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Large-scale timber construction in the past 10 years

Wegweisende Ingenieurholzbauten der letzten 10 Jahre

Costruzioni di carpenteria in legno innovatrici degli ultimi 10 anni

Document in English

Large-scale timber construction in the past 10 years

Introduction

All over Europe there has been a revival in construction in timber. In the UK this has been seen in the increasing use of timber in housing but also there have been significant advances in its use in large scale structures. This paper will examine some of the most successful of these structures.

1 Glue - Laminated Structures

1.1 The Sheffield Winter Garden

Sheffield is a city with an industrial heritage particularly concerning with steel. It is still a leading centre in high quality metals and precision engineering, but the large scale city centre foundries have closed. The Winter Gardens and the adjacent sister project, the Millennium Galleries are the catalyst for the regeneration, providing the city with a new focus and identity embodying the spirit of a proud city.

1.1.1 Form and Material

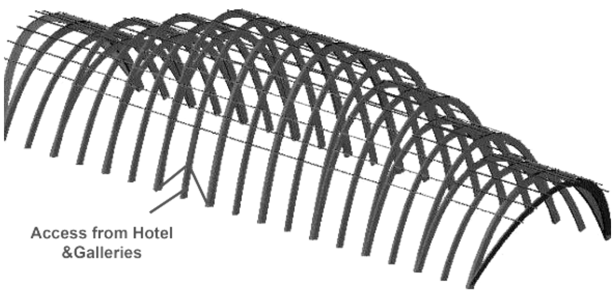
The planting of the Winter Garden required a tall large volume space clear of structural support on the long narrow site. Catenary arches fulfilled these objectives. For a building consistent with the message of regeneration and sustainability, timber was a natural choice for the structure.

The profile steps from 11m high arches at the entrances to the tallest 22m high arches at the centre; this presents human scale entrances to embrace visitors into a building designed for the public.

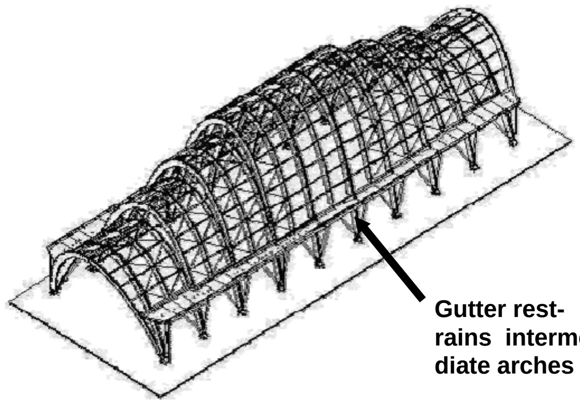
1.1.2 Superstructure

The use of catenery arches results in a structurally simple and efficient scheme. The catenery, the profile formed by a hanging chain, results in pure axial forces under gravity loads and provides a tall, large volume space within the confines of the narrow site. The arches are designed as continuous with pinned bases tied at by the ground floor slab.

The solution uses arches at 3.75m centres. The scheme was developed with alternate arches stopping at gutter level. The axial loads are supported by the raking struts, whilst the horizontal thrusts due to the vertical loads, as well as direct lateral wind loads, is transferred through the gutter to the arches that continue to the ground.



The gutter is formed from galvanised steel plate, as well as transferring the forces noted above, it also provides a maintenance walkway and service route. The width of the gutter is determined by the gap between the arch and the building boundary.



Each roof level is designed as an independent module, the steps are formed by two arches of each height placed side by side with a small gap. Other than the gutter, there is no connection between each height module.

The principal structural element sizes are:

- Arches - 210mm wide x 910mm deep
- Purlins - 150mm wide x 225mm deep
- Raking Struts – 245 mm diameter

All timber is Polish Larch, the fabrication was undertaken in Germany by Merk. The steelwork is mild steel, galvanised to avoid staining the wood.

1.1.3 Substructure

The building is built on a concrete podium providing basement parking and delivery access to the adjacent Millennium Galleries, hotels and offices.

