

Design and construction of the Downland Gridshell

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A gridshell is a structure that gains its strength and stiffness through its double curvature configuration. Its advantages are a minimum use of materials, structural efficiency and the creation of a large volume, as well as the potential for quick and cost-effective construction. However, few gridshells have been built due to a lack of knowledge and data. The process of creating the Downland Gridshell, as a specialist museum workshop completed in the spring of 2002, is a case study of successful collaboration and innovation in architecture, engineering and construction led by a multidisciplinary team of practitioners. This gridshell structure was composed of a double layer of mats comprising four layers of thin timber laths. These were harnessed together as a flat mat and then formed into a three-dimensional structure by a carefully orchestrated lowering of each supporting scaffolding prop, thereby harnessing gravity to pull the mat into shape. Many innovations are described in detail: team working, risk sharing, multidisciplinary design, structural modelling, the creation of new structural components, cladding, and construction processes including the sequence and techniques of gridshell forming. Advances made in this project have added to the knowledge of gridshell behaviour, construction and cost, thereby making the design and construction of future timber gridshells a more viable option.

Keywords: alternative technology, construction process, design, dynamic structural analysis, gridshell, sustainability, timber engineering, timber

Une structure en voiles minces est une structure qui tire sa résistance et sa rigidité de sa configuration à double courbure. Ses avantages sont une utilisation minimale de matériaux, son efficacité structurelle, et la création d'un grand volume, aussi bien que les possibilités de réalisation rapide et rentable de construction. Cependant, peu de structures en voiles minces ont été construites, en raison d'un manque de connaissances et de données. Le processus de création du Downland Gridshell, terminé au printemps 2002 et utilisé comme atelier d'un musée spécialisé, est un cas type d'innovation et de collaboration réussies en matière d'architecture, d'ingénierie et de construction, menées par une équipe interdisciplinaire de praticiens. Cette structure était constituée d'une double couche de mats (coques) comprenant quatre couches de minces lattes en bois de construction. Celles-ci étaient assujetties ensemble sous forme d'un mat plat auquel fut ensuite donnée la forme d'une structure tridimensionnelle par l'abaissement soigneusement orchestré de chaque étau soutenant l'échafaudage, en tirant ainsi parti de la gravité pour donner sa forme au mat. De nombreuses innovations sont décrites en détail: travail d'équipe, partage des risques, conception pluridisciplinaire, modélisation structurelle, création de nouveaux éléments de construction, bardage, et procédés de construction comprenant la séquence et les techniques de formage de la structure à voiles minces. Les progrès réalisés sur ce projet ont contribué à la connaissance de la tenue, de la construction et du coût d'une structure à voiles minces, faisant ainsi de la conception et de la construction de futures structures à voiles minces à coque bois une solution plus viable.

Mots clés: technologie alternative, procédé de construction, conception, analyse structurelle dynamique, structure à voiles minces, durabilité, technique de construction en bois, bois de construction

Introduction

A shell is a structure that gains its strength and stiffness through its double curvature and in-plane shear properties. Its advantages are a minimum use of material and structural efficiency; it resists applied loads through its inherent configuration. A gridshell is a shell with large openings in it in a manner that allows the remaining strips or grids to behave, structurally, as a shell. Alternatively, it can be considered as grids arranged in such a way as to have the properties of a shell. The gridshell is a very effective way of addressing the various structural and architectural demands. By concentrating the shell into strips, openings are easily created. By adjusting the depth of the strips, the stiffness out of plane, and thus the buckling capacity, can be modified. By making discrete strips, pre-fabrication is possible. In computer form finding, the engineer and architect work together to develop a practical, pleasing shape that is sound and efficient.

The first double-layer timber gridshell in the UK was recently constructed as part of a new building for the Weald and Downland Open Air Museum, near Chichester, Sussex. A double-layer timber gridshell was comprised of four layers of timber laths, which formed two three-dimensional mats harnessed together. It was formed during construction from an initial flat mat of straight timber laths. Despite their many advantages, double-layer timber gridshells are uncommon; the Downland Gridshell is only the fifth of its kind ever to have been built. The reluctance to adopt this type of structure may stem from the perceived difficulties associated with its design and construction.

This paper describes the generation of the design, the various types of structural modelling and how some of the problems of realizing such an innovative solution were addressed. It also describes how a multidisciplinary team of engineers, architects, researchers, carpenters and clients engaged in a process leading to several innovations and the sharing of risk. The commitment of the client in supporting the innovation process was essential. It then describes the construction process, showing the level of skill required.

Major innovations during the project included the following:

- Software advances
- Advances in timber gridshell technique
- Labelling of timbers when laid out in flat mat, before forming

- Innovative node clamp
- Monitoring of gridshell forming
- Sequence and technique of gridshell forming
- Elimination of fire treatment
- Locally grown timber used for naturally durable cladding
- 'Improved timber' using high-speed finger jointing
- Integrated mixture of craft and modern techniques
- Minimization of waste.

Background

Ted Happold (1930–96), founding partner of Buro Happold, worked on the Mannheim gridshell in Germany (Architect Frei Otto, built 1975), when he was with Ove Arup & Partners. For many years after its completion, Happold promoted the benefit of the timber gridshell as a construction technique and stated that he could not understand why it had not been adopted more widely. He perceived the benefits to be in the efficiency of the construction method to enable doubly curved (shell) structures to be constructed quickly and cost effectively. A doubly curved structure offers the benefits of a minimal use of materials and therefore an efficient coverage of space. Such a structure can be made either in situ in the case of concrete or in a factory in the case of steel or aluminium. Except in the case of a spherical gridshell, the repetition of the elements is very limited and the shell is made from a complex set of components. In contrast, a timber gridshell enables doubly curved structures to be formed from a set of straight, prefabricated, identical components. A number of Happold's partners at Buro Happold had worked with him on the Mannheim gridshell and, when the opportunity arose to design a series of small landscape structures at the Earth Centre, near Doncaster, UK, in 1994, gridshells were proposed.

The key to the modern use of timber gridshells is the development of computer methods in modelling complex three-dimensional shell structures. For the Mannheim structure, the primary method of form finding was the use of physical models. The Earth Centre structures were small and easily modelled using wire mesh, but when Buro Happold were commissioned to design the Japanese Pavilion for Expo 2000 in Hannover (Architect Shigeru Ban), it was apparent that

much more sophisticated computer form finding and analysis would be necessary.

Dr Chris Williams at the University of Bath, UK, has been working in the field of non-linear analysis of structures for many years. While at Arup in the 1970s, he carried out the analysis of the Mannheim shell. Over the subsequent years, he has refined his methods and now uses dynamic relaxation methods to form find timber gridshells. The technique is explained in more detail below.

The architectural design for the Downland Gridshell followed on from the completion of the Westminster Lodge student residence building at Hooke Park, Dorset, UK, by Edward Cullinan Architects (Burton *et al.*, 1998). The range of possibilities available from small diameter thinnings of considerable length made a great impression on the Cullinan/Happold team. As the lengths of timber are generally limited by the size of the tree, long timbers are usually associated with mature trees. Traditionally, the design of timber structures has been dominated by the resolution of the joints. At Westminster Lodge, immature thinnings were splice-jointed into lengths of 20 m. The use of immature thinnings also had environmental benefits. At the Downland Gridshell, the laths were of oak improved by cutting out shortgrain and other irregularities and spliced into very long lengths. There are two particular benefits of long timbers. First, as discussed above, structurally a curved gridshell generates axial (in-plane) forces in its component elements. Generally, in-plane forces are more efficiently carried than out-of-plane forces that generate bending stresses. With very long structural components, the axial forces are carried efficiently to the points where they can be resisted. Second, in architectural terms, long elements have visual elegance, they are not disrupted by joints and they enable detailing to be consistent.

The confluence of the structural engineering knowledge of Buro Happold, the analytical capability of the University of Bath and the design flair of Edward Cullinan Architects enabled a radical concept design to be submitted to the client for this building.

Concept

Client brief

The Weald and Downland Open Air Museum is a centre of excellence for the restoration of timber buildings. It was opened in 1970 and for more than 30 years Christopher Zeuner, who died in January 2001, was its director. For much of that time, Zeuner worked with Richard Harris (not the author) to build the Museum into an innovative, highly respected organization. More than 45 historic structures from the South East of England have been rescued and rebuilt on the site.

These either have been at risk due to neglect or have been threatened by development.

A new workshop was needed to enable this highly skilled work to be continued and the restoration process displayed to the visitors to the Museum. The medieval framing techniques used in the restoration work involve laying out the timber frames on the workshop floor and scribing and cutting the joints between the members. The structures need to be framed in three dimensions, the elements being framed in one dimension and then disassembled before being framed in another. Traditionally, timber-framing workshops have been housed in large agricultural buildings. The space needs to be sufficient to lay the frames out and, for more complex structures, to stand them up. The Museum's workshop restores traditional English timber buildings, which use green (unseasoned) oak for their primary structure. This material is much easier to work than dry oak. To maintain the moisture content and provide a comfortable environment for the hard manual work of framing, a requirement for the main workshop space was for it to be unheated. As in workshops in the past, it is likely that the carpenters will leave the end doors of the building wide open to allow a good flow of air through the building. In this way, temperature and relative humidity levels will be maintained naturally and consistently in the work areas and for the materials. The smaller, enclosed workshops enable the teaching spaces to be conditioned to the levels of comfort required, without affecting the larger space.

The client brief called for an artefact store and a workshop. As the artefacts were fairly robust objects made of iron and wood, the store did not need a closely controlled environment, but the conditions should not fluctuate rapidly. The site available for the new building was a terraced hillside and the natural solution was to excavate the store into the ground to benefit from the moderating effect of temperature below ground.

At early stages of the project, there were no lofty notions of a gridshell structure. Steve Johnson, Project Architect, described the initial idea as:

a box on top of a box where the rectilinear timber framed workshop was situated on top of subterranean artefact store. ... At that stage the workshop was to be a covered yard; a covered area to stop the rain going down the backs of the carpenters. We were keen to have a good flow of air through this area.

Client Richard Harris (now Director of the Museum) remembered that:

the first suggestion was using round wood in a single lattice with plastic tags at the nodes.

As the design progressed, it became obvious that a more technically challenging solution was required. Many clients would find the associated risk off-putting, but according to Gail Kittle, the Museum's Operations Director:

The museum is not risk adverse and always had a positive 'can do' attitude towards this project.

Given the remarkable reputation of the Museum, clients Zeuner and Harris were determined to appoint a design team that would create something special. The buildings in the Museum represented the best of their type. They wanted a new building that would be the best that the early 21st century could produce. There could be benefits in aiming high, and one of these, they came to understand, was how it was possible to put a strong case for funding a building that was special for those associated with it. The Heritage Lottery Fund (HLF) was constant in its support for the building. Their assessor and monitor, Terry Doyle, came to the project from the commercial world of office development. His understanding and constant support of the aims of the project was vital to its success. The HLF funded the project to the scheme design stage and then allowed the early appointment of the Green Oak Carpentry Co. (GOCC) to help the team finalize the methods and details before the main contractor (E. A. Chiverton Ltd) was appointed.

The environmental and sustainability credentials of the building were an important consideration. A major part of the funding was to come from the HLF. This was dependent, among other things, on the proposal to test the possibilities of making use of local British timber in an innovative way. Project Architect Steve Johnson remarked:

The aim was to use local materials and skills. Quality and cost issues meant that we had to extend this to regionally available materials. However all materials are biodegradable, reusable or recyclable. A remarkable feature of this building is that there is almost no plastic. Even the polycarbonate glazing is recyclable.

