange visit to the United States in 1952 he met Eero Sarinen and also, Fred Severud who was working on the Arena for the Raleigh State Fair designed by Matthew Nowicki. This was a large tensioned cable roof supported by a ring beam of two crossed and slanted arches to form a doubly curved surface. This inspired Otto to study tensile structures for his doctorate that was completed in 1953. His interest was expanded by his own experimental work with Peter Stromeyer of the tent making firm of L. Stromeyer & Co. and by further discussions with other engineers such as Walter Bird, David Jawerth, Lev Zetlin. His doctorate thesis plus other work was published in 1962 and 1966 as Tensile Structures Vols. 1 & 2. [1] It was translated into English and published by MIT in 1967 and 1969.

Otto's work with Stromeyer in the late 50s and early 60s was based on using physical formfinding models to define the shape and then in the case of tents develop the fabric cutting patterns. Prestressed tensioned surfaces have to adopt an equilibrium geometry in which the tensile forces in two directions are balanced. The perfect representation of this is a soap film in which the surface tensions are the same in all directions but they are difficult to measure. This forms a "minimal" surface and is a good starting point for a surface tensioned structure. Otto's modelling process would often start with soap film models and then move on to more robust stretch fabric models from which he would develop the fabric patterns using strips of paper.

His work moved up a gear with the design of the cable net tent for the West German pavilion at the Montreal expo in 1967. This was well before the arrival of computer methods and the design work was completed with the making of a large-scale "measuring model" which was used to define the cable lengths as well as measure the tensions in the cables under load. The modelling method defined the construction system as well as the actual geometry.

A trial structure was built for the Montreal tent which had a single mast and contained all the details such as cable cross clamps, connections to boundary cables and a trial eye loop at the mast head. This structure was re-erected at Stuttgart University and became Otto's research centre, The Institut fur Leichte Flachentragwerke (IL), that continued with research and published much of his work which included investigations into natural forms as well as lightweight structures (Figs. 1–14).

2. Work on gridshells

As well as tensile structures, in the late 1950s Otto became interested in light-weight shells which could be formed using the Hookean principle of inverting a hanging net (According to Lisa Jardine, Robert Hooke used this method to show Christopher Wren how the Dome of St Paul's might work [2]). The formfinding method also suggests a construction method using an equal mesh square grid of timber laths or steel rods thin enough to be readily bent into shape. A square grid can be moulded to a doubly curved surface by the deformation of the grid squares into rhombi. Such a structure Otto described as a gridshell (gitterschale).

In 1962 he built, with some students at Berkeley, a trial structure of a dome standing on four points using steel rods. Later that same year he made a trial timber structure at Essen on a15 m × 15 m super-elliptical plan (Fig. 1). Two small auditoria were required within the Montreal Expo 67 tent and these were made using grid shell construction. The meshes were prefabricated in Germany and sent to Canada folded into bundles, where they were opened up and installed on site. The grids were clad with thin plywood sheets to form the enclosures.

3. Initial design for the Mannheim shells

In January 1970 it was decided to hold the Bundesgartenschau 1975 in Mannheim. Carl Mutschler & Partners of Mannheim were selected as architects and Heinz H Eckebrecht of Frankfurt as landscape architect for the Herzogenriedpark. The a multipurpose hall building was to be the central feature arranged alongside a through route and with a restaurant on the

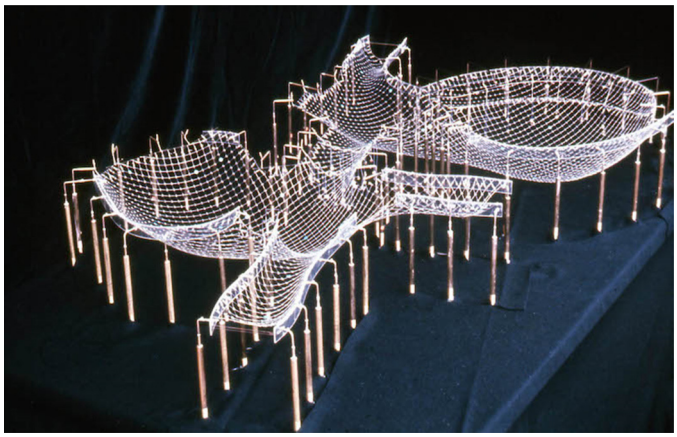


Fig. 2. Final Hanging chain model for Mannheim.

