

Construction of the Downland Gridshell

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Summary

The first double layer timber gridshell in the UK has recently been constructed as part of a new building for the Weald and Downland Open Air Museum in Sussex. Despite their many advantages, double layer timber gridshells are uncommon; the Downland Gridshell is only the fifth of its kind ever to be built. The reluctance to adopt this type of structure may stem from the difficulties associated with their construction, which entails the formation of the doubly curved final shape from an initial flat mat of laths.

The challenges presented by the formation process had to be overcome during the Downland Gridshell project. Issues that had to be addressed included the formfinding, specification of the timber laths, the development of an appropriate formation technique and methods to monitor and assist the formation process. Some of the solutions were highly innovative; an example of this is the patented nodal connection.

This paper describes the challenges presented in erecting the double layer gridshell and the solutions and techniques that lead to the successful completion of the project.

1.0 Introduction

A shell is a three dimensional structure that resists applied loads through its inherent shape. 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. The three dimensional structural stability is maintained through in plane shear strength and stiffness, provided by preventing rotation at the intersections of the grid members (nodes), or by introducing bracing.

In timber gridshells, the lattice can be initially laid out as a flat mat and then pushed into shape. The development of a doubly curved gridshell from a flat, square or rectangular grid is made possible by the low torsional stiffness of timber. During formation the timber lattice must allow rotation at the nodes and bending and twisting of its constituent laths. Once formed, shell action is accomplished by diagonal bracing, providing in-plane shear strength and stiffness.

There are 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 1.1. In this case the lattice is composed of four layers, effectively two single layer mats sitting one upon the other. The laths are of sufficiently small section to permit bending of the lattice into the desired geometry. Upon formation timber shear blocks are installed. These enable the transfer of horizontal shear between parallel layers and thereby endow the lattice with the properties of a deeper section. The potential for this type of system is enormous.

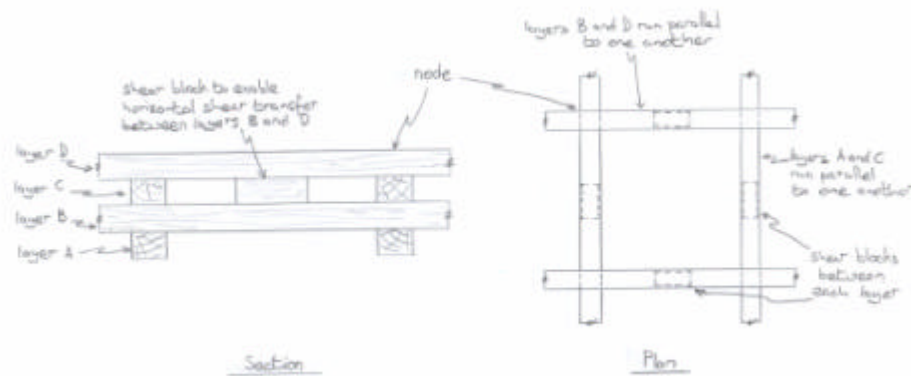


Figure 1.1: Double Layer Gridshell

The first double layer gridshell was erected for the Bundesgartenschau in Mannheim, Germany, in 1975. Since then only two further gridshells of this type have been constructed, both in Japan. The reason for the apparent lack of enthusiasm may stem from the unique challenges associated with the design and formation process. The first double layer gridshell in the UK has recently been constructed at the Weald and Downland Open Air Museum in Sussex. During this project the challenges of the process were identified and overcome. This paper describes the methods used to attain the desired final shape.

2.0 Background to Project

The Weald and Downland Open Air Museum is a leading international centre for historic buildings. It is dedicated to rescuing vernacular buildings from the surrounding region of Kent, Sussex, Surrey and eastern Hampshire; threatened buildings are dismantled, repaired and reassembled to their original form on the museum grounds. The 50-acre open air site is situated in the South Downs at Singleton, near Chichester, and comprises more than 45 preserved 15th - 19th century buildings, a major collection of artefacts and a specialist library. It attracts 140,000 visitors a year. *Figure 2.1* is a photograph of some of the restored buildings and gives a sense of the museum and its setting.



Figure 2.1: The Weald and Downland Open Air Museum; Shops, Market Hall, Crawley Hall and North Cray House (left to right)

The new building is intended to be a national facility for the study and practice of building conservation, especially the timber-framing tradition of England. It will allow the Museum to make its research, conservation and restoration programme for vernacular buildings accessible to the general public for the first time. Furthermore it will act as a store for the Museum's collection of artefacts providing a greater level of security, environmental stability and visibility.

Given the nature of the museum, the brief was for a building that would reflect craft construction, not just mirroring the past, but also serving as an exemplar structure for modern rural buildings. The proposal was for a two level building; a clear-span timber gridshell set upon a sealed space of reinforced

masonry sunk into the hillside to enhance the energy efficiency and a provide naturally stable environment for the artefact store.

Figure 2.2 is the Architect's drawing showing the building cross section.