Part of the client's brief was that the building should employ craft techniques. It was not necessary to use high craft skills in the building but, with the brief asking for an expression of craft skills and with a contractor possessing an abundance of them, a number of carpentry craft techniques were employed, particularly in the end walls and for the cladding. The structure was clad with a loose system of hanging western red cedar boards. The difficult-to-drain upper pitches of the building were clad in an undulating ribbon of water-tight monolithic roof, which was supported on a complex framework of timber posts. A polycarbonate glazing zone was incorporated between the 'ribbon roof' and the cedar boards.

Conceptual solution

The whole solution proposed for the building was to use relatively heavy construction for the artefact store; it has a concrete floor and reinforced masonry walls. The roof of the store is a timber structure consisting of glue laminated beams. These support heavy timber boards forming the workshop floor. The beams cantilever over the masonry walls. From the edge of the workshop floor springs the workshop roof, a clear spanning timber gridshell (Figure 1).

The triple hourglass-shaped shell used for the roof was a very efficient structural form (Figure 2). The curvature of the valleys provided horizontal strength and

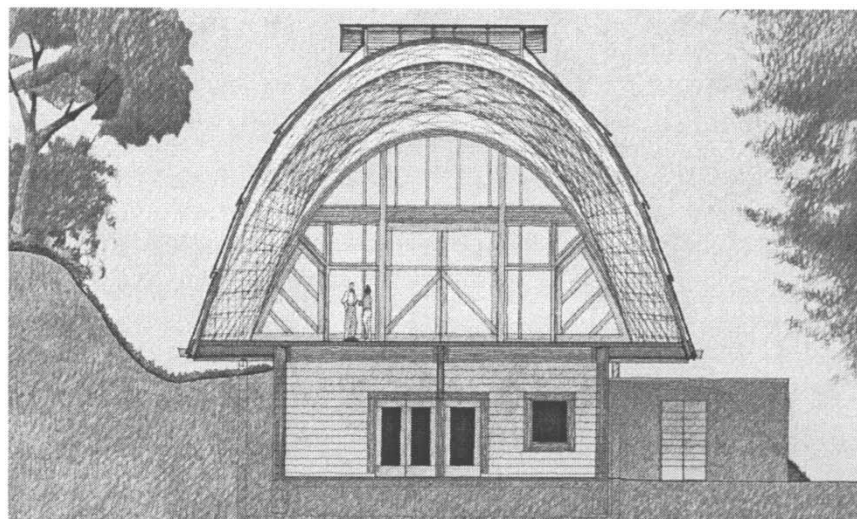


Figure 1 Architect's section

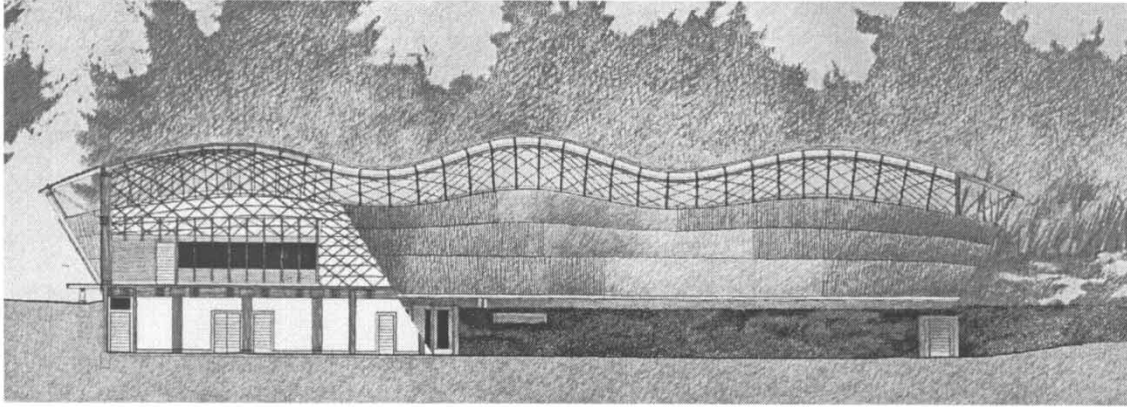


Figure 2 Architect's elevation

stiffness that a simple barrel-vaulted structure would not provide. The bulk of the space created by the gridshell roof was used for the framing workshop. Access was from large doors at both ends. For teaching, two enclosed workshops were provided within the large space.

Structure

Timber gridshell

A shell is a three-dimensional structure that resists applied loads through its inherent shape. There are a number of types that belong to this group of load-bearing structures, which carry the applied loads mainly by way of membrane forces. They are structurally efficient and carry loads by way of tension, compression and shear forces in the plane of the shell, and for this reason thin sections are possible. Because they are slender, the buckling behaviour out of the plane of the surface must be carefully studied. In terms of minimum use of material, a doubly curved shell is the most efficient structure, the forces being resisted by membrane action in simple tension or compression. The membrane cannot buckle in plane; the tendency to buckle out of plane is a function of the extent of double curvature and whether or not the forces experienced are in tension or compression. It is possible to build structures with stable surfaces either both curved in the same sense (synclastic) and in tension or curved in opposite senses (anticlastic) with the tensile forces in one direction stabilizing the tendency of the compressively stressed direction to buckle out of plane. These structures are limited by the tensile or compressive strength of the material.

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. No true shell structures are possible in timber; wood is anisotropic, that is its properties are different in all directions, thus timber 'shell'

structures are always made up from three-dimensional frameworks. For many years, there has been a search to find a regular structural form with identical members to form such frameworks; the use of regular members facilitates mass production. Richard Buckminster Fuller (1895–1983) was granted a patent in 1954 for an arrangements of plane figures that could be joined together to create a regular three-dimensional shape. This form, the geodesic dome, is generated by projecting an icosahedron (a 20-sided three-dimensional figure composed of equilateral triangles) onto an enclosing sphere. This form generates a surface contained within a sphere. Five triangles meet at each node, and if the whole surface is filled with triangles, a net is created made up of triangles that form hexagons with pentagons at the nodes. Clearly, the icosahedron can be projected onto a surface other than a sphere, but if the enclosing shape is not a sphere, the edge members of the plane figures are not regular. Very large structures have been constructed from geodesic domes (1967 World Expo, Montreal) and similar regular combinations of triangles and hexagons (1982 Tacoma; 1991 Superior Dome, Northern Michigan). These are synclastic structures gaining stability from their double curvature.

In contrast to the geodesic dome, the timber gridshell technique enables *irregular* complex doubly curved shapes to be created from a set of standard components.

Practical building design is driven by more than the need to minimize structure. There are requirements for enclosing space, providing openings and practical construction. Thus, structural shape is likely to be a compromise. The gridshell is a very effective way of addressing the various structural and architectural demands. By concentrating the shell into strips, openings are easily created. By adjusting the depth of the strips, the stiffness out of plane, and thus the buckling capacity, can be modified. By making discrete strips,

pre-fabrication is possible. In computer form finding, the engineer and architect work together to develop a practical, pleasing shape that is sound and efficient.

In the construction of timber gridshells, typically the lattice can be initially laid out as a flat mat of identical components and then pushed (upwards) 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. However, for construction and safety reasons, the Downland Gridshell uses a new construction process where the timber mats are constructed at high level and then pushed (downwards) into position. This is described in detail below.

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 with tight radii of curvature. The solution to this problem is to use a double-layer gridshell (Figure 3). In the case of the Downland Gridshell the lattice is composed of four layers, effectively two single-layer mats sitting one upon the other. The laths were of sufficiently small section to permit bending of the lattice into the desired geometry. After formation in a horizontal plane, timber shear blocks were installed. These enabled the transfer of horizontal shear between parallel layers and thereby endowed the lattice with the properties of a deeper section.

For three-dimensional structural stability, a gridshell must have in-plane shear strength and stiffness, which is provided either by preventing rotation at the intersections of the grid members (nodes) or by introducing bracing.

Modelling

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. A combination of both physical and computer modelling played an essential role in determining the final geometry. The development of these models is discussed.

Physical models

Physical modelling proved invaluable throughout the design and construction of the gridshell. Good physical representations were essential to enable effective discussion of concepts and the development of ideas.

The initial models (simple wire mesh models built to a scale of 1:100) were used to illustrate to the client and the design team the three-dimensional form of the proposed geometry. They also served to illustrate several engineering principles. The first was the formation of the shape from a flat rectangular mat that, through the imposition of the boundary conditions, could be manipulated into the complex three-dimensional form. Furthermore, they showed the stiffening effect of the bracing; in the wire models, this was provided by cotton thread tension elements.

Further development of the structural scheme led to the adoption of oak lath bracing, termed 'rib-laths', in lieu of steel cables for the structural bracing. This timber

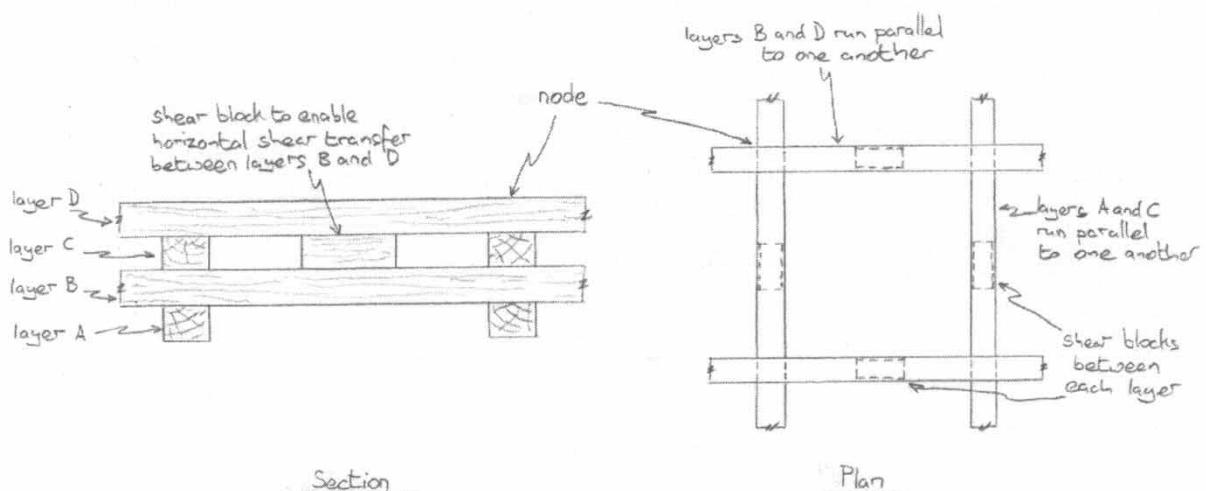


Figure 3 Double-layer gridshell

bracing system offered several advantages over the steel cable option. Steel cable can only act in tension and hence each rhomboid would require two cables running orthogonally. However, timber can carry both tension and compression, meaning that it is only necessary to run a bracing lath in one direction across a given rhomboid. An added benefit of this system that became immediately obvious that the cladding panels could be attached directly to the bracing, thereby reducing the complexity of their connection. The final gridshell had longitudinal rib-laths running along the sides of the building picking up the cladding, whereas higher up transverse rib-laths ran across the top of the building acting as support for the ribbon roof. Figure 4 shows the wire mesh model demonstrating the rib-lath bracing.

The next stage was the construction of a 1:30 scale model using strips of wood to represent the laths (Figure 5). This model was very instructive in developing a feel for the likely behaviour of the structure during the erection process. Furthermore, its geometry was used to determine the boundary conditions for the computer form-finding model. It also proved very persuasive in illustrating the viability of the scheme to the funding bodies.

As the design progressed, discussions about the forming process led to an undergraduate project at the University of Bath which examined the behaviour of the mat in translating from flat to curved. This project was described in detail by Jensen (2001).