other side. A feature of the site in the flat plain of the Rhine was a large mound formed from demolition material left from the war and the landscape architect wanted a continuation of the hilly form by architectural means. After some crazy ideas the architects remembered Otto's grid shell trials and went to meet with him at Atelier Warmbronn. After some preliminary shapes were made with wire mesh the architects and the collaborators at the Atelier Warmbronn, particularly Evald Bubner, developed a 1:500 wire mesh model with two large dome structures and linking covered walkways. This was the sketch design. After this was agreed the architects finalised the boundary lines and the Atelier started work on the final hanging chain model that would define the geometry of the building (Fig. 2). This was made with hooked links that connected with small circular rings that would be the nodes. The model scale was 1:100 and the chain grid dimension was 1.5 cm representing every third lath line on the real structure. The ends of the link lines were connected to the boundary line with small springs that could be adjusted to achieve a reasonably uniform tension in the grid. Without such springs it is very difficult to get the forces reasonably well shared between the two directions of the grid.

The model was measured by stereo photography and the photos processed to get the coordinates of the nodes. The form was then processed by the engineers in the Institut Fur Anwendungen der Goedesie im Bauwesen at the university of Stuttgart which was led by Professor Linkwitz. They used the method of force densities which had been recently developed in that department.

Drawings and specifications were prepared from the measured model. These were sent out to various companies to get prices for the ground works, the timber shells and the fabric coverings. The three selected companies would form an arbeitsgemeinshaft for the construction.

The Mannheim engineers Bräuer und Späh were entrusted with the statical calculations. In the middle of 1973 they realised that the stability of the shell was not accessible to purely mathematical calculations and on the suggestion of Frei Otto the London firm of Ove Arup & Partners, represented by Edmund Happold and Ian Liddell, were engaged in September 1973 while Brauer und Spah continued with the ground works.

At this point the opening of the exhibition was 19 months away on 18 April 1974 and construction was due to start on site in December 1973. The specification of the shell was for the lattice to be made from 50×50 mm laths of Western Hemlock timber of which a reliable source of very fine grain high quality material in long lengths had been found. Most of the shells were planned to be constructed from single layers of laths in each direction at 50 cm spacing although some area of double layer construction had been included in the contract. The engineers had not encountered such a construction before and had concerns that the buckling collapse load would be too low for such a large shell structure.

The form of the shells had been developed by hanging chain models so theoretically the self-weight loads would produce only compression forces in the laths. Any disturbing loads would cause bending effects in the laths that would cause the laths to deflect from their theoretical funicular shape leading to increase in bending from the uniform load forces. At a critical uniform load there would be no resistance to any disturbing loads leading to a buckling collapse. Additional stiffness would be required and this would mean additional materials and additional cost so it was important that the engineers should be able to communicate their work to all parties including the proof engineer, Prof. Fritz Wenzel.

The principle of construction was that the laths would be laid out at ground level and all the node bolts inserted but not tightened. They would then be lifted up to their intended shape as a doubly curved shell. In this process the squares of the meshes are distorted into parallelograms and the ends of the laths have to move in to their edge boundaries. The grid would have to be supported in this shape until the node bolts are tightened and it becomes stiff enough to bear its own weight. So flexibility is required for the installation and rigidity thereafter.

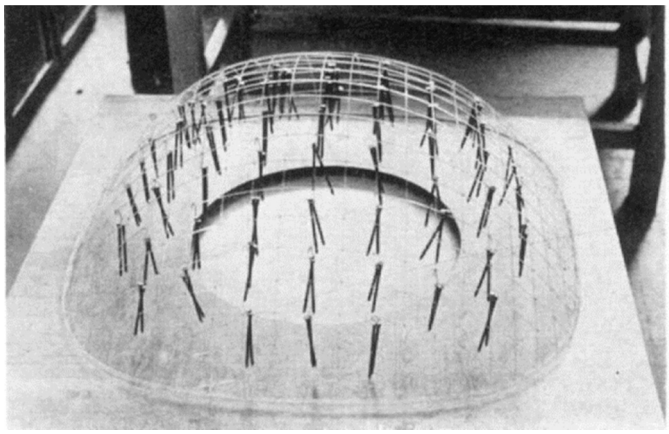


Fig. 3. Model load test on the Essen gridshell.