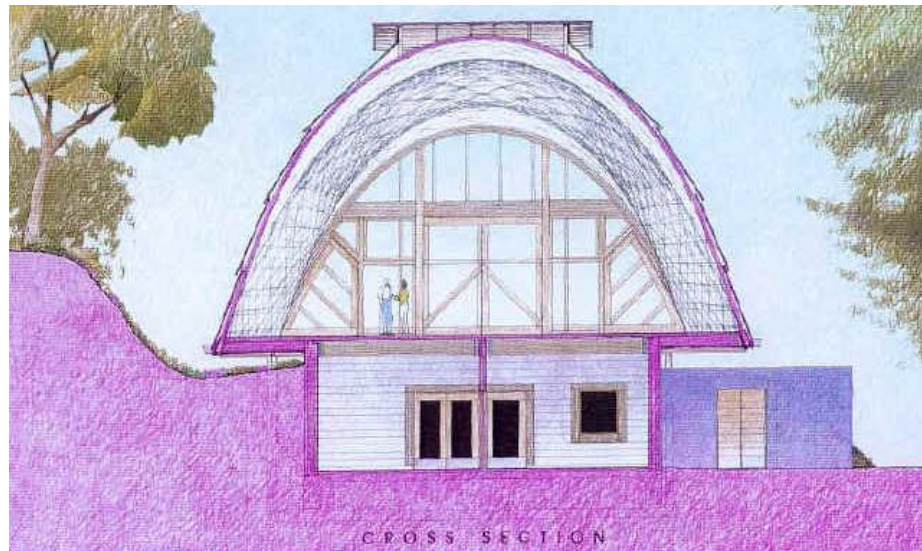


Figure 2.2: Architect's cross section

The gridshell is an organic triple-bulb hourglass shape with access from both ends. It will be clad with a loose system of hanging western red cedar boards. The difficult to drain upper pitches of the building will be clad in an undulating ribbon of watertight monolithic roof. A polycarbonate glazing zone will be incorporated between the "Ribbon Roof" and the cedar boards.

The two levels are separated by a built-up floor structure of glue laminated softwood beams on a central row of glue laminated softwood columns supporting a sealed and insulated solid timber joistless deck. From the outside the building will appear to be a single storey structure with its undulating shape mirroring the rolling West Sussex Downs.

3.0 Building Design

General

The first double layered timber gridshell was constructed for the Mannheim Bundesgartenschau in 1975 and described in detail in the paper, by Liddell and Happold, "Timber lattice roof for the Mannheim Bundesgarten" in the Structural Engineer of March 1975. The Mannheim gridshell was constructed by laying out the flat lattice on the ground and then pushing it up using spreader beams and scaffolding towers at strategic locations. In transforming the flat lattice to the final shape there was a significant component of lateral movement related to the gain in height. To accommodate this the scaffolding towers were moved using forklifts, as shown in *Figure 3.1*. The building has been very successful and remains as one of the finest buildings of the 20th century, despite its original two-year design life. The process of pushing up on discrete areas during erection did concentrate stresses within particular areas, the consequence of which was a notable number of breakages of laths and finger joints. It also required operatives to work at height and under the temporarily supported grid; a scenario that would not be permitted under today's CDM regulations.



Figure 3.1: Construction of the Mannheim Gridshell

More recently Buro Happold have designed two single layer gridshells, one in timber, the other in cardboard. The first were the gridshell sculptures at the Earth Centre in Doncaster constructed in 1998, *Figure 3.2*. These were small timber lattice structures composed of a single layer of thin timber laths. A crane was used to lift the lattice into position and then it was manipulated with struts and ties from a flat grid to the final shape. An important lesson learnt on this project was that the nodes need to be extremely loose to enable rotation during formation.



Figure 3.2: The Gridshell at the Earth Centre in Doncaster

The second project was the Japanese Pavilion at the Hanover Expo 2000. This building was similar in shape to the Downland Gridshell and composed of cardboard tubes, *Figure 3.3*. The erection used the modular scaffold system PERI-UP, shown in *Figure 3.4*. The flat mat was laid out on a low-level scaffold bed and was pushed up into position using proprietary PERI jack known as a MULITPROP. Due to the similarity of the shape of this shell with the Downland Gridshell, a great deal was learnt from the experience of erecting the Hanover building.



Figure 3.3: The Japanese Pavilion, Hanover Expo 2000



Figure 3.4: Erection of Hanover Gridshell using PERI Scaffolding.

The Downland Gridshell has a triple bulb hourglass shape; it is 50m long, varies in width from 12.5m at the valleys to 16m at the crowns, while its height varies from 7.35m in the valleys to 9.5m in the central dome. *Figure 3.5* is a computer-generated model illustrating the shape. The lattice comprises a double layer of 50mm wide x 35mm deep laths. Further 50 x 35 oak lathes are used, after formation of the shell, to brace the structure and to support the cladding. The bracing laths running along the shell, below the window zone, support the cedar boards and are called “longitudinal rib-lathes”, those running across the shell and supporting the “Ribbon Roof” are called “transverse rib-laths”.