A 1:43 scale model of the lattice was made using wire mesh (Figure 6). The scaled stiffness of the unbolted

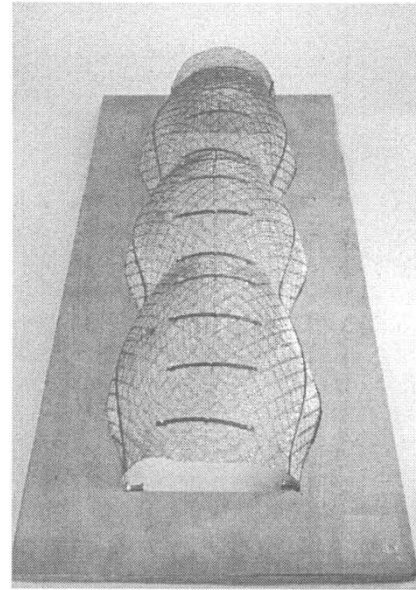


Figure 4 Scale 1:100 wire mesh model with rib-lath bracing

lattice was achieved by increasing the weight of the mesh by a factor of seven by hanging 128 nails under the mesh. Scaffolding and ties were modelled using dowels and twine. The model confirmed that the lattice would deform under its own weight during lowering. It also indicated that geometric stiffness would cause difficulty in forming the valleys and, even with the perimeter edge in position, it would be necessary to use external ties to force the valleys into position. It also showed that the gable end condition would be difficult

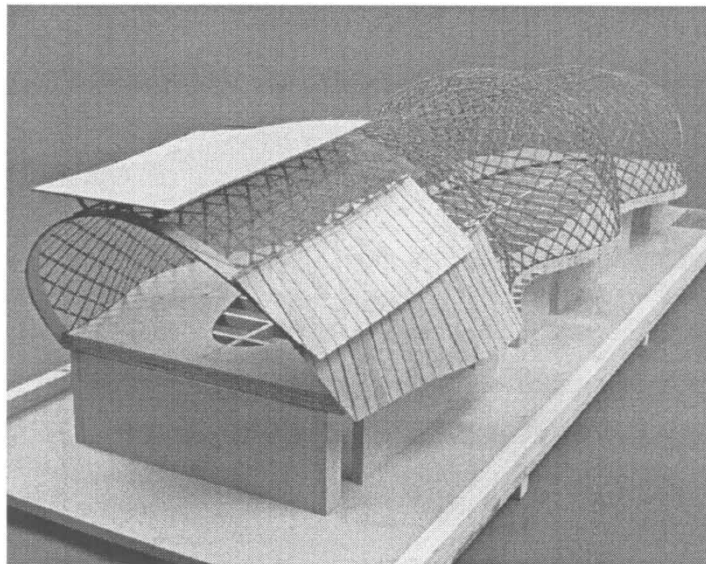


Figure 5 Scale 1:30 presentation model

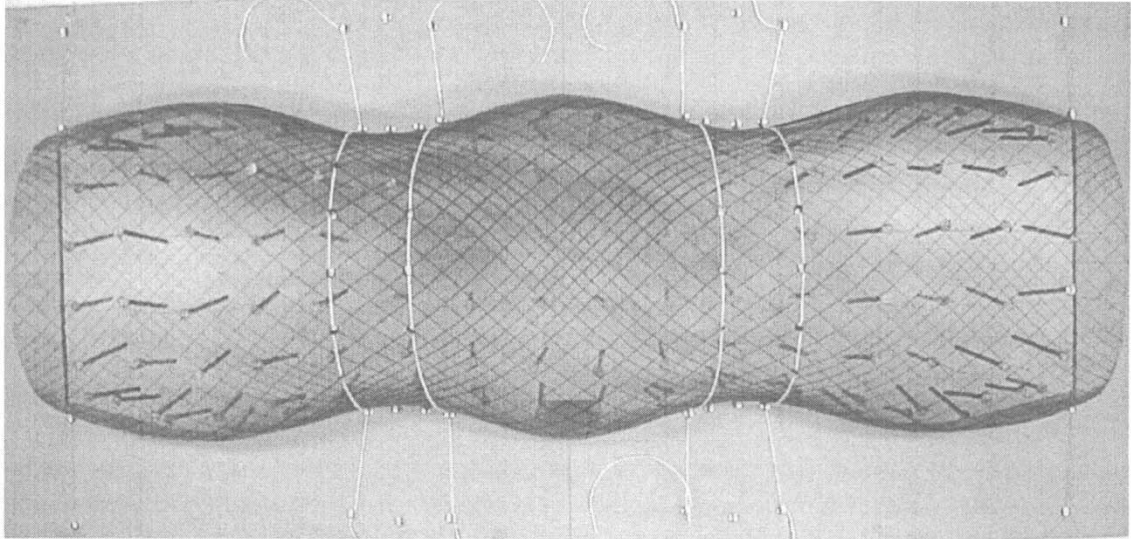


Figure 6 Scale 1:43 wire mesh model

to achieve. This information led to modifications in the proposed formation process, as discussed below.

This model 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. The behaviour of the accurately scaled wire mesh model was an excellent tool to show the extent that adjustments to the position in the shell in one area would affect other areas. Proposed movements could be examined empirically in the model. The adjustments to the gridshell could be selected, made and then checked against the model. Two viewing platforms had been set up for photographing the formation of the gridshell. These were ideal vantage points for viewing the actual structure to compare its shape, as it deformed, with the model. The use of the model was just part of the process. Accurate measurements could not be made on the model for direct transfer to the workforce making adjustments to the structure, but as a means of avoiding problems and checking that the adjustments were leading towards the final shape, comparisons were very helpful.

Computer models

The physical models were based on the architect's sketches, which in turn helped derive a computer model of the shape. The form finding was performed using a computer program specially written for the purpose by Chris Williams of the University of Bath. The starting point of the analysis was the sinusoidal plan and elevation and the requirement of forming this shape from a mesh with uniform lengths.

For the Mannheim gridshell, constructed in 1975, form finding was based on hanging chain models in which the structure was represented by an inverted chain net that hung under tension. A hanging model is particularly appropriate for masonry structures with a high self-weight and which cannot carry tensile forces; when the hanging model is inverted, the tension forces are replaced by compressive forces. Antonio Gaudí (1852–1926) used this technique for the Colonia Güell chapel and the Sagrada Familia (construction begun in Barcelona in 1910). It is also appropriate for lightweight structures made from timber, which creep under long-term gravity load. It was this technique that was used for the Mannheim timber gridshell, for which Frei Otto built the physical model. The technique can only model 'funicular' structures, i.e. structures curved in such a manner that they can be formed by elements only in tension under their own weight (and therefore compression when inverted).

Funicular structures are appropriate where the dominant load is self weight. This is often the case with long span (e.g. Mannheim) or heavy (e.g. Sagrada Familia) structures. For the Downland Gridshell, the self weight of the shell itself was small. The loading was dominated by lateral (wind) loads and the heavy strip of flat (ribbon) roof along its spine. Thus, the non-funicular shape was chosen. The reverse curvature of the valleys meant that the lattice must be manipulated into a shape in which the elements had induced shear force (and bending moments). Thus, it was not possible to create the desired profile from a hanging model. A funicular shape would be more of a 'barrel vault', which would have less lateral strength and stability than the form chosen. After forming, the timber gridshell was triangulated by longitudinal and transverse oak rib-laths to lock in its shape.

Computer analysis was based on the dynamic relaxation technique, 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 monitoring the kinetic energy of the model as it is made to oscillate. It was invented by A. S. Day (1965) and further developed by Mike Barnes, Professor of Civil Engineering, University of Bath. It is the computer technique commonly used in the modelling and analysis of tension (including fabric) structures, since it can handle wrinkling and other types of non-linear behaviour.

The Downland Gridshell was not a purely funicular shape; a hanging chain model could not be used to form the shape. Chris Williams modified the software to enable it to make allowances for the bending stiffness of the timber laths. He used members with elastic bending stiffness, enabling them to take tension, compression and shear forces during the form-finding operation. In order to push the shell into shape, external springs were added, particularly to give the correct amplitude of rise and fall to the elevation.

For this project, he found a doubly curved shape that could be produced from a flat mat of components, the output including details of the final curvature of all the structural members. The output could be presented on the curved shape or on the initial flat mat.

Figure 7 shows the computer model of the form-finding grid, while Figure 8 shows the structural grid of actual members that was obtained from the form-finding grid. Over some of the surface the actual grid was the same as the form-finding grid, and in other areas only every other form-finding line was a real member. This change in grid spacing was to ensure that the timber members were distributed most efficiently for load carrying.

As well as analysing the shell under load using the non-linear computer program, commercial software

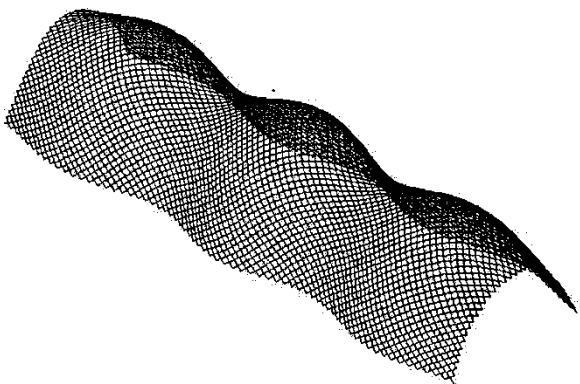


Figure 7 Form-finding grid

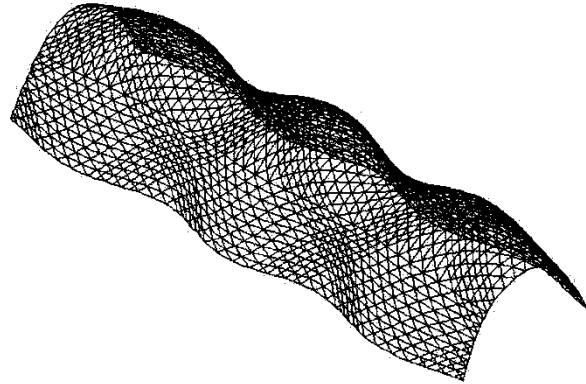


Figure 8 Structural grid

was used as an independent check. The first computer model had a double lath system with 50×30 mm laths spaced at 0.5 m centres and braced with timber rib-laths. Buckling analysis of this gridshell showed that it performed more than adequately and it was decided to try a lattice with the laths spaced at 1.0 m centres. This would effectively halve the quantity of timber required with added benefits with respect to the ease of erection and cost. However, this gridshell could not provide the required buckling resistance. It was therefore decided to try a double lath system with 50×35 mm laths at 1.0 m spacing. Again, the required performance was not achieved, but the analysis highlighted regions of weakness at the side of the domes. By reverting to the lath spacing of 0.5 m in these regions, the desired performance was achieved. The resulting grid had 0.5 m spacing in highly stressed strips and 1.0 m spacing in more lightly loaded areas.

The form was refined further to achieve the shape sought by the architect. This interactive process led to shapes at the gable ends where the natural flow of the gridshell was to start to form a valley, but the architecture required the gridshell to continue on a downward flow. The central dome was set higher than the outer domes to guard against the optical elusion of a sag in the centre of the building. Computer modelling enabled these important manipulations to be carried out; the same would not be possible with physical modelling.

Prototype

The shape of the gridshell was primarily driven by stiffness requirements; the double curvature of the shell generated geometric stiffness and was 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 was firmed up, the need for a full-scale prototype to test the behaviour of the lattice during



Figure 9 Prototype panel

formation became apparent. To this end, a 5×2.5 m prototype panel of the gridshell was constructed on site and subjected to double curvature, with the tightest radius reaching 5 m (Figure 9). This curvature had a radius smaller than that which would exist in the building, highlighting formation problems that might be encountered.

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 530 mm. Hence, there were approximately 225 finger joints of which seven failed. This represented a failure rate of 3% and allowance was then made for a similar percentage in the real structure.

Materials

The gridshell used 50 mm wide $\times$ 35 mm deep oak laths.

