The Use Of Timber Gridshells For Long Span Structures

Summary

The paper describes the multi-layer timber gridshell technique. It uses the authors’ past and current experience of projects to illustrate its potential and to outline the techniques of design and construction.

Key Words: gridshells, timber structures, double-layers, node

1. Introduction

For a series of Timber Gridshells designed by the authors, the paper compares the structural details used at the nodes and supports as well as the various timbers used for the grid elements. Despite their many advantages, double layer timber gridshells are uncommon. The reluctance to adopt this type of structure may stem from the difficulties associated with their design. The Mannheim Bundesgartenschau structure, built in 1975, used physical models as the primary method of form-finding. More recently much more sophisticated computer form-finding and analysis provides the key to the modern use of timber gridshells. The Timber Gridshell technique allows doubly curved shells to be realised using a set of identical components. Thus doubly curved shell roofs can be formed at a cost that is lower than techniques using materials other than timber. Architects can achieve radical design concepts at an affordable cost to their Clients.

2. The Timber Gridshell Technique

2.1 The technique and its advantages

2.1.1 Shell Structures

A shell is a three dimensional structure that resists applied loads through its inherent shape. There are a several forms of structure that belong to this group of loadbearing structures, which carry applied loads mainly by way of membrane forces. They carry loads by way of tension, compression and shear forces in the plane of the shell and thus are structurally efficient and for this reason thin sections are possible. It is possible to build structures with stable surfaces either both curved in the same sense (synclastic) or curved in opposite senses (anticlastic) with the tensile forces in one direction stabilising the tendency to buckle out of plane in the other direction which is being compressed.

Shell structures take many forms. If regular holes are made in the shell, with the removed material concentrated into the remaining strips, the resulting structure is known as a gridshell.

2.1.2 Timber “Shells”

No true shell structures are possible in timber, wood is antisotropic, that is its properties are different in all directions. Hence timber ‘shell’ structures are always made up from three dimensional frameworks.

2.1.3 Timber Gridshells

Unlike the geodesic dome patented by Richard Buckminster Fuller (1895-1983) in 1954, which has a regular shape, the timber gridshell technique utilises irregular complex doubly curved shapes that are created from a set of standard components.
To form the gridshell rotation at the nodes and bending and twisting of the constituent laths must be possible. Once formed, shell action is accomplished by diagonal bracing, providing in-plane shear strength and stiffness.

There are practical and physical limitations on the tightness of curvature to which laths of a particular cross section can be bent. Hence the depth of lath required in a single layer gridshell to achieve relatively large spans may be too deep to permit bending of the flat lattices to a final shape that has tight radii of curvature. The solution to this problem is to utilise a double layer gridshell, illustrated in Figure 2.

### 2.2 Modern uses of the Double Layer Technique

Timber Gridshells have not been widely used. Their history can be traced back to the turn of the 19th Century when German engineer Sodlingen started making lamellar arch structures (ref. 1) for agricultural buildings. First world War zeppelins- and then World war II bombers used timber shells, but it was the German Architect, Frei Otto, who really developed the timber gridshell technique. Early gridshell projects in Essen and Montreal were followed by his remarkable building in Mannheim.

#### 2.21 Mannheim Bundesgartenschau Multihalle Ref. [1]

This building was designed and constructed as a temporary building in 1976. It was so successful that it is still in use today.

One of the lightest building structures ever made, the Mannheim gridshell, *Figure 3*, spans up to 80 metres with a 4 layer gridmesh (2 layers in each direction) of 50mm x 50mm hemlock. Construction was intended to start in 1973 but, due to engineering difficulties this was delayed. In October 1973 a team of engineers, lead by Ted Happold, working with consulting engineers Ove Arup, was appointed to provide Structural Engineering design services (two and a half years before Ted Happold started his own practice).