Figure 3.5: AutoCAD Model of Gridshell

Prototype

The shape of the gridshell is primarily driven by stiffness requirements; the double curvature of the shell generates geometric stiffness and is fundamental to its structural action in resisting asymmetric loads. Both physical and computer modelling played an essential role in determining the final geometry.

As the design progressed, discussions about the formation process lead to an undergraduate project, conducted, by Frank Jensen under the supervision of Dr Chris Williams, at Bath University to examine this issue. This was described in detail in *The Structural Engineer* 20 March 2001 Vol 79 No 6.

As the design was firmed up, the need for a full-scale prototype to test the behaviour of the lattice during formation became apparent. To this end a 5m x 2.5m prototype panel of the gridshell was constructed on site and subjected to double curvature, with the tightest radius reaching 5m, as shown in *Figure 3.1*. This represented a more onerous condition than would exist in the building, highlighting formation problems that might be encountered.



Figure 3.6: Prototype Panel

The prototype showed that the nodal connection, described in greater detail below, performed well and did not lock up as long as its bolts were kept loose. It also showed that tight radii of curvature were achievable.

The prototype was constructed from 120 linear metres of improved green oak; the individual lengths of the timber pieces averaged 530mm. Hence there were approximately 225 finger joints of which 7 failed. This represents a failure rate of 3% and allowance was then made for a similar percentage in the real structure.

4.0 Formation Technique

The initial concept for forming the Downland gridshell is illustrated in *Figure 4.1*. Upon completion of the artefact box the gridlines were to be marked on the floor deck. Scaffolding was to be erected on the workshop floor and extended over the adjacent terraces to create a level working-platform. The four layers of the lattice would then be laid out in a rectangular grid formed by squares with an edge length of 1m. Jacking towers to lift the lattice clear of the scaffold platform would be introduced enabling the removal of the scaffolding platform. It was noted that the base of these jacking towers require a system that would enable lateral movement as the lattice was raised. Safety scaffold towers would also have to be installed for protection of personnel in the event of accidental failure. This system foresaw the formation of the central dome first and, after it had been fully formed and fixed at its boundary, the outer two domes would be formed. Straps would then be installed over the valleys and between the floor and valleys in order to pull the valleys into shape. Upon forming the valleys the outer domes would be adjusted to their final shape and tied in at their boundaries. The actual sequence was markedly different from the initial concept.

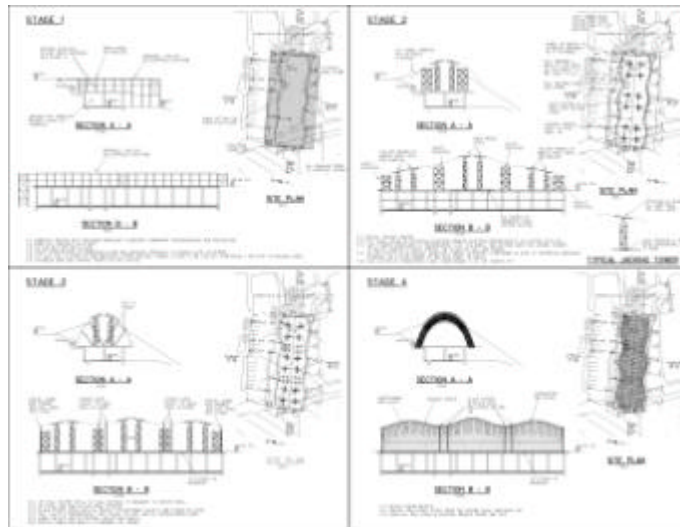


Figure 4.1: Initial Concept to Erect the Downland Gridshell

The physical models and the experience of the Hanover gridshell in particular were very influential in learning about the formation process. Leading on from this experience, three of the most significant decisions for Downland Gridshell were the level at which the laying out platform was to be set, the sequence to achieve the triple bulb hourglass shape, and the use of the PERI scaffolding system.

An innovation was the choice of layout level. For the Downland Gridshell the laying-out platform would be erected to the height of the valleys enabling the lattice to be lowered into position. This was a notable departure from previous projects where the strategy was to push against gravity, the larger the gridshell the greater the weight that had to be lifted. By starting at an elevated level the formation process for the Downland Gridshell would harness gravity in achieving the desired shape.

The triple bulb hourglass shape could be achieved by first forming a barrel-vault shape and then squeezing it to form the waists. This was the approach taken when building the models and it was found that significant out-of-plane forces were required to draw in the waists. It was felt that this would be difficult in the real structure and that it may cause a large number of breakages. Thus it was decided that the method should be progressive formation where the crowns and the valleys are formed simultaneously.

PERI scaffolding was used in the construction of the Japanese Pavilion where it had proved to be very suitable and effective. Its main advantage stems from the fact that it is a modular system coupled with several innovative patented accessories that endow it with the flexibility demanded in gridshell construction. Furthermore PERI would be able to bring their experience to bear in deciding the best procedure for formation. These factors combined made the selection of PERI scaffolding the obvious choice.