Selection of timber

A number of timber species were considered for use in the gridshell, including larch, Douglas fir, chestnut and oak. They were selected for the following reasons:

- They were all naturally durable, creating the possibility of omitting the timber treatment

- Oak and chestnut were the most common materials used in the Museum's collection of buildings
- They were all readily available from sustainable sources in the UK

Tests carried out on laths at the University of Bath indicated that the performance of the oak exceeded that of the other species. While it was stiffer than the other timbers tested, needing a larger force to achieve a given curvature, it had a considerably higher bending strength, achieving a smaller bending radius before failure. In addition, the failure mode was not sudden: there was a degree of plasticity at failure.

Short grain

The straightness of the grain along the length of the log is a function of the way in which the tree grows. This varies from species to species and while there are trees that grow with a more spiral pattern, oak does not grow with the straightness of grain of a timber such as Hemlock (chosen for the Mannheim gridshell for this reason). It is difficult to follow the grain of oak accurately when sawing timber out of the log. This means that when the saw cuts across the grain it produces timber with a lack of continuity of longitudinal fibres, leading to considerable reduction in strength. This effect is 'short grain'. In grading, it is measured as the angle of the grain to the longitudinal axis of the timber. In a sufficiently large timber, the twisted grain can be contained within the section. In small sections, the problem is increased considerably.

The gridshell used small timbers, and to overcome the problem, the latest jointing technology was used on

normal grade timber to cut out the defects and rejoin the lengths with finger joints, so forming laths of the required length and of a consistently high quality. The technical term for this process is 'optimization'.

Timber grade

The gridshell was analysed and designed in accordance with Eurocode 5: Design of Timber Structures, using a timber grade of D30. Eurocode 5 uses load and material factors in the design; timber grade D30 has a characteristic bending strength of 30 N/mm^2 .

Fireproofing of laths

It was unnecessary to treat the timber against fire. As a roof, a fire resistance period is not required. For flame spread, the increase in lath spacing from 500×500 to 1000×1000 mm (generally), the thin sections could be compared with window frames and so did not need treatment to comply with Building Regulations Approved Document B2 Section 7.

Preparation of oak laths

Owing to its acidity, oak is a notoriously difficult material to joint with adhesives, all the more so when green. The green oak used for the Downland Gridshell had moisture contents of up to 65%. The Swiss adhesive manufacturer Collano developed a one-part polyurethane liquid adhesive under the trade name Purbond HB 530 that was not adversely affected by the acidity of green oak. This adhesive was designed to cure under the influence of material moisture and humidity; the ideal moisture content for curing is 18%, but greater moisture contents will not inhibit curing. Curing is rapid without the need for expensive high-frequency heating. This adhesive cleared the path for the use of green oak.

The timber was optimized in a highly automated process using the GreCon Dimter OPTICUT 101 mechanized saw. Finger jointing was performed using the GreCon Dimter SUPRA continuous feed finger-jointing machine.

The gridshell lattice would require 6000 linear-metres of lath; considering that individual pieces of graded lath averaged 0.6 m, this represented 10 000 finger joints. Using the specialist machines, this work was completed in three shifts. Although the timber had to be transported to the specialist machine, the total weight was only 6 tonnes. Such a small quantity presented little difficulty to transport in one load.

The advantage of the above approach when producing the 'improved' oak laths was that the quality of the material was maximized very quickly and cheaply with minimum wasted. Figure 10 shows a typical finger joint after the laths were planed down to 50×35 mm section. The finger joint was almost indistinguishable within the lath; low visual impact was one of the advantages of this jointing method.

Timber specification and validation

The specification stipulated the following:

- Maximum slope of grain on either face of 1:10
- No dead or live knots. Small clusters of pin knots were allowed provided they did not form more than 20% of the width of any one face
- No shakes or splits
- No sapwood (heartwood of oak is naturally durable and resistant to infestation, but its sapwood is not)

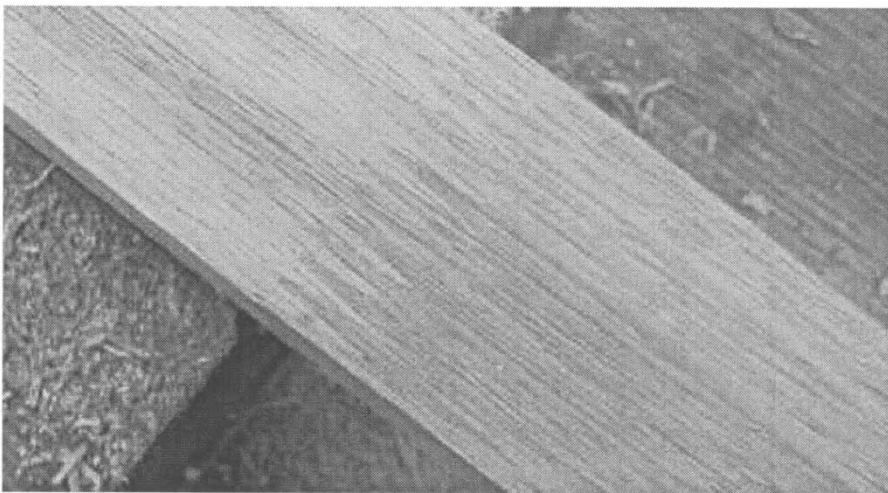


Figure 10 Finger joint

Using the finger-jointing technique, this specification could be achieved with almost any source of oak. The problem was that the lower the quality, the greater the number of defects and the larger the amount cut out and discarded. This would add significantly to the cost of the final product. It was necessary to find the balance between low cost, poor-quality timber with a high rejection rate and a higher cost source material with a lower rejection rate. For this reason, suppliers suggested that the timber should be sourced in Normandy, France. Norman oak timber is derived from the same species, *Quercus robur*, as English. The variation between the timber derived from trees grown under different conditions in England is greater than that between trees grown under the same conditions in England and France. It is only possible to produce high-quality timber from managed woodland. In Normandy, the cultivation of oak plantations has continued on a large scale, while in England it has declined. Thus, it is possible to purchase high-quality, straight grain French oak at a lower price than poorer quality English oak.

The Norman oak forests were also approximately the same distance from the site as the few commercial English oakwoods on the Welsh borders. The distance of around 250 km is across land in England, but to reach the site, Norman timber was transported 100 km overland in France, 100 km by sea and 50 km overland in England. Thus, Norman timber could be considered a local source: it was shipped into local ports and came from plantations as near as the equivalent English ones.

Site jointing

The next stage in the process was to join the 6-m lengths of 'improved' timber to produce continuous laths up to 37 m long for the lattice laths and 50 m long for the longitudinal rib-laths. This work was carried out on site under the protection of a polytunnel. The 6-m lengths were joined using scarf joints with a slope of 1:7. This slope gives the scarf joints a glue-line area the same as that for the finger joints. Figure 11 shows the construction of a typical scarf joint. There is an interesting contrast in the two jointing methods used: the finger joints were the latest timber-joining technology, whereas the scarf joints had been used for centuries.

Of the 10 000 joints in the structure, there were approximately 145 breakages during forming. Almost all were failures of the finger joints. The cause of these failures included:

- Pinching of the lattice on the scaffold support
- Tight curvature
- Tension build up because relative sliding between the two layers was restricted
- Dry joints

The low failure rate vindicates the design test and construction methods. The simple repair technique consisted of introducing solid blocking at the point of failure.



Figure 11 Construction of a scarf joint

Waste reduction

The offcuts generated by optimization and site jointing were used to make the shear blocks connecting layers of timber for composite action. In addition, offcuts from the workshop floor construction were used to make the internal workshop structures.

Nodal connection

The double-layer gridshell is a lattice system with two 50 mm wide × 35 mm deep laths placed one above the other, with the space between being formed by the lath system running in the opposite direction. Upon completion of the forming process, shear blocks were inserted to join the two layers; this formed a composite section that has significantly greater strength than the individual laths.

To form the shape from a flat mat, the nodes must allow rotation and, with a double-layer system, because of the difference in the curvature and so relative lengths of the upper and lower layers, the layers must slide relative to one another.

At Mannheim, the problem was overcome with the use of slotted holes in the two outermost layers (Figure 12). The bolt through the bottom two layers fixed the distance between nodes and allowed all layers to rotate. The slotted hole in the two outer layers allowed them to slide relative to the inner layers. However, cutting slotted holes was not only an expensive and time consuming exercise, but also it reduced the cross-sectional area of the laths and hence made them weaker.

The Downland Gridshell team developed an alternative method. Andrew Holloway from the GOCC suggested that a system with plates to clamp the joint

rather than passing a bolt through the timbers would be preferable. Everyone agreed, but it was clear that it was necessary to locate timbers on a grid. Simply using clamps would allow them to slide. Holloway came up with the ingenious idea of using three plates, with a pin through the central plate to locate the node. Buro Happold analysed the system sizing the plates and bolts to obtain the clamping action and to allow the appropriate amount of rotation. Three plates were more visually obtrusive than a simple bolt. Steve Johnson from the architects proposed profiles that made the node acceptable visually. The client, Zeuner, encouraged the development of the node. While it was GOCC and Buro Happold that carried the cost of node development and which had the responsibility of the risk of its performance, all parties contributed to the successful implementation and were named in the patent. It is hoped that the team members can benefit from the use of the node on future projects.

The patented nodal connection is illustrated in Figure 13. The central plate has a pin that inserts into the central layers fixing the position so that the nodes are a constant 1 m apart and able to rotate. The outermost layers are effectively passengers free to slide relative to the central layers but which will rotate in tandem with its associated central layer as it is forced to do so due to the bolt arrangement of the nodal connection.

This nodal detail offered additional advantages. Two opposing bolts could be lengthened enabling the attachment of the rib-laths that stiffened the gridshell in the outer plate. The plates were shaped to minimize the quantity of steel. The thickness was optimized to allow the plates to bend and bed into the outer laths to clamp the timbers tightly. There was a tapped hole in the plate on the underside of the node to enable light loads to be suspended from the shell.

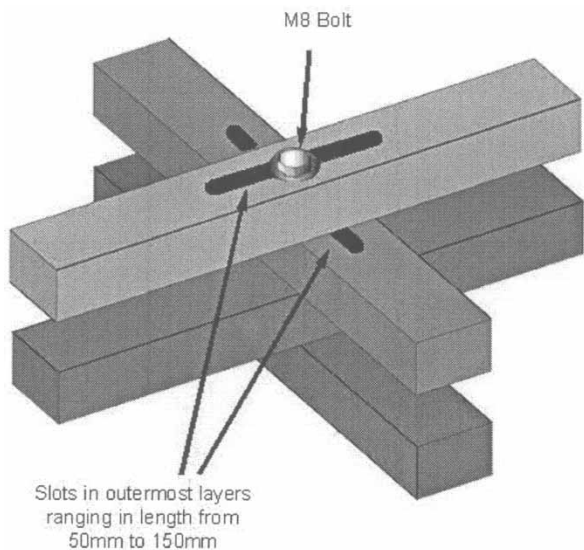


Figure 12 Slotted hole option

Construction technique

Background

The first double-layered timber gridshell was constructed for the Mannheim Bundesgartenschau in 1975 (Liddell and Happold 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 (Figure 14). The building has been very successful and remains 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 concentrated stresses within particular areas, the consequence of which was a notable number of

nodal connection.