The shell grid of 500 mm x 500 mm was chosen on grounds of safety. Frei Otto argued that a mesh of this size is too small for a construction worker to fall through (onto the concrete 20 metres below). A sound enough argument but not one that would convince the safety officers of the 21st century!
2.22 Japan Pavilion Hanover Expo and Earth Centre Gridshell

The Japan Pavilion for the Hanover Expo 2000 and the Earth Centre Landscape Structures, Figures 3 and 4 respectively, were both designed by Buro Happold. The former gridshell was constructed using cardboard tubes. Its shape, a triple hourglass, was similar to the Downland Gridshell and so the construction techniques for this building were further developed for the Downland Gridshell. The latter, though much smaller than the other shells described in this paper, enabled the gridshell technique to be trailed and demonstrated for the first time in the UK. It was a forerunner to the Downland Gridshell in the same manner that the Essen shell was used as a forerunner to Mannheim.

2.23 The Downland Gridshell Figure 5 Ref. [2]

The Downland Gridshell was completed in 2002. It uses a double lath system with 50mm x 35mm laths. The analysis highlighted regions of weakness at the side of the domes and the lath spacing of 0.5m was used in these regions with 1.0 m elsewhere.

The initial form was refined to achieve the shape sought by the architect. This interactive process lead to shapes at the gable ends where the natural flow of the gridshell is to start to form a valley but the architecture required the gridshell to continue on a downward flow. The interactive nature of formfinding process is important to achieve the full capability of the gridshell technique.

The in-plane bracing for this building comes from the timbers (longitudinal and transverse) used to support the cladding.

The timber laths are fabricated from oak that is improved by cutting out defects and re-jointing with finger-joints into long lengths.
2.41 Savill Garden Gridshell

The Savill Garden building is for a shop, restaurant and visitor facility for a historic garden in the centre of Windsor Great Park, west of London. The timber gridshell is in four layers. It is a regular 1 metre grid of 80 x 50mm larch timbers. It is formed into a three-domed doubly curved sinusoidal shape. The overall length of the roof is 90 metres and the transverse span is 25 metres (maximum). The shell perimeter is a tubular steel beam, which is supported on steel quadrapod legs. The perimeter forms a dramatic elevation onto the garden, varying in height between 4.5 and 8.5 metres.

2.3 Modelling and Analysis

2.3.1 Physical models

When the Mannheim Multihalle shell was designed, computer analysis had very limited capabilities and was a slow and specialist technique. Physical models were commonly used to gain a better understanding of complex structures and for the Mannheim shell Frei Otto used hanging chain models to form-find the geometry. Node locations were determined from this model using geodesic measurement taken by stereoscopic cameras. Initially, to gain an understanding of the structural behaviour, Arup constructed and tested a 1/16 scale Perspex model of a simplified dome (Frei Otto’s Essen dome) and, using this, calibrated results of tests on 1:60 Perspex model of the Multihalle.

For the Downland Gridshell, the initial models were simple wire mesh models built to a scale of 1:100. These models were used to illustrate, to the client and the design team, the 3-dimensional form. The next stage was the construction of a 1:30 scale model, using strips of wood to represent the laths, which was very instructive in developing a feel for the likely behaviour of the structure during the erection process. Its geometry was used to determine the boundary conditions for the computer form-finding model. Modern computer form finding allows the shape to be manipulated and smoothed from an initial approximation. Finally, a 1:43 scale model of the lattice was made using wire mesh. [3] This model confirmed that the lattice would deform under its own weight during lowering. It was also used during the actual lowering of the gridshell with the model being adjusted in tandem with the actual lattice. Comparisons between the two led to a more complete understanding of what was happening to the lattice during formation.

2.21.2 Analytical models

The Downland Gridshell shape was not funicular, it was not based on a hanging chain model and so its members are not purely in compression under self weight. The computer analysis for form-finding was based on the dynamic relaxation technique. This is an interactive process of computer analysis that solves a set of non-linear equations. The technique modifies an initial approximation to the desired shape by minimising the kinetic energy of the lattice as it is made to oscillate. As noted above, the form was developed and modified to achieve the desire architecture; a process that was not possible in the 1970’s when the funicular form dictated the shape. Finally the shell was analysed under multiple load combinations, using proprietary finite element software; both linear and non-linear analysis was used. For the Savill Garden Gridshell a similar process has been used but without the use of physical models, computer analysis and technique has progressed sufficiently to enable formfinding and analysis to be carried out following the most rudimentary of wire mesh conceptual models.
2.4 Nodes and Support Details

2.4.1 Nodes

Gridshell structures have very large numbers of nodes and so the node detail is crucial to the success of the structure. During formation the lattice has to be able to rotate at nodes and parallel layers have to be able to slide relative to one another. In the final condition the nodes can also be utilised to transfer horizontal shear between parallel members in the double layers to effectively form a composite section.