Layout of Flat Mat

The lattice was laid out as a flat mat composed of squares with a 1m edge length; the resulting lattice mat would be 47m long x 25m wide stretched longitudinally to achieve the 50m length of the completed structure. In this way the central node in each of the three domes was positioned according to their final longitudinal and transverse location. This meant that longitudinal changes in length were minimised adding a control; the central node of each dome could be monitored to check that their movement was only vertical. This changed the layout mat from a series of squares to a system of quadrilaterals, each edge 1m long, with two 96° and two 84° internal angles. *Figure 4.2* is a drawing of the layout mat, which was 49m long x 24.2m wide.

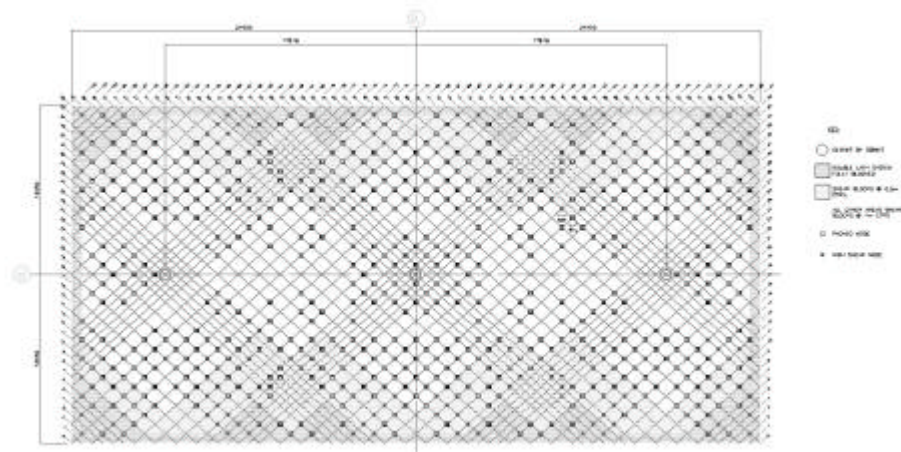


Figure 4.2: Drawing of the Layout of the Flat Lattice Mat

As the laths were made each had its 'address' written on it, in accordance with co-ordinate system shown in *Figure 4.8*. The zones in green and blue colours indicate the different shear block details; the nodes at the extremes of these zones were painted the appropriate colour in the layout so that they could be easily distinguished in the completed form.

A similar control was used to denote the extent of longitudinal and transverse rib laths. Plastic ties of two different colours were attached to each node; a red tie indicating a node to which a longitudinal lath is attached, while a yellow tie indicated a transverse rib lath.

The laths were laid out to the correct pattern by marking where the ends of each lath crossed the outermost PERI beam of the supporting scaffold. *Figure 4.3* is a photograph of the completed layout mat.



Figure 4.3: The Completed Layout of the Flat Lattice Mat

Scaffolding System

The scaffolding used on the project was the PERI-UP system. This is a modular scaffold system with many features that made it suitable for the formation of the gridshell.

The system uses the PERI MULTIPROP, adjustable jacks with built-in length gauges. This provided the construction team with an efficient and accurate means of altering the height of the scaffolding to deform the lattice. *Figure 4.4* is a photograph of main type of MULTIPROP used in this project, the MP 480, which enables a vertical adjustment of up to 2.2m.



Figure 4.4: The PERI MULTIPROP

A birdcage of scaffolding with a plan area the size of the layout mat was built to a height of 7m above the workshop floor. The platform to support the timber lattice was created using PERI's universal girder, which is neatly supported at both ends by a fork head attachment to a MULTIPROP, as shown in the photograph in *Figure 4.5*. The PERI beams were orientated parallel to the longitudinal axis of the building. When the laths were being laid out there was a continuous line of PERI beams along each longitudinal line of standards.

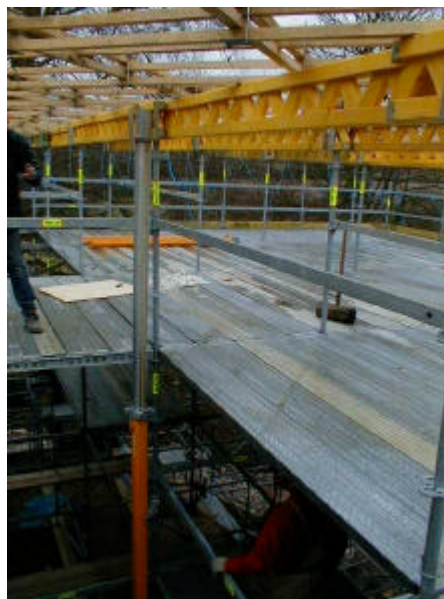


Figure 4.5: The PERI Universal Girder

The layout platform was high above the deck and this presented the logistical problem of getting 36m long timber laths onto the platform. Fortunately the topography of the site presented an opportunity. The building is constructed on a terraced site and the scaffold platform was extended to bridge from an existing higher terrace to the layout platform. The laths, which were very flexible, could then be carried from the workshop in which they were constructed up to the upper terrace and across the bridge to be laid out. *Figure 4.6* shows the carpenters carrying a lath onto the platform.