3.1. Stage 1, initial engineering assessment

The engineers were faced with an absence of knowledge as to how the grid structure would behave and were required to confirm in four weeks that they thought it could be safely built. They made an immediate start on three fronts:

a) Investigations into the design loads
b) Desk studies and hand calculations on shell buckling
c) Model testing
d) Hand calculations to get a approximation of the member forces

The load studies were wind tunnel testing and snow load studies which were carried out at Cranfield Institute. The critical snow loads were agreed to be 15 kg/m^2 on the closed heated areas and 40 kg/m^2 on unheated areas. The self weight of the two layer structure was 20 kg/m^2.

Hand calculations were based on a paper by D T Wright on buckling in reticulated shells [6]. This paper gave a simple formula for the buckling load of a fully triangulated doubly curved shell with pin-jointed members. This arrangement is not the same as that for grid shells but the formula did indicate that 100 × 100 mm laths would be required rather than 50 × 50.

At this time the detailed geometry for the structure was not available but the geometry for the much simpler Essen dome was, so the engineers set about making a structural model of that from Perspex strips joined with pins which they thought could be scaled to give some information on the buckling capacity (Fig. 3). The model was loaded with nails as a convenient unit of weight. Uniform load was applied in stages by using 1–4 nails at every node. At each load stage the central point and two other points were loaded with additional nails and the deflections recorded. For each test point the point load/deflection curves were plotted. The load that caused the structure to deflect to the ground was recorded. This load was plotted against the UDL for the tests and extrapolating the line to zero point load gave the collapse load for that structure.

The structure was varied by altering the in-plane diagonal stiffness by adding ties and gluing the joints. Buckingham's method of dimensional analysis was used to evaluate the scale factors so the results could be applied to the largest of the Mannheim shells. The predicted collapse load for the Multihalle shell with single layer was 3.8 kg/m^2, with a double layer it was 100 kg/m^2 and with ties it was 160 kg/m^2. This information gave the design team the confidence to proceed with the project.

3.2. Stage 2, the engineering work to validate the load carrying capacity

A.) In this stage a programme of timber testing was carried out
B.) A Perspex model of the Multihalle was made and tested in the same way as the Essen model (Fig. 4)
C.) Computer modelling was undertaken to make a more refined assessment of the buckling load taking in the unusual features of the construction

The Perspex strip model of the Multihalle was made at 1:60 scale with one member representing 6 full scale members. The loading was applied with nails in the same way as the Essen model and the collapse load for the model was found to be 2.8 kg/m^2 without ties and 12.5 kg/m^2 with ties. These were scaled up to predict a collapse load of 63 kg/m^2 without ties and 280 kg/m^2 with.

The timber testing included load/rotation tests on the grid intersections and creep bending tests of the laths. The capacity of the boundary connections was also tested. Of particular concern was the transmission of shear force between the upper

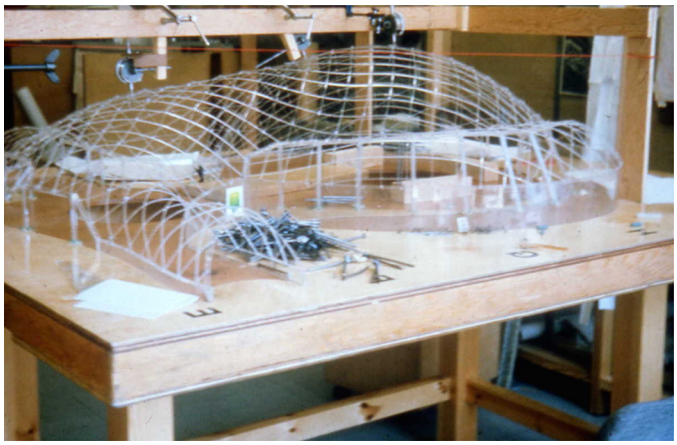


Fig. 4. Mannheim model load testing.

Fig 5. Testing for shear stiffness.

and lower members of a pair of laths. The structure relied on a pair of laths acting as a beam with the theoretical stiffness being increased 26 times that of a single lath. The compound stiffness relies of the rigidity of the shear connection which is formed of single 50 mm square laths crossing at right angles held by a single bolt. Changes in moisture content will cause the timber to expand and contract, if the bolt is done up tight the expansion will increase the stress in the timber causing it or the bolt to creep or yield so when it dries out and shrinks it will become loose. To prevent this it was decided to use disc springs to ensure that the compression was maintained. Tests were carried out with varying amounts of spring compression and this indicated a reasonable amount of joint stiffness until the bolts were completely slack (Fig. 5).