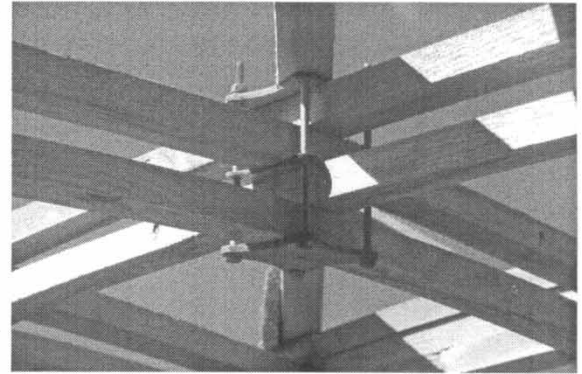
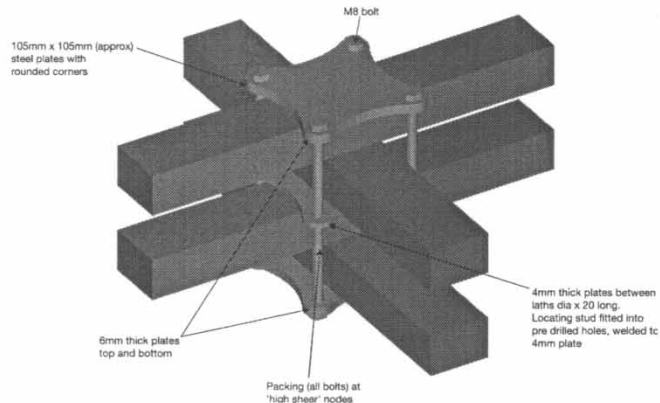


Figure 13 Nodal connection

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 the UK's Construction (Design and Management) Regulations 1994. These regulations require that construction hazards be identified as early as possible in the design process, eliminated if possible, and be properly managed during the construction and operation of buildings.

The gridshell sculptures at the Earth Centre in Doncaster constructed in 1998 are shown in Figure 15. These were small timber lattice structures composed of a single layer of thin timber laths. A crane lifted the lattice into position and the lattice was then

manipulated with struts and ties from a flat grid to the final shape. An important lesson learnt on this project was that the nodes needed to be extremely loose to enable rotation during formation.

Another project was the Japanese Pavilion at the Hannover Expo 2000. This building was similar in shape to the Downland Gridshell and composed of cardboard tubes (Figure 16). The erection used the modular scaffold system PERI-UP (Figure 17). The flat mat was laid out on a low-level scaffold bed and pushed up into position using a proprietary PERI jack known as a MULITPROP. Owing to the similarity of the shape of this shell with the Downland Gridshell, a great deal was learnt from the experience of erecting the Hannover building.

The PERI system is discussed in more detail below. The successful use of the system at Hannover led the team to invite PERI to submit a tender for the scaffold for the Downland Gridshell. As they had already used the system at Hannover, they priced the risk accurately and advised on the best equipment to use.

Risk reduction

The Buro Happold engineers responsible for the design and construction supervision at Hannover were able to recount their experiences candidly to the Downland Gridshell team. After this meeting, the carpenter worked up their proposed method in some detail and submitted it for critical scrutiny by the rest of the team to look for areas where allowances for risk or cost had not been properly identified.

As discussed below, the methods developed throughout the design and construction process. The culture of non-adversarial working across disciplines to find and agree solutions within a clearly defined and understood set of responsibilities was very important. As far

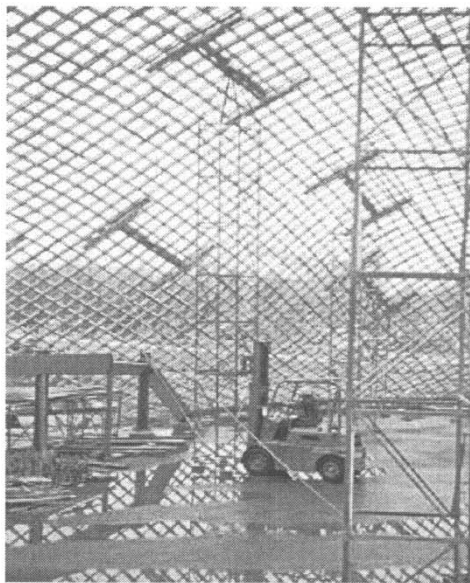


Figure 14 Construction of the Mannheim gridshell

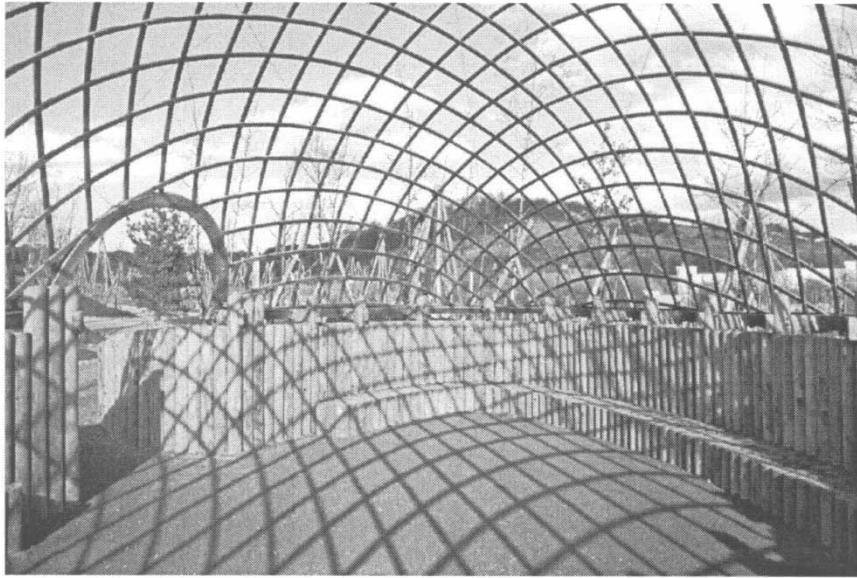


Figure 15 Gridshell at the Earth Centre, Doncaster

as the gridshell construction was concerned, the engineer provided the details of the final form and took responsibility for the long-term performance of the permanent structure. The specialist carpentry subcontractor was responsible for determining the method and its successful implementation. The engineer provided additional information to help the contractor with determining the methods and intermediate geometry, but without taking responsibility for the success of the method. The subcontractor's responsibility passed

through the main contractor (E. A. Chiverton) to the client and there were some serious discussions of the risks carried by the various parties and what would happen in the event of an unforeseen problem that would halt the project. This is the nature of innovative work. It was the mixture of creative thought, careful analysis, properly developed method statements, good communications and the will to succeed that saw the project through to completion within time and budget constraints. The financial risks carried by many of the

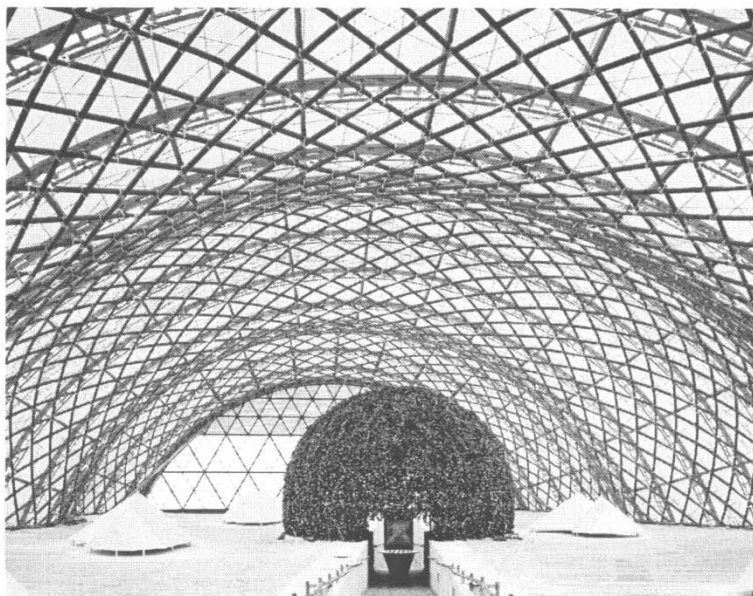


Figure 16 Japanese Pavilion, Hannover Expo 2000

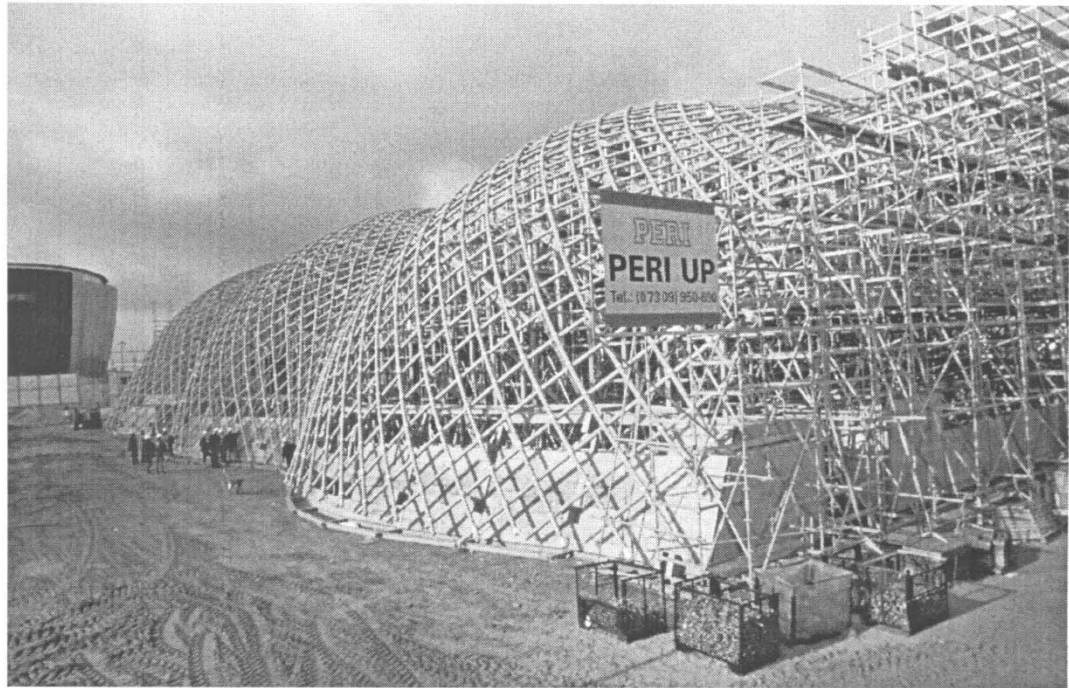


Figure 17 Erection of the Hannover gridshell using PERI scaffolding

parties were high and could not be discharged until the shell had been formed.

Construction procedures

The final design for the Downland Gridshell had a triple bulb hourglass shape; it was 50 m long, varied in width from 12.5 m at the valleys to 16 m at the crowns, while its height varied from 7.35 m in the valleys to 9.5 m in the central dome. A computer-generated model was used to illustrate the shape (Figure 18).

The lattice comprised a double layer of 50 mm wide $\times$ 35 mm deep laths. Further 50 $\times$ 35 oak laths were used, after formation of the shell, to brace the structure and support the cladding. The bracing laths running along the shell below the window zone supported the cedar boards and were called 'longitudinal rib-laths'; those running across the shell and supporting the 'ribbon roof' were called 'transverse rib-laths'.