1.1.4 Glazing

The roof is clad in approximately 1,400 glass panels. These panels are articulated to accommodate the flexure of the arches under wind loading in a similar manner to the plating of an armadillo. Each panel is supported at the top end by a hinged fixing attached to the purlins between arches. The bottom edge is supported by a sliding joint that only resists wind load perpendicular to the panel.

80% of the glass panels are of an identical size and all panels use the same framing system, fixings and glass thickness.

Figure 1: Photo Buro Happold/Mandy Reynolds

1.1.5 Construction

The simple repetitive forms provide elegance and economy of effort. The arches were brought to site in two pieces. Two cranes were used to lift the two halves. The bottoms of the arches were located in the steel shoes and slowly lowered allowing the arches to meet at the apex.

A solitary worker in a cherry picker hammered in the dowels to complete the apex flitch plated connection.

In all, 4 workers and 2 crane drivers erected the entire timber frame in just 8 weeks, an impressive display of the benefits of pre-fabrication.

1.1.6 Building Environment

In horticultural terms the building is a cool temperate house suitable for plants from the Mediterranean and similar climate zones in the southern hemisphere. The majority of the plants are from of the southern hemisphere, where they have evolved quite differently to our own.

In summer, there is solar shading from surrounding buildings. Vents in the roof and at either end of the building open up (in 4 steps) to provide ventilation and induce transpiration cooling from the plants. In winter interior is protected against rain and wind and conserve heat gains from the surrounding buildings and the sun. Frost protection is provided by under floor heating utilising a district heat

Throughout the year, high level fans induce air movement dissipating any local climatic extremes. As well as equalising the internal climate, this minimises the risk of fungal growth.

Figure 2: Sheffield Winter Garden - Building Environment

1.1.7 Engineering & Architectural Benefits of using timber

Long life buildings such as this favour the use of materials that are inherently durable and require minimal maintenance as these costs can be significant over a long period of time. The planting precluded the use of paints, preservatives or solvents in the maintenance of the building. Otherwise the plants would need to be removed on a regular basis as at Kew Gardens, London.

A secondary benefit was a reduced construction cost and programme as there were no finishes to complete, no paints to apply or internal cladding to fix.

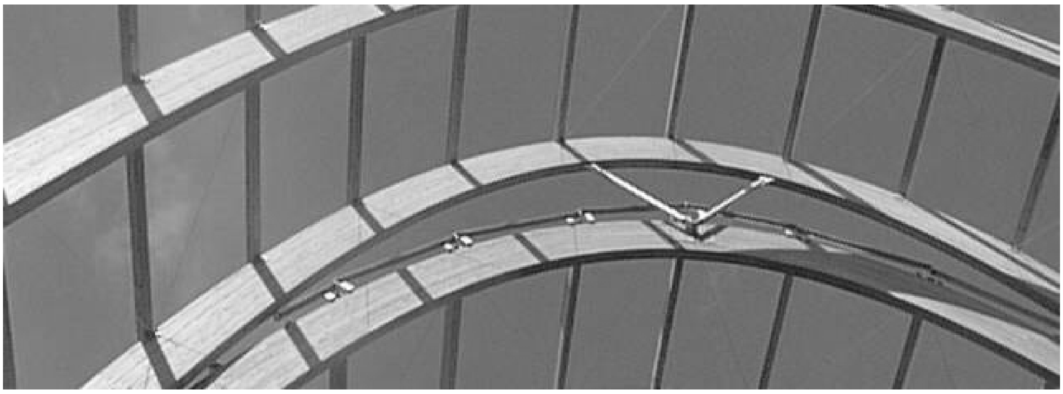


Figure 3: Durable timber fulfils

Untreated durable timber fulfils these requirements more readily than steel or concrete.

Architecturally, timber has an inherently pleasing aesthetic. Crucially, this aesthetic matures and lasts without dating, independent of the whims of fashion.