Figure 4.6: Carrying Laths on Scaffolding Platform

Monitoring the Formation Process

The opportunities presented by the flat layout pattern were fully utilised to install measures to monitor the formation. The longitudinal centre line of the lattice does not move transversely; throughout formation it should form a straight longitudinal centre line. The top of all the nodes along the longitudinal centre line were painted white to provide a visual means of checking that a straight line is being maintained, as shown in *Figure 4.7*.



Figure 4.7: Nodes along the Longitudinal Centre Line were Painted White

Plum-lines were attached to control nodes along the longitudinal centre line. This provided another means of visually monitoring that the longitudinal centre line remains straight.

The central nodes in each of the domes only need to move vertically towards their final location; hence another monitor was to mark the transverse and longitudinal location of these nodes on the scaffolding platform and checking that these only moved vertically.

Spreadsheets

Spreadsheets were used extensively to guide the formation process from a flat lattice to the doubly curved shape of the gridshell. From the formfinding geometry, the starting position of the flat mat and the final shape of the lattice were known at all the MULTIPROP locations. With this information intermediate shapes for formation could be predicted using linear interpolation, effectively giving a series of increments from layout to final shape. This interpolation was extended to give prop readings at the end of a given increment. By taking the end of day prop readings the total vertical change in prop height could be calculated and from this the height of the lattice above the deck. Using this information the shape of the lattice was always known and the actual shape could be compared to the theoretical shape for a particular increment during formation. *Figure 4.8* shows a typical spreadsheet graph showing the starting position, the final shape, and comparing the actual with the theoretical incremental shape for a section through the valleys.

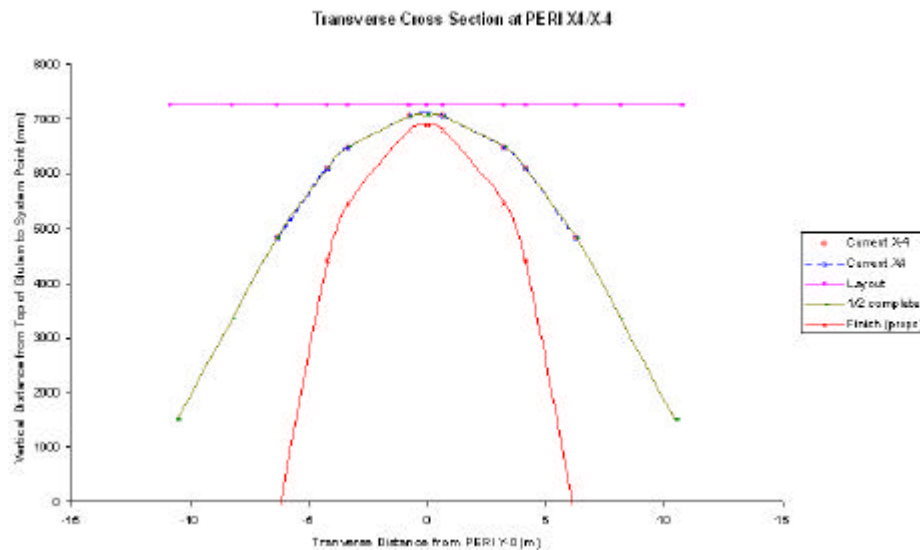


Figure 4.8: A Typical Spreadsheet used to Monitor the Formation Process

The maintenance of symmetry of the lattice about both its longitudinal and transverse centrelines was an essential consideration throughout formation. The spreadsheets proved to be an effective means of monitoring this. Although the spreadsheets proved to be very useful, there is no substitute for observing what the structure is doing. Indeed it has been suggested that markers on the scaffolding indicating a series of incremental positions may have been sufficient guidance but a method of determining the increments would be required and spreadsheets would be the easiest way of doing this.

Scissoring and Sliding

In the formation of a double layer gridshell it is essential that both scissoring and sliding occur. Scissoring is basically rotation of the laths at the nodes, while sliding is the relative movement of the outer layers with respect to the inner layers.

Scissoring of the lattice involves longitudinal simultaneous elongation of the quadrilaterals in the valleys with transverse elongation within the crowns. This process pushes materials from the valleys and into the crowns, thereby squeezing the valleys and enlarging the crowns. Initially 11 manipulation zones were identified. Within these zones in-plane ratchet straps were attached in the plane of the shell. These ratchet straps were then tightened effectively pretensioning the zones and resulting in a predisposition to scissor in the desired direction. *Figure 4.10* is a photograph of the in-plane ratchet straps in one of the manipulation zones.