For clear and confident communication, the team coined terms that described elements of the building:

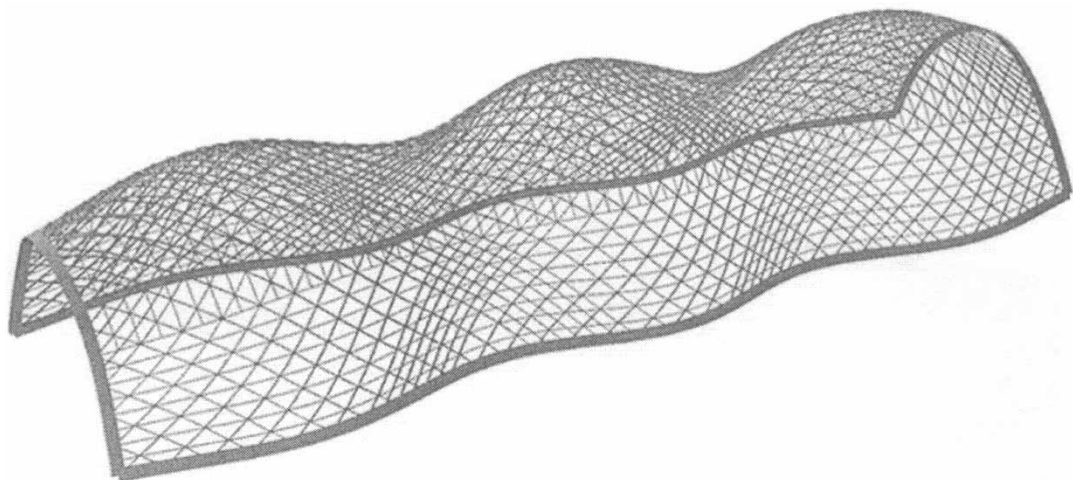


Figure 18 AutoCAD model of the gridshell

- Gridmat: flat mat of timber laid out before forming
- Lath: timbers forming the gridmat
- Rib-lath: timbers triangulating the gridmat after forming
- Longitudinal rib-lath: rib-laths running horizontally on the lower slopes of the shell
- Transverse rib-laths: rib-laths running across the shell, under the ribbon roof
- Nodal connectors: innovative clamps
- Shear blocks: timber blocks connecting two layers of laths

The initial concept for forming the Downland Gridshell is shown in Figure 19. 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 1 m. Jacking towers to lift the lattice clear of the scaffold platform would be introduced, enabling the removal of the scaffolding platform. The bases of these jacking towers would require a system to 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.

The physical models and the experience of the Hannover gridshell in particular were very influential in learning about the formation process. Leading on from this experience, three of the most significant decisions for the 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.

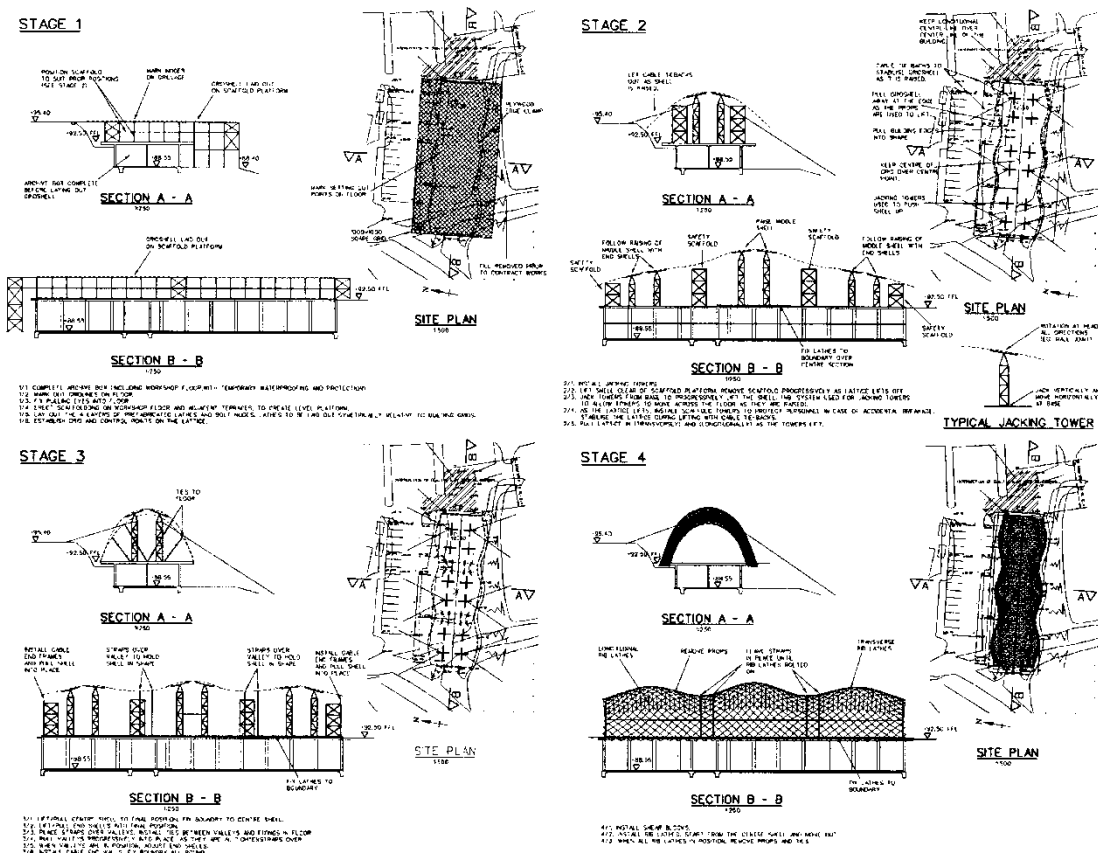


Figure 19 Initial concept to erection of the Downland Gridshell

An innovation was the choice of layout level. For the Downland Gridshell, the laying-out platform was to be erected to the height of the valleys enabling the lattice to be lowered into position. This sequence was first suggested by the client at a project team meeting and then independently suggested by PERI. It 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 proposal to work in this manner was made by Howard Ball of PERI at the very first meeting to discuss the method, during the tender process for the scaffold. It was worked up and priced by the carpenter (GOCC) who showed it to be the most cost-effective way of forming the shell from a safe working platform. By laying out the mat at high level, the whole perimeter, including the gable end walls, could be in position before the forming commenced. Thus, throughout the forming process, there were physical perimeter points towards which all edge nodes on the shell could be directed.

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 might cause a large number of breakages. Thus, it was decided that the method

should be progressive formation where the crowns and valleys were 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 stemmed from the fact that it was a modular system coupled with several innovative patented accessories that endowed it with the large, accurate vertical movement of the supports demanded in gridshell construction. Furthermore, PERI would bring their experience to bear in deciding the best equipment most suited for the task. These factors, combined with the innovative approach in evidence during the tender, made the selection of PERI scaffolding the obvious choice.

Layout of the flat mat

If the lattice were laid out as a flat mat composed of squares with a 1 m edge length, the resulting lattice mat would be 47 m long $\times$ 25 m wide. The actual mat was stretched longitudinally to achieve the 50 m 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 minimized adding a control; the central node of each dome could be monitored to check that its movement was only vertical. This changed the layout mat from a series of squares to a system of quadrilaterals, each edge 1 m long, with two 96° and two 84° internal angles. Figure 20 is a drawing of the layout mat, which was 49 m long $\times$ 24.2 m wide.

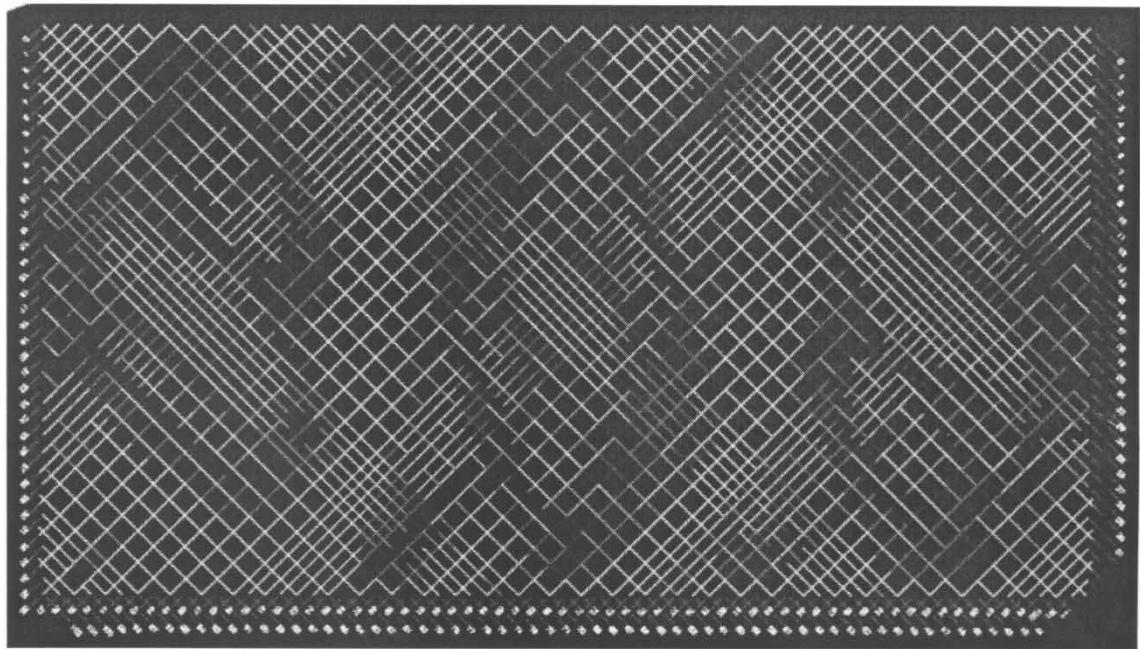


Figure 20 Layout of the flat lattice mat



Figure 21 Completed layout of the flat lattice mat

It was very difficult to identify a particular position on the shell after it had been formed. An innovation introduced on this project was to label the laths in the flat gridmat. As the laths were made, each had its 'address' written on it in accordance with a coordinate system. Zones on the drawing indicated the different shear block details. There were standard shear block details, but the size and spacing varied around the shell to meet the structural requirements. The closer to the perimeter support, the higher the out-of-plane shear, the more shear blocks were required. In the finished curved shape, it was very difficult to locate particular positions on the shell. By painting the laths the appropriate differentiating colour in the flat layout, each position could be easily distinguished in the completed form. A similar control was used to denote the extent of the 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 was attached and a yellow tie indicating a transverse rib-lath. Figure 21 shows the completed layout mat.

Scaffolding system

The scaffolding used 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 PERI MULTIPROP, a system of adjustable jacks with built-in length gauges, gave the construction team an efficient and accurate means of altering the height of the scaffolding to deform the lattice. Figure 22 shows the main type of MULTIPROP used on this project, the MP 480, which enabled a vertical adjustment of up to 2.2 m.

A birdcage of scaffolding with a plan area the size of the layout mat was built to a height of 7 m above the

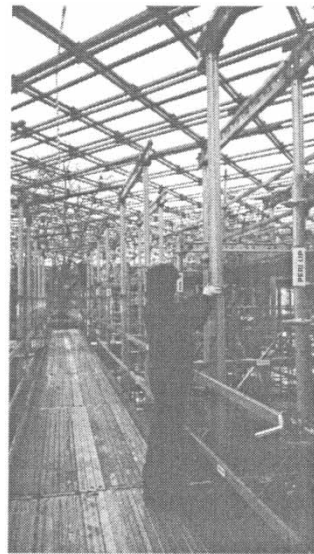


Figure 22 PERI MULTIPROP

workshop floor. The platform to support the timber lattice was created using PERI's universal girder, which was neatly supported at both ends by a fork head attachment to a MULTIPROP (Figure 23). 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.

Monitoring the formation process

The opportunities presented by the flat layout pattern were fully used to install measures to monitor the

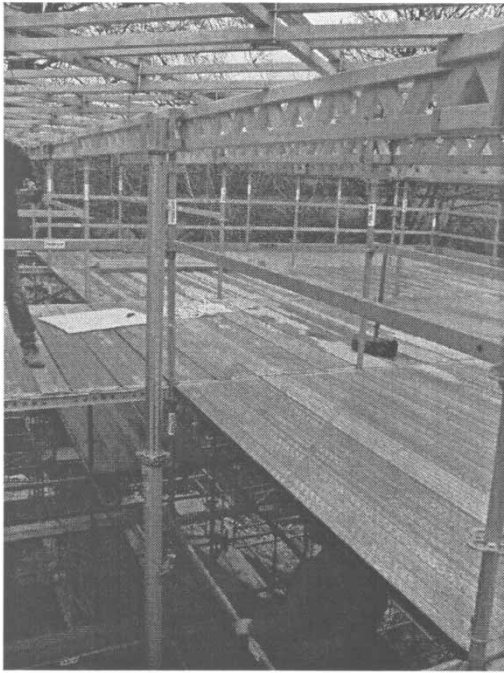


Figure 23 PERI universal girder

formation. The longitudinal centre line of the lattice did not move transversely; throughout formation, it should form a straight longitudinal centre line.