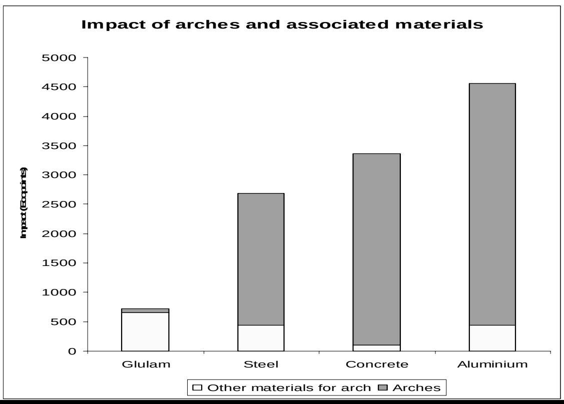
1.1.8 Sustainability

A research study funded jointly by Buro Happold and the UK Department of Trade & Industry examined the sustainability of the project, including embodied and operating energy. This study compared the timber frame with concrete and steel alternatives using the UK's Building Research Establishment ENVEST software to establish the ecopoint rating.

The study examined three components:

- Energy to extract and manufacture components
- Energy to transport to site
- Energy to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building

Material	Energy MJ/Kg	Water used in manufacture litre/Kg	Specific EE EE/unit stiffness
Concrete slab	1.3	450	.25
Timber	2.5	330	.18
Brick	2.5	520	2.5
Glass	15.9	680	1.0
Steel	32	3,400	1.2
Aluminium	227	50,000	4.5



The environmental impact of constructing the building in timber was compared with that of concrete and steel. This showed the timber as a material had an eco-rating of less than 5% of that for steel or concrete alternatives – a 95% reduction in energy used in the construction.

In addition to this advantage, the weight of the Glulam frame is 65% of the weight of the steel alternative and 15% of the concrete scheme. This represented a cost saving and reduction in environmental impact including less material needed in the foundations.

Figure 4: Sheffield Winter Garden – Finished Building. Photo: Buro Happold/Mandy Reynolds

1.2 Norwich Cathedral Visitor Centre

The second glulam building to be presented is the Norwich Cathedral Visitor Centre. This building is constructed on the site of the historic refectory building adjacent to the cloisters of Norwich Cathedral. It could not be a more sensitive site and laminated English Oak is used for its structure.

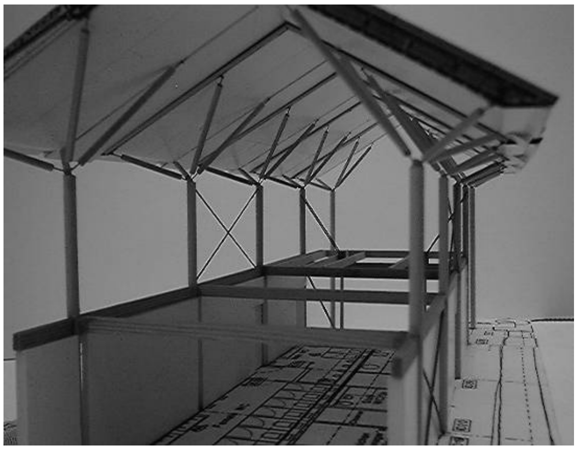


Figure 5: Glulam Building Project

Although to building is of a modest size it has made a considerable impact on the image of timber structures in the UK, showing that high quality design and construction is worthy of the cost and effort. It is included in this paper to reflect the impact it has had on the image and its effect on the adoption of timber for prestigious buildings in the UK.

The building uses laminated oak for its primary structure. The roof is constructed with Kerto LVL and roof spreading is resisted with principle rafters of steel, with a moment joint at the ridge. The structure consists of timber plates supported on slender trees.

Structural continuity of the roof provides resistance against overturning of the trees, which are thus made of simple, elegant laminated oak poles.