The computer modelling was done on a Univac 1108 with magnetic tape drives for input and output. The solution technique was the Newton–Raphson iteration scheme in which successive approximations are made and terminated when a sufficient degree of accuracy is obtained. Since the model has to be re-set for each iteration this can be a slow process so care has to be taken in setting up the model to make it as efficient as possible. A standard analysis program was selected but

Fig. 6. Detail of grid construction.

it had to be modified to take into account that one straight member represented a number of curved members and the fact that shear deflections which would reduce the out-of-plane bending stiffness could not be ignored and that same stiffness would be reduced by axial force.

The ties were modelled as timber sections, hence the wire area was increased by the modular ratio. The ties in the model could take compression as well as tension, the problem of one tie going slack was ignored since the stiffness was quite low.

The Multihalle model had 192 nodes, 297 members and 254 ties. The buckling collapse load for the structure was found to be 105 kg/m^2, which was considered satisfactory for the heated Dome. However further testing on the shear stiffness generated by the cross nodes was actually 40% of that used in the computer model. Runs with this value of shear stiffness had indicated that failure would occur. Hand calculations indicated that members with high axial forces would fail in compression so it was decided that the shear stiffness had to be increased in these areas.

3.3. Stage 3, construction details

The 50 × 50 mm laths came in various lengths up to 6m. They were joined in the factory into lengths 30–40 m long by finger-jointing. Site joints were made by nailing 50 × 25 mm laths on to each side. This technique was also used to repair any joints that broke during installation.

Bending tests were made on the laths to find the minimum radius of curvature before they broke. It was 10–12 m. Where the radius was less than this the laths were split into two layers of 25 mm depth.

3.3.1. Node joints

The two lower laths at the cross nodes (Fig. 6) had single holes at 500 mm spacing to take 8 mm threaded rod. The upper two layers had slotted holes to allow the members to slide over each other to take account of the bending of the pairs of laths during the lifting process. To maintain bolt tension during the dimensional changes from shrinkage and expansion caused by seasonal moisture variation 4 disc springs were used, 3 on the top and 1 below bearing on 55 mm diameter plain washers (Fig. 7). The springs would generate 450 kg of force when compressed by 6 mm

Where additional shear capacity was required folding wedges 300 mm long were inserted between the laths and slid together so they were a tight fit. 3 - 8 mm bolts were inserted through the wedges with disc springs as at the nodes.

3.3.2. Cable ties

Computer runs showed that a pair of 6 mm 19 wire strand through every sixth node in each direction would provide suitable stiffness. Some small aluminium cable clamps were found from the electrical industry that would take the two 6 mm cables and were clamped with 2–8 mm bolts. The lower part of the clamp had threaded holes so it could replace the top nut on the node bolts with the nut replaced to provide clamping action. The other hole was simply used for clamping.

3.3.3. Boundary connections

Otto had proposed a detail that would accommodate all the angles of the shell where it was attached to the boundary concrete wall. It used a half round timber section on which a plywood board was screwed at the correct angle. The laths were then to be screwed to the board (Fig. 8). The engineers' tests had demonstrated that this would not be strong enough for the calculated forces. They proposed that 2 layers of 25 mm plywood should be bolted to steel brackets set to the correct angle.

The laths could then be bolted to this plywood layer during the installation process. The setting out for this boundary came readily from the geometrical data.

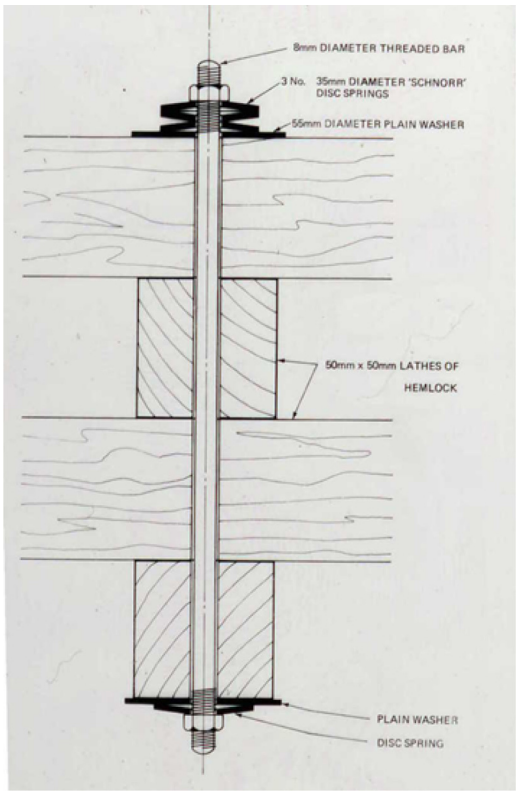


Fig. 7. bolting details.