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

The central nodes in each of the domes only needed 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 to check 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 form-finding 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.

The maintenance of symmetry of the lattice about both its longitudinal and transverse centre lines 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 was no substitute for observing what the structure was doing. Indeed, it was 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 were 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 into the crowns, thereby squeezing the valleys and enlarging the crowns.

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. Figures 24 and 25 show sketches of the strapping system (type A) used in the valleys and the locations where the system was installed on the layout plan.

Sliding of the layers relative to one another within the double lath system was necessary owing to the two layers of laths having a different overall length in the completed shape because the outer layers were bent to a slightly greater radius of curvature. Therefore, if relative sliding was prevented, the lattice would 'lock-up' and induce breakages.

The only place in the building where this relative movement did not occur was across the longitudinal centre line. 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. It also meant that the extra length of the uppermost layer with respect to its inner partner could be calculated taking into account the change in curvature of the laths along their length.

Formation of the gable ends

Owing to the 'unnatural' shape required for architectural purposes, forming the shape of the gable ends presented a particular challenge. The natural tendency for the lattice was towards the shape of another valley at its ends. However, the required shape did not conform to this natural flow; it represented a discontinuity of shape that had to be imposed on the lattice. Within a distance of 3–4 m, the scissoring action had to change from vertical elongation to form the crowns to horizontal elongation to form the gable end. This dramatic

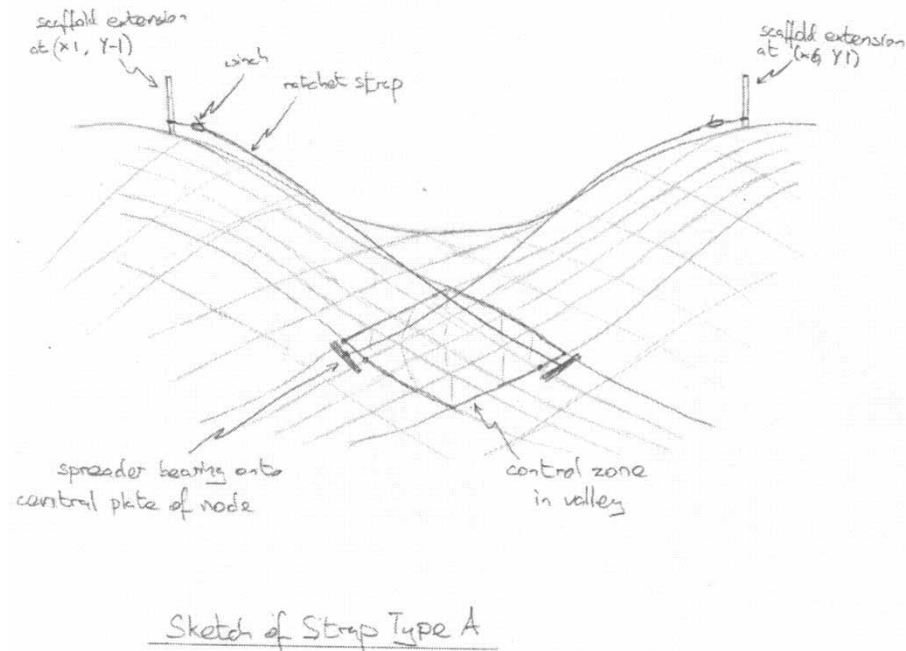


Figure 24 Strapping system type A

change in condition could only be achieved by using superimposed external forces.

Figures 26 and 27 show the strapping system used. The central three diamonds each had a tensioning strap running transversely from node to node, producing in-plane tension in this zone.

Raking props

The time taken to manipulate the flat mat to the final curved form was six weeks. Most of this time was taken up in carefully modifying the scaffold. When the forming process was just over 50% complete, direct vertical support was no longer appropriate at the edges and raking MULTIPROPS were installed. These were

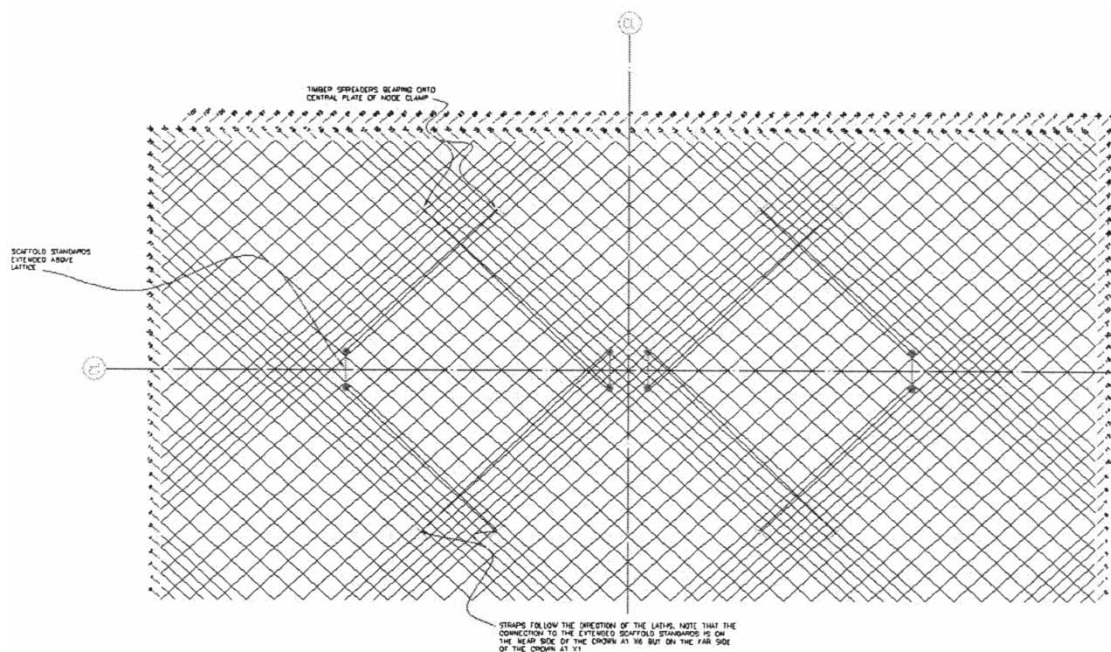


Figure 25 Locations of strapping system type A

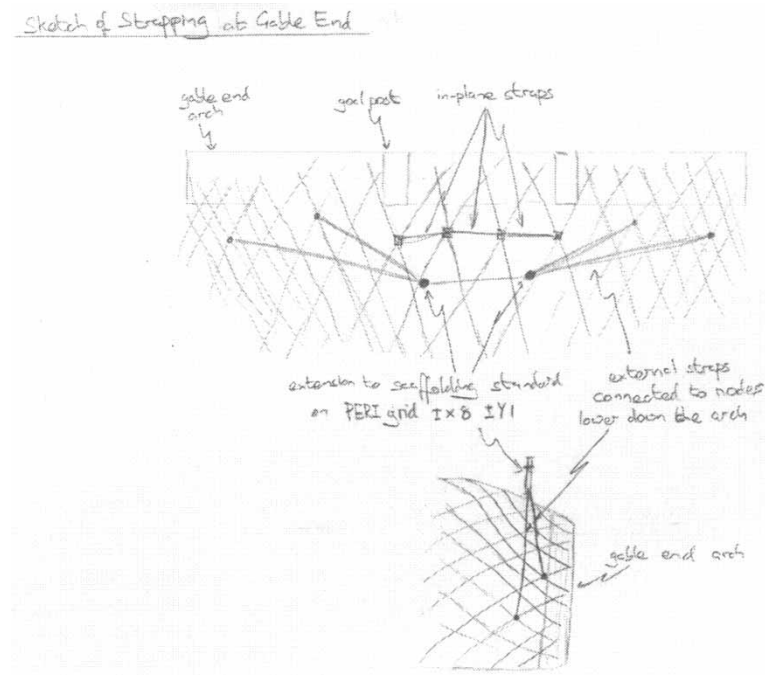


Figure 26 Gable end strapping system

fixed to the scaffolding cage using raking scaffolding standards. These props were attached to individual nodes in the lattice (Figures 28 and 29).

Trial-and-error approach

Although a detailed method was agreed before starting the forming process, it was agreed that trial and error during construction would be permitted. This proved

to be the best way of determining the 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 process.



Figure 27 Gable end strapping system

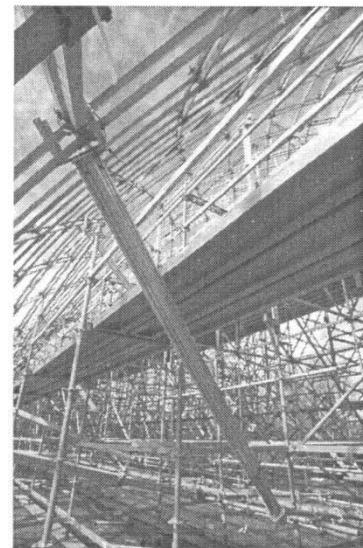


Figure 28 Raking MULTIPROP

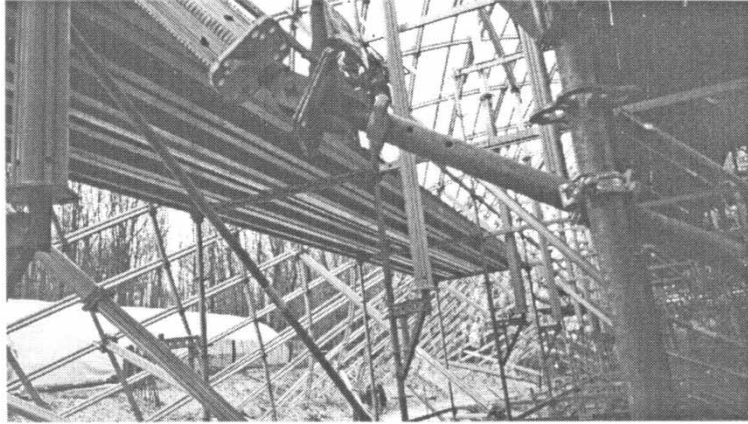


Figure 29 Universal joint at the base of the raking MULTIPROP

The small straps 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. Note that all the strapping was arranged to maximize in-plane and minimize out-of-plane forces. Out-of-plane forces needed to be avoided because they would lead to a build up of friction, restricting the passage of the laths over the PERI beams and relative sliding of the double lath system.

Final adjustments to the gridshell

When the lowering of the gridshell was complete, further adjustment was required to bring it into its final shape. The valleys defined the head room requirement of the building. By achieving the shape in these areas, the correct height and volume would be achieved. Both valleys coincided with the theoretical shape remarkably well.

The gable end detail also had to be considered. The approach of the laths was too shallow for the existing gable end arch. 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.

Propping was installed under 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 only 100 mm lower than theoretical height; also, the position of the highest point was in its correct place.

The completed shape is shown in Figures 30 and 31.

Cladding

Gridshells and other lightweight structures are covered with various types of membranes. For the Downland Gridshell, the team was keen to continue using local green materials and to study the aesthetic potential of their potential use; hence, the armadillo like appearance of the flowing planes of the exterior. The top plane was the ribbon roof, which was solid having a RoofKrete covering sloping up and down, hump to hump along the building. The next plane was of polycarbonate letting the light in at clerestory level. Polycarbonate was chosen as it was lightweight and easily installed at height. Additionally, the geometry of the shell required a small twisting of the panels to meet the curvature of the shell; this would not be possible with glass. The remaining three planes down the flanks of the building were made from straight planks of western red cedar from a nearby forest. The disengaged quality of the planes enhanced both the three-dimensional curving lattice of the gridshell and the two-dimensional flow of the planes. The planes sometimes floated clear of the shell and sometimes were fixed tight to it, thus enhancing the syncopation.