Mannheim has 33,000 joints. The lattice was assembled on temporary supports above the ground. Bolts were passed through the four layers of timber, which had normal round hole in the inner two layers and slotted holes in the outer two. These slots enable relative movement between layers during formation while the single bolt enabled rotation at the node.

Fig. 7 Mannheim Node

Fig. 9 Downland Gridshell Node

The Earth Centre gridshells are single layer lattices and so only rotation at the node had to be maintained during erection. This was achieved by keeping the bolts loose until the required shape was achieved. Slotted and oversized holes reduce the cross section of the lath available to resist load. For the Downland Gridshell this was a critical consideration that ultimately lead to the development of a patented node clamp. The clamp comprises three plates, one central and two outer plates, held together by four bolts. The central plate has a pin that penetrates the two central laths thereby fixing their relative position but still enabling them to rotate. The two outermost laths are held by the two outer plates but are free to slide relative to the inner laths and to rotate. Another advantage of this node is that it readily accommodates the gridshell bracing. In all gridshells prior to the Downland Gridshell steel cables were used to brace the lattice; as cables can only carry tension forces they must be installed to orthogonally cross each other. However by utilised elongated bolts timber bracing was used for the Downland Gridshell; this bracing carries both tension and compression and thus had to be installed in one direction only. A further advantage of this is that the cladding was installed by directly attaching it to the bracing.

2.21.3 Edge details

The usual method of forming the edge of a gridshell is by means of a clamp. This is the detail that was used in the Mannheim Gridshell and is illustrated in Figure 10.

Fig 10 Mannheim Edge Detail
For the Downland Gridshell a continuous support was provided by sandwiching the lattice between continuous plywood bands, as illustrated in Fig 11.

### 2.5 Materials

Each the gridshells discussed used different materials as indicated in Table 1. The materials each had their own peculiarities that needed to be considered in design and construction. However the principles remain the same and lessons learnt on each project have been implemented in subsequent projects leading to more efficient design and construction.

**Table 1. Summary of Structural Elements of shells**

<table>
<thead>
<tr>
<th>Gridshell</th>
<th>Span</th>
<th>No. of layers</th>
<th>Lathe Size</th>
<th>Material</th>
<th>Bracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mannheim 60m x 60m</td>
<td>4</td>
<td>50 x 50mm at 0.5 m.</td>
<td>Hemlock</td>
<td>Twin 6mm cables every 6“ node</td>
<td></td>
</tr>
<tr>
<td>Japan Pavilion 72m x 35m</td>
<td>2</td>
<td>120mm dia at 1.0m.</td>
<td>Cardboard tube</td>
<td>Glulam ladders</td>
<td></td>
</tr>
<tr>
<td>Earth Centre 6m x 6m</td>
<td>2</td>
<td>32 x 15 at ??</td>
<td>Oak</td>
<td>Twin 6mm cables alternate nodes</td>
<td></td>
</tr>
<tr>
<td>Downland Gridshell 48 m x 15 m</td>
<td>4</td>
<td>50 x 35mm at 1.0 m.</td>
<td>Oak</td>
<td>Timber cladding rails, alternate nodes</td>
<td></td>
</tr>
<tr>
<td>Savill Garden 90 m x 25 m</td>
<td>4</td>
<td>80 x 50 at 1.0 metre</td>
<td>Larch</td>
<td>mm plywood roof</td>
<td></td>
</tr>
</tbody>
</table>

### 2.6 Conclusions

Double curvature in form, is usually complex and expensive to achieve. With the gridshell technique there is a way of making complex shapes from a set of standard elements. Complex curved boundaries can be accommodated; irregular organic shapes are possible. The Mannheim Bundesgartenschau Multihalle demonstrated what is possible; the Downland Gridshell demonstrated that it is a cost-effective technique for creating buildings of high value. Savill Garden will further extend the technology. The analysis is complex and time consuming and this can mean that schemes do not develop beyond concept. However the fact that a number of buildings have now been constructed should lead to wider use in the future.

### 2.7 References