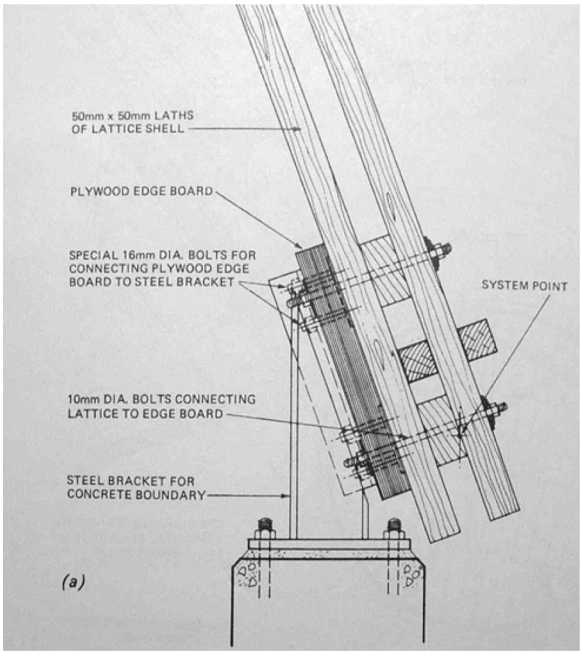
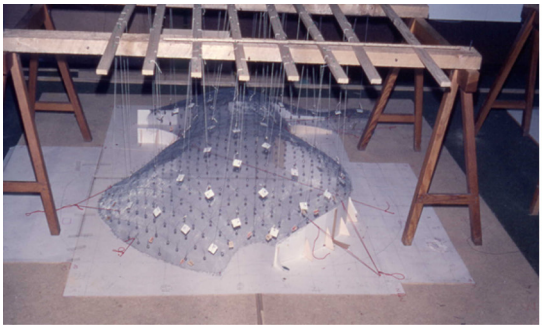


Fig 8. Detail of Boundary connection.

Fig. 9. An arched opening with severe twist.



Figs. 10 & 11. Model of lifting positions and arrangement on site.

As well as a concrete wall there were three other different types of boundary structure. Arched openings, laminated timber beams connected to steel columns, cable structures supported on steel columns. The valley beam was a 500 mm circular laminated timber beams with plywood boards attached to it by steel brackets in a similar way to the concrete.

The arches were laminated from plywood cut to the developed shape. The system lines were provided with the geometry but the laminated ply had to be twisted so it lay in the surface of the shell (Fig. 9). The same problem existed for the laminated beams which were laid up from 6 cm wide boards. With both these elements there was a difficulty in defining the planes of the end connections plates so the beams or arches could be bolted to them. The defined geometry grid was at 1.5 m spacing so manual interpolation was required to define the end connections. In the case of the beams the pairs of end connection plates were welded to steel tubular columns requiring the plan angle, altitude angle and twist to be defined by the cutting shape of the plates.

4. Installation on site

The installation started with the contractors laying out of the laths for the Multihalle shell on the ground without having a plan for lifting it. Their idea was to lift it with cranes but they realised that the shell would have to be supported in its correct position while all the nodes were set to the correct level, the node bolts tightened and the all boundaries fixed. The additional shear block and diagonal ties would also have to be installed before the supports could be removed. To assist the contractors with understanding the problems involved the engineers made a model using wire mesh weighted so that the bending stiffness and self weight were modelled (Figs. 10 and 11). This indicated that the supports needed to be on a 9×9 m spacing. The contractors then proposed to use a scaffold tower system with timber spreaders to distribute the loads. The towers were jacked up in 33 cm stages with extra sections being added in. When the grid was lifted to give sufficient headroom forklift trucks were used to both jack up the towers and to move the bases to keep the towers vertical.