Figure 4.10: In-Plane Ratchet Strap

A number of different strapping systems were used. When the formation was around 25% complete it was observed that the lattice was not scissoring in the valleys. The laths in these areas had remained straight with little or no evidence of geodesic curvature. *Figure 4.11* is a sketch of one of the strapping system (type A) used in the valleys and *Figure 4.12* shows the locations where the system was installed on the layout plan. Winch pulleys with spreader beams were connected to the central scaffolding bay; ratchet straps connected these to timber spreaders that bore upon the central plate of the double layer system. In total, eight of these systems were installed, each pulling on two laths.

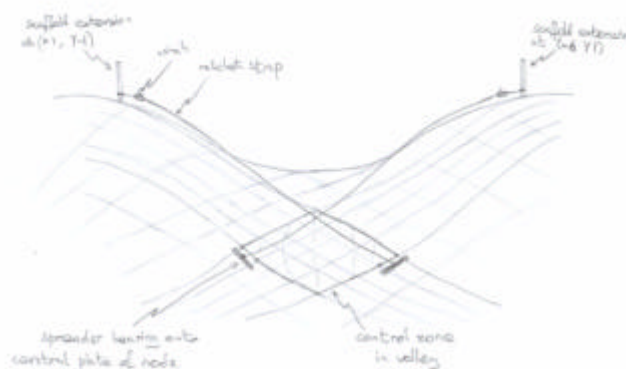


Figure 4.11: Sketch of Strapping System Type A

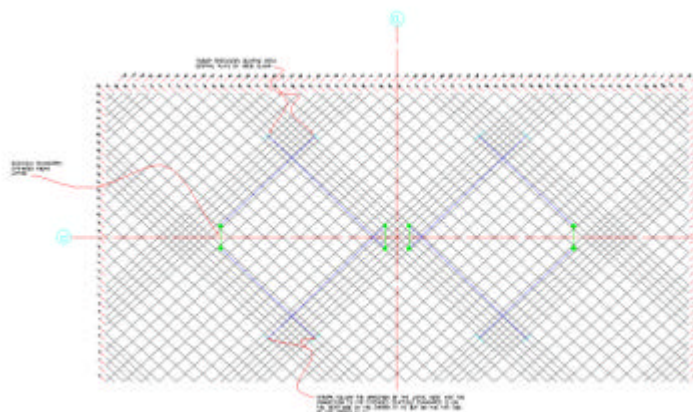


Figure 4.12: Locations of Strapping System Type A

Sliding of the layers relative to one another within the double lath system is necessary due to the fact that the two layers of laths have a different overall length in the completed shape because the outer layers are bent to a slightly greater radius of curvature. Therefore if relative sliding is prevented the lattice will 'lock-up' and induce breakages.

The only place in the building where this relative movement does not occur is across the longitudinal centreline. Therefore the node clamps were not required along this line and instead a single bolt was inserted through these nodes; this enabled rotation but prevented relative movement of the laths. This meant that the extra length of the uppermost layer with respect to its inner partner could be calculated taking into consideration the change in curvature of the laths along their length.

Formation of the Gable Ends

The shape of the gable ends presents a particular challenge. The natural tendency for the lattice is to form the shape of another valley at its ends. However the required shape does not conform to this natural flow; it represents a discontinuity of shape that has to be imposed on the lattice. Within a distance of 3m to 4m the scissoring action has to change from vertical elongation to form the crowns to horizontal elongation to form the gable end. Needless to say this dramatic change in condition can only be achieved by using superimposed external forces.

Figure 4.13 is a sketch of the strapping system used and shows the strapping on the layout plan. The central three diamonds each had a tensioning strap running transversely node to node producing in-plane tension in this zone. However it was quickly identified that further measures would be required to achieve the desired shape. The scaffolding standards on PERI grid $\pm X8 \pm Y1$ were extended above the upper plane of the lattice. Long tensioning straps were attached to these standards extension at one end while the other end to a node located at lower portion of the gable end. The fact that the straps were not continued to the other side of the section curve meant that out-of-plane forces were minimised. These straps were kept tense with the nett effect being that the superimposed forces enabled the gable end shape to be formed. Figure 4.14 is a photograph of this arrangement.

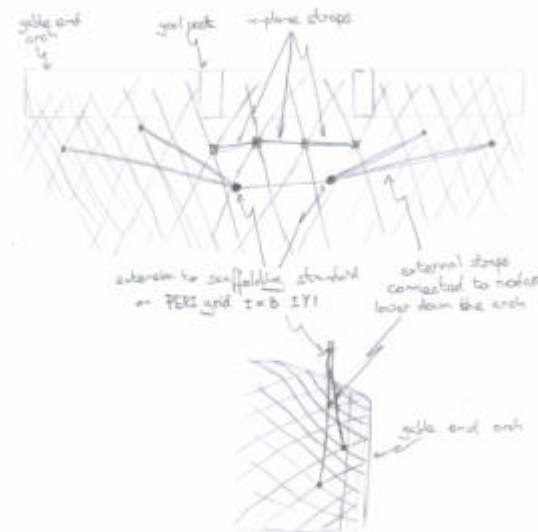


Figure 4.13: Sketch of Gable End Strapping System



Figure 4.14: Photograph of Gable End Strapping System

Formation of the Crowns

The lattice was initially laid at a height equivalent to the finished level of the valleys. At the early stages of formation to crowns were easy to push up but this became progressively more difficult as more shape was induced. Thus it became necessary around the half way stage to install a winch system. *Figure 4.15* and *Figure 4.16* illustrate the winch systems used.