Western red cedar was chosen as being the most durable softwood available. It was chosen in preference to oak for its better dimensional stability. The building being surrounded by trees meant that care had to be taken in the detailing of the boarding. The boards were lapped vertically, which allowed for the introduction of grooves routed into their back faces for water to run down clear of the supporting battens. A single line of stainless screws fixed the boards back to their supporting battens to allow for seasonable movement in the timber without deformation. The copper lightning conductor on the top section of the roof and copper strips nailed to the ends of the cedar boards were positioned to allow rainwater runoff. Through a very weak solution of copper salts, the build-up of moss and deleterious mould growth was reduced on the timber

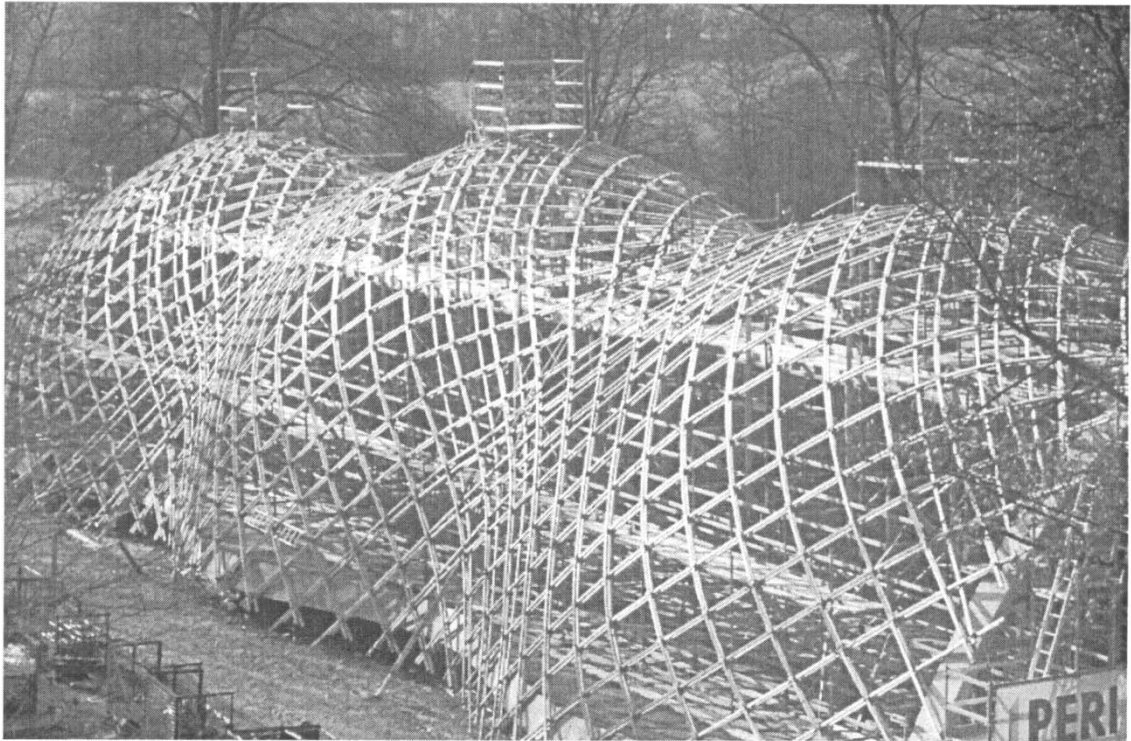


Figure 30 Final shape from the east scaffold tower



Figure 31 Final shape from the west platform

cladding. This was particularly important on the shaded north elevation. The design life of 40 years should be achieved with this cladding.

A significant advantage of the gridshell structure was the access provided to the outer surface. It is very difficult to clad structures with curved walls. Scaffolding would have to cantilever out over the surface. By using the gridshell as an access ladder, it served as a working platform for the application of insulation, membrane and boarding. The lower boards had to be applied first to provide a weathering overlap for the higher boards and personnel had to use slings and be attached to the structure for safety. Despite these restrictions, the saving in time and cost of not using an access scaffold was very significant.

Building costs

This paper is about design, innovation and construction. The reaction of many people is that this process must have cost a great deal of money. The Museum is a private organization and although not risk averse, it is very constrained by funds. The programme was not of the importance that it might have been in other projects; the construction itself was an exhibit in the museum and less satisfactory but workable facilities already existed (Table 1(a)). The programme only became an issue towards the end of the building construction when the Museum was committed to vacating other storage premises. Cost, however, was always significant. Table 1(b) shows that when compared with other similar buildings, far from being expensive, the Downland Gridshell represented excellent value.

Collaboration and innovation

Successful buildings are the result of people working together to optimize design through the individual application and mutual understanding of diverse skills and knowledge. The craftsman brings an intuitive understanding of materials and the experience of what can be done. This input is important on all construction projects and the failure to recognize this frequently leads to problems. For example, for high-quality finishes with in situ concrete, the craft skills of the concrete worker must be recognized and understood to enable the work to be properly detailed and specified. A failure to appreciate and take account of craft skills makes it impossible to achieve the best results. With a proper understanding, the engineer and architect can choose either to eliminate elements of the work if the skills are not available or to incorporate and express them in celebration of quality workmanship.

Timber is a difficult material. Not only is it produced from hundreds of different species of tree, but also it varies according to where the trees were grown and

how they were processed. Among other problems, its properties vary according to the direction in which it was loaded and its moisture content. Over the centuries, craft knowledge and skills have developed slowly to address the difficulties encountered with the use of timber at every stage of its production, from felling trees to the sanding and polishing of the final finish.

Engineering has enabled innovation that has led to advances in the use of materials that would never have been possible through the development of craft skills alone. Despite this, many engineers are very wary of applying their methods to timber. In contrast, there are many craftsmen who specialize in timber because of the challenge it represents and the potential for creating beautiful structures.

The success of the gridshell was due to the collaboration of the design team and the craftsmen. Innovation was achieved by combining a thorough understanding of load paths, stresses and strains with an intuitive knowledge of what should, or should not, be feasible. Working together, craftsmen, engineers, architects and other designers fulfilled their aspirations to produce a structure that not only met their clients' needs, but also was a joy to those who use the building. In addition, the vision and positive encouragement of the client created the conditions for innovation and collaborative working to occur.

Conclusions

The Downland Gridshell is the first double-layer timber gridshell in the UK and only the fifth world wide. A number of innovative techniques and procedures were used in designing, modelling and calculating the form, the structural forces, and the design of a new nodal connection. Innovation in the construction processes included using a technique to lower the mats into the formation of a three-dimensional shell using a combination of gravity and specialist scaffolding. Innovation was achieved through very modest R&D budgets by construction companies working on a live project.

The skills, knowledge and commitment gained through a series of former projects and collaborations provided a firm basis for further innovation and development. The creation of the Downland Gridshell has created new knowledge in a team of consultants and carpenters. This knowledge can be further extended and deployed in future projects as well as spread across to others in the construction industry.

The success of the Downland Gridshell project is the result of close cooperation of the design and construction teams. In this spirit of non-adversarial teamwork, many of the problems that arose were overcome by constructive input from all concerned. All team mem-

Table 1(a) Outline programme of the whole design and construction process

Task Name	1995				1996				1997				1998			
	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Initial client enquiry	◆															
Concept design																
Preliminary funding from HLF											◆					
Scheme design																
Funding from HLF																
Appointment of carpenter																
Detail design																
Tender documentation																
Final HLF funding																
Appoint of main contractor																
Foundations and walls																
Gridshell preparation																
Gridshell forming																
Gridshell cladding and glazing																
Finishing works																
Completion																

Task Name	1999				2000				2001				2002			
	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Initial client enquiry																
Concept design																
Preliminary funding from HLF																
Scheme design																
Funding from HLF			◆													
Appointment of carpenter				◆												
Detail design																
Tender documentation																
Final HLF funding																
Appoint of main contractor																
Foundations and walls																
Gridshell preparation																
Gridshell forming																
Gridshell cladding and glazing																
Finishing works																
Completion																

bers carried risks. It took considerable courage and vision by the client to set a demanding brief. It took enormous strength to see through the project. The Museum has been rewarded with a building that is

admired internationally and compared with buildings that cost much more. The risks were high, but for a fairly modest sum the client has gained an internationally recognized building.

Table 1(b) Table of costs: proportion of costs of various elements of building as a percentage of the total and comparison of costs per square metre of gross floor area of the Downland Gridshell with other typical visitor/education centre buildings

Element	Downland Gridshell	Typical building		
		High	Medium	Low
Concrete and masonry lower level	10%			
Timber workshop floor	12%			
Gridshell roof	16%			
Cladding and glazing	12%			
Total building cost	£1097	£1520	£1140	£780

As a prototype, the project demonstrates the financial viability, buildability and efficiency of this construction form, which has long been argued.

Of all the technical problems encountered, Managing Director Andrew Holloway of the GOCC believed that the lath fabrication needs further study, research and development:

There were too many dry finger joints. This is because the adhesive is moisture curing and tended to gum up the glue delivery system.

However, he also noted:

To obtain the same quality of timber only using scarf joints the material costs would be four times greater.

During construction, observation was seen as the key control. Problems and potential problems were most



Figure 32 Completed building

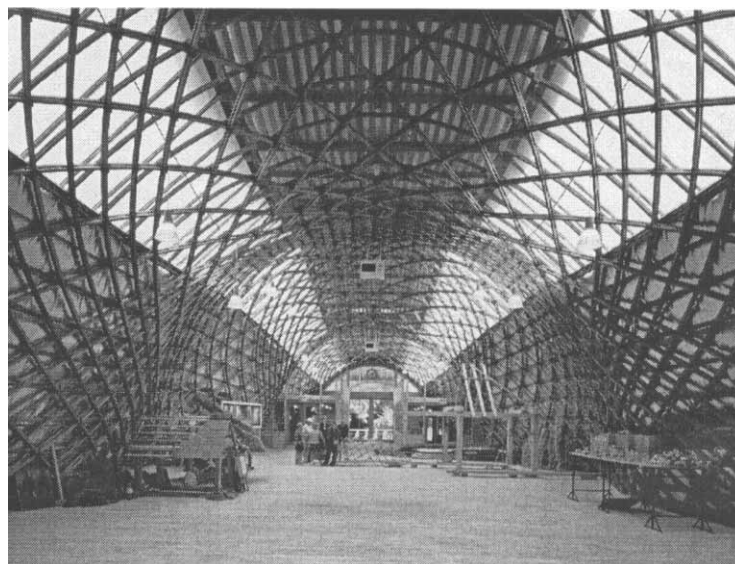


Figure 33 Completed building

effectively isolated by continually observing the lattice and its behaviour. There are important implications here for close liaison between contractors and consultants, flexibility, etc.

The creation of the Downland Gridshell has brought new knowledge for a team of consultants, carpenters and builders. This knowledge can be further extended and deployed in future projects as well as spread to others in the construction industry.

The project was a collaboration between the funder, client, architect, engineer, cost consultant, craftsman and builder. All needed commitment in helping to meet one another's challenges. All needed to understand, at least at the interfaces, one another's problems. The result is a unique building that may stand as a model for replication by others either in its physical form or in the manner of its creation.

Acknowledgements

Of particular note with regard to the funding of the project is the Heritage Lottery Fund. The monitoring and recording of the process were made possible through a research grant from the Department of Trade and Industry (DTI) through the Fast Track Research fund. This has been a team project and many individuals from the various organizations involved in the design and construction have made significant con-

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