Figure 6: The oak was from sustainable English woodland

Figure 7: Steel flitches

The oak was from sustainable English woodland and was laminated using an epoxy adhesive. For the more heavily loaded elements, steel flitches were used to strengthen the oak elements

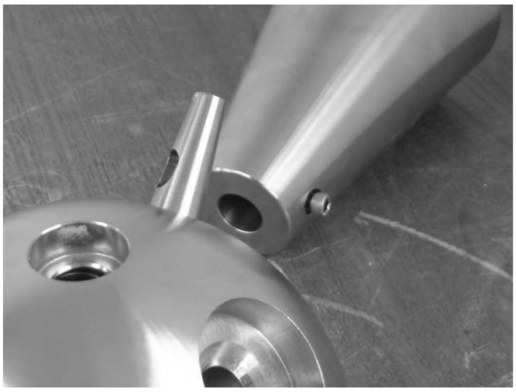


Figure 8: Stainless steel caps were used to cover the ends of the struts.

Figure 9: The roof with plywood

The roof is sheathed structurally with plywood and then clad with high-quality English oak.

The building won the UK's top award for timber buildings, the Wood Awards Gold Award. It has been very successful for our client, who has commissioned a second phase.

Figure 10: Norwich Cathedral Visitor Centre - The Completed Building

2 Timber Gridshells – Downland Gridshell and the Savill Building

The first timber gridshell structure was created in the German city of Mannheim in 1976. It took 25 years for the technique to be adopted in the UK and then two structures were created in short succession. This paper will discuss the precedents for the structures, including the Japan Pavilion for Hanover EXPO 2000, and present the design and construction of the two recently completed buildings.

2.1 The Downland Gridshell

The first double-layer timber gridshell in the UK, for the Weald and Downland Open Air Museum in Sussex, created international interest, quite disproportionate to its size, amongst architects, engineers and carpenters.

The project is relatively small (€2 million construction cost) but it has been reported on national television, shortlisted for the 2002 Stirling Prize and featured in national press and many of the major trade journals. There is such interest partly because the building is so unusual architecturally. but also because there are a number of features of the building that are innovative and may be adopted for future use or be seen as examples of how problems can be overcome and turned to advantage.

Figure 11: Photo Buro Happold/Mandy Reynolds

2.1.1 What is a timber gridshell?

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 a gridshell. The three dimensional structural stability is maintained by shear stiffness in the plane of the shell, achieved by preventing rotation at the nodes or by introducing bracing.

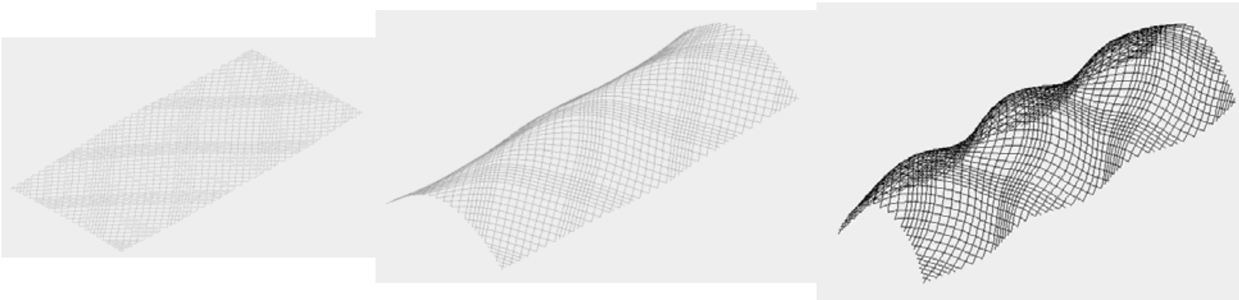


Figure 12: Computer simulation of forming timber gridshell

2.1.2 Why a double layer gridshell?

Limitations on the tightness of curvature to which laths of a particular cross section can be bent. 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 is to utilise a double layer gridshell. For the Downland gridshell, the lattice is composed of four layers - two single layer mats sitting one upon the other. The laths are of sufficiently small section (50mm wide x 35mm thick oak) to permit bending of the lattice into the desired geometry. Upon completion of forming, timber shear blocks were positioned between the lath layers and fixed with screws. properties of a deeper section