The grid deflected significantly between the towers so a procedure involving over lifting the towers or using intermediate push-ups to get the areas between to the right height and tightening the bolts on those lines. Then lowering the towers again to get those areas back to the correct level. With this procedure the shells were eventually manoeuvred into the correct shape and all the stiffening work completed.

Fig. 12. The gridshell covered with dark but translucent PVC coated mesh fabric.

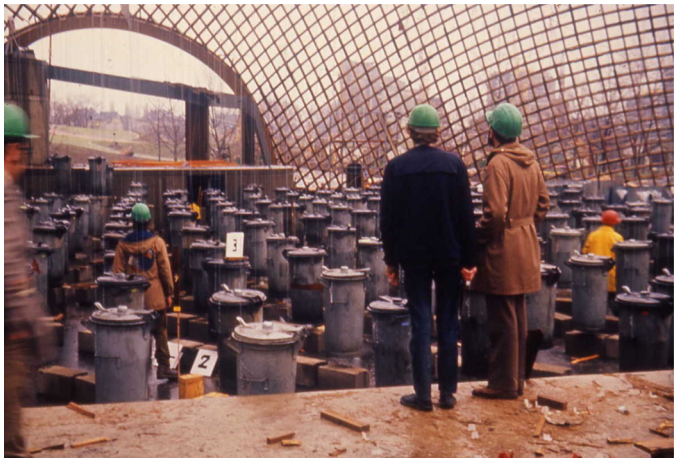


Fig. 13. Load testing with garbage bins filled with water.

5. Covering

The timber grid was originally covered with a PVC coated grid weave cloth. The PVC was transparent with a bronze tint and the yarns of the grid weave were coated with black PVC before the final coating was applied (Fig. 12). This was fixed with staples to a "nailing strip" of timber that was fixed to the uppermost laths with spacers so the nailing strip ran over the protruding bolts. The joints between the sheets of fabric were heat sealed to make them waterproof and the staples were covered with small patches of PVC.

6. Load testing

The Proof Engineer, Prof. Fritz Wenzel had demanded a load test to demonstrate the accuracy of the calculation used to predict the buckling load. It was agreed that an area of 500 m^2 should be loaded to a load of 1.7 times the design load. This meant a load of 40 kg/m^2 was to be applied to an off centre area of the computer model. The computed deflections were mapped as contour lines.

After the main Multihalle shell was completed the test loading was planned using municipal garbage bins hung from the grid filled with an appropriate amount of water (Fig. 13). On the day of the test there was a large turn-out of dignitaries and officials from the city as well as most of those associated with the project who had come to watch. The deflections were measured at 13 points and compared with the computed contours. The centre point, which had a computed deflection of 70 mm, was measured to be 79 mm and the others were similarly close. The loading curve indicated some non-linear behaviour while the unloading was completely linear with a residual deflection of 10 mm. This was probably due to some bedding in and joint slip. It was noted that the timber was very wet at the time, which would have reduced the value of Young's modulus, so the engineers felt that the assumptions made for the mathematical modelling were suitably pessimistic.

7. Performance and on-going life

The garden show opened on the due date, 18 April 1975 with a huge flower show in the Multihalle. The fabric for the cladding allowed in about 20% of the direct sunlight. Unlike a white pigmented fabric there was little reflection of the light

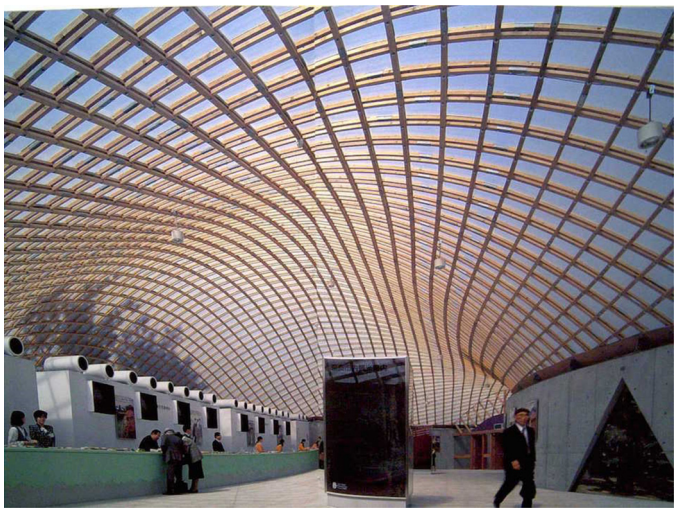


Fig. 14. Nara park gridshell 1988.

back to the sky so most of the light energy that did not pass through was absorbed into the cloth. The result was that there was little diffuse light inside most of the light being directional light from the sun so shadows could be seen. This gave the interior a special feel that was different from most fabric structures. Unfortunately the coating was heavily damaged by UV and infra-red light. The black coating to the yarns caused them to heat up and this caused the PVC to shrink and crack so that after a few years it let water in. The fabric had to be changed and a more white conventionally coated fabric from Sarnafil was selected and has lasted well.