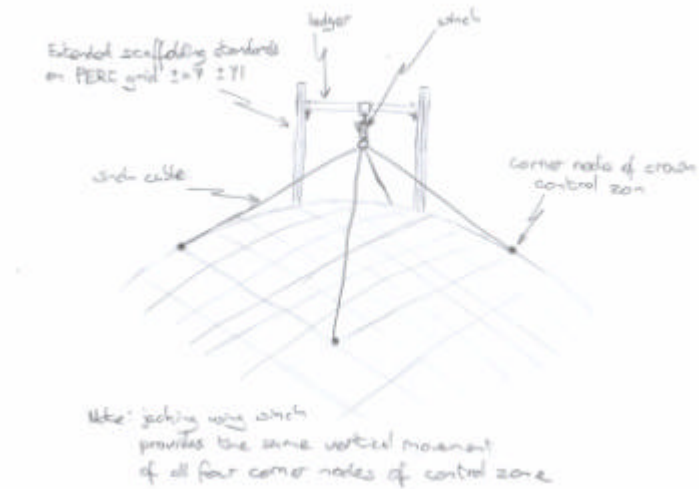


Figure 4.15: Sketch of Winch System for Outer Crowns



Figure 4.16: Winch System for Centre Crown

Raking Props

When the formation process was just over 50% complete direct vertical support was no longer appropriate at the edges and raking MULTIPROPS were installed. These were fixed to the scaffolding cage using raking scaffolding standards. These props were attached to individual nodes in the lattice as shown in *Figure 4.17* and *Figure 4.18*.



Figure 4.17: Raking MULTIPROP



Figure 4.18: Universal Joint at base of Raking MULTIPROP

Monitoring the Movement of Individual Nodes

The form finding model generated the co-ordinates for each and every node in the completed shape relative to an origin. Hence the final theoretical position of any node could be located.

This information proved especially useful in defining the perimeter. The final form is very much dependent on the correct boundary shape being attained and the location of every third lath was marked along the perimeter. Nylon ropes were used to guide the appropriate lath to its relevant location.

In addition to the perimeter nodes a number of nodes within the lattice were selected and their x and y co-ordinates were marked on the deck. This corresponded to the point above which the node should come to rest in the final shape. A rope was tied from the marked point on the deck to the selected node, its length adjusted so that it was taut at the end of each move. Thus when the node had reached its final theoretical position the rope would be perfectly vertical. Furthermore a white flag was attached to the rope at a distance equal to the theoretical height of the node above the deck in the final form, so if the node reached its theoretical final position the rope would be vertical and the white flag would be on the node.

One particular problem that no control could guard against was the development of areas where individual laths were locally over-stressed to a point that could induce failure. Thus the carpentry team were continually watching out for this. Failure of the lattice to scissor adequately or for the laths to slide relative to one another were considerations throughout formation against which observation proved to be the most powerful tool.

Trial and Error Approach

Trial and error proved to be the best way of determining effective layout of the strapping arrangement. A strapping system would be installed and its performance continually monitored. Generally it was found that effective strapping worked well for a time but needed to be modified as formation progressed. Hence strapping arrangements were being continually reviewed and observation played a central role in this.

The small straps in the 11 manipulation zone were not effective on their own because there were too few of them to build up sufficient force to induce scissoring. However longer external straps were successful in bringing them into play. It is important to note that all the strapping was arranged to maximise in-plane forces and to minimise out-of-plane forces. Out-of-plane forces should be avoided because they lead to a build up of friction which restricts passage of the laths over the PERI beams and relative sliding of the double lath system.

Final Adjustments to Gridshell

When the lowering of the gridshell was complete further adjustment was required to bring it into its final shape. Prior to making the final adjustment the building was measured using a plum-line to the scaffolding grid, see *Figure 4.19*, and a comparison was made with theoretical shape. This information complimented observing the actual structure and comparing its shape this with that of the wire mesh model.



Figure 4.19: Measuring the Gridshell with a Plum-line

Both valleys coincided with theoretical shape remarkably well. The valleys defined the head room requirement of the building and since the correct height and volume was achieved in this region no modification was required.

Measurements showed the height of the domes to be too low by 250mm; there was also a notable absence to volume indicating the need to force these domes into a more bulbous shape.

The perimeter nodes around the outer domes were appropriately 300mm too low. Hence the nodes directly above the perimeter edge were not forming the desired straight line. A white nylon rope was run along the nodes corresponding to the line of the highest longitudinal rib lath. Comparisons of this line with its equivalent on the wire mesh model indicated that the wave shape of this longitudinal rib lath was not being achieved.

The gable end detail also had to be considered. The approach of the laths was too shallow for the existing gable end arch. Again this suggested that more height and volume was required in the outer domes to capture the correct angle of approach for the gable end arch.

Adjustment of the lattice was performed considering each half of the outer domes in turn. A long ratchet strap was fixed at about mid-height on the outer dome. This strap prevented scissoring by maintaining a constant distance between nodes as the dome modified. Small MULTIPROPS were positioned on each node in the line directly above the perimeter, a photograph of which is shown in *Figure 4.20*. In areas of particular flatness additional raking MULTIPROPS were installed.



Figure 4.20: Small MULTIPROP pushing up Perimeter Node

This procedure was carried out on each quarter of the outer domes in turn. The results of the alteration process were very satisfactory. Both outer domes gained the volume that they lacked before. The lines of both the lower row of nodes and the highest longitudinal rib lath were consistent with the wire mesh model. Furthermore the approach slope of the lattice to the gable end arch was close to that being sought. Measurements showed that the outer domes were now only 100mm lower than theoretical, also the position of the highest point was located in its correct place.

Photographs of the completed shape are presented in *Figure 4.22* and *Figure 4.23*.



Figure 4.22: Final Shape from East Scaffold Tower



Figure 4.23: Final Shape from West Platform

5.0 Health and Safety

Health and safety issues were paramount and there have been no reportable accidents nor near accidents. Many of the procedures and practices implemented in this project simply follow the guidance provided in the Construction (Design and Management) Regulations 1994. Application of some of the basic principles followed on this project could have similar benefits for any construction project, not just for the formation of a gridshell.

First and foremost there was one person in charge, in this case Steve Corbett of GOCC. He was responsible for all aspects of the project. Everybody involved with the site was informed that any unsafe practices were to be reported to him so that immediate action could be taken.

PERI Scaffolding was an integral part of the formation process. It was decided that the team of carpenters should construct and modify the scaffolding rather than a team of scaffolders. Continuity of the team meant that as the project progressed the whole team was being educated in the structure and the means of forming it. This engendered a spirit of teamwork and encouraged comments on procedures, and in particular safety; furthermore in a number of cases it led to innovations that made construction easier.

The team was briefed each morning on the day's work so that everyone knew what areas were being reconfigured and why. The first issue addressed at these morning sessions was always the previous day's work. This gave everyone the opportunity to comment on procedures that they felt uneasy with and a chance for the whole team to derive a solution. This established a feedback loop engendering continual improvements to safety.

The highest risk of accidents was identified as the lifting of heavy equipment, falls and falling objects. Appropriate measures were taken to negate these risks.

With respect to lifting PERI scaffolding components are designed to a maximum weight of 20kg, with average weight of 10kg. Hence all scaffolding components could be handled safely by one or two operatives. The timber laths were of small section and thus it was the length of the laths that was the deciding factor in the number of carpenters required to carry them.

The scaffolding has integrated hand rail and stair systems. However given the nature of the project there was a need to work with incomplete scaffold. In such cases the areas concerned were distinctly marked out-of-bounds, with access restricted to those working on that particular area. When working at heights the carpenters wore safety harnesses clipped to the rosettes on the standards or to the lattice, as shown in *Figure 5.1*.



Figure 5.1: Safety Harness when working at Height

The nature of the work meant there was a great increase of the risk of slipping or falling with inclement weather; hence the site was closed during heavy rain, high wind, snow and icy conditions.

To reduce the risk of falling objects lanyards were attached to tools and equipment. There were also toe rails at the edge of all scaffolding decks.

Conclusions

The Downland gridshell is the first double layer timber gridshell in the UK and only fifth worldwide. Despite being an efficient and environmentally sustainable structural form there seems to be a reluctance to adopt double layer timber gridshells. A possible reason for this is the difficulties encountered in forming the double curvature of the complete shape from an initial flat mat of laths.

The success of the Downland gridshell project is the result of close co-operation of the design and construction teams. In this spirit of teamwork many of the problems that arose were overcome by constructive input from all concerned.

The initial concept for the formation technique was developed by learning from the experiences of past projects and through the construction of physical models and prototypes.

Spreadsheets were extensively used to assist and monitor the formation process.

The starting point for the formation process was to lay out the flat lattice on a scaffolding platform at the height of the valleys in the final shape, thereby taking full advantage of gravity throughout formation.

PERI-UP was the scaffold system used. This modulated system has several innovative features, especially the MULTIPROP, which offered many advantages for the method of construction used.

It was necessary to install several different strapping systems to aid scissoring of the lattice. These systems were continually reviewed and modified as demands of the lattice dictated. Only in-plane strapping was used because out-of-plane forces could cause potential difficulties, particularly by increasing friction.

Observation was seen as the key control. Problems and potential problems were most effectively isolated by continually observing the lattice and its behaviour.

Health and Safety was paramount on the site. There was a debriefing session every morning providing the opportunity to review and discuss safety. The result was no reportable accidents nor near accidents.

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This has been a team project and many individuals, from the various organisations involved in the design and construction, have made significant contributions in realising this unique project.

They are as follows:

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Mechanical and Electrical Engineers – Buro Happold
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