8. Reflections on gridshell construction

As Frei Otto remarked in the book on the Mannheim gridshells "it is an un-polished building, there are many things that could be done better".

There is one building for the "Silk Road Exposition" in Nara Park, Japan that was built in 1988 using similar technology to Mannheim (Fig. 14). The Architect was Itsuko Hasegawa Atelier and the project architect for the shell was probably Toshiyuki Shirayanagi who studied gridshells at the IL between 1971 and 1973 and helped with the volume IL10. Apart from a photo in a book of membrane structures by Taiyo Kogyo [7] there is little information on this structure. The expo also featured several tension fabric structures and it is likely that all was removed after the event.

The photo shows that the structure has a simpler form avoiding the large changes of curvature, has laths of planed timber that are wider than they are deep and are joined at the nodes with disc springs and washers in the same way as Mannheim. The boundary on a concrete wall is also similar. There are no diagonal ties and the site joints are made with pressed metal channels that wrap around the laths. The cladding appears to be a high translucency fabric. The result has a more polished appearance than Mannheim.

In Southern England a smallish gridshell was built at the Weald and Downland museum for which the engineers were Buro Happold. It is 48 m long,11–16 m wide and the height varying from 7 to 10 m in three humps. It is built from oak laths 53×38 mm in section. The oak was delivered in 3 m lengths. Any defects were cut out and the pieces were finger jointed together to create long lengths of straight-grained clear timber. The nodes were joined with 3 layer square steel plates bolted at the corners. It is clad with western red cedar lapped boards. The grid was laid out flat at high level and the sides were then lowered progressively while the laths moved into place to form the final shape.

There is another Gridshell by the same engineers at the Savill Garden in Windsor Great Park built in 2006. It is 90 by 25 m, also a three humped form, but with a lower profile, supported by tubular steel edge members braced to take the thrust loads from the shell. The geometry was generated by moving parabolas along a curved centreline using 3D geometrical CAD software. The timber is Larch, taken from the Great Park, and is 80 mm wide and 50 mm deep in section finger jointed to get clear straight-grained timber. It was constructed by laying out the 2 lower sets of laths to their final positions with the 160 mm deep blocking pieces that form a deep web already in position. The top two layers were then added and bolted together.

The Mannheim gridshell was an experimental structure that was a product of its time. Its large and complex form was generated by using a hanging chain-net formfinding method to fit the architects' complex plan for the building. The result produced a wide range of curvatures and shapes. In one part of the multihalle the grid slopes outwards at the boundary and at another in the restaurant shell there is an arch that twists through 90° from one springing to the centre and twists back again from the centre to the other. The form was generated by physical modelling and modelling was used to help understand the structural behaviour and to understand the lifting requirements for the installation.

It is unlikely that such a large and complex structure would be built again. Computer modelling has taken over from physical modelling. The funicular form generated by hanging chain-nets is of some benefit to the timber gridshell structure but a fully triangulated reticulated shell can carry a wide range of load patterns with out bending loads and can also accept flat panel glazing. Recent developments in computerised steel fabrication has enabled sufficiently accurate cutting that structures of any geometry can be prefabricated in sections and assembled on site with full moment carrying connections. An example of this technology is the glazed roof of the British Museum courtyard.

The result is a building that is unique. Its form has attracted many favourable comments comparing it to whales and other bodies. It is simply a shell with a uniformly thick surface. There are no ribs within the surface indicating the load paths so its stability is magic and such a structure will not be built again. To their credit the Germans have listed it as a protected structure that must be retained. Unfortunately after 40 years it has deflected out of shape quite badly in places and is in need of some major attention to restore it. But it could be done and the building made safe for another 40 years but there are also the problems that the building has little use and the work will be very costly. We can only hope that this remarkable building will stay as a memorial to Frei and his ways of thinking about structures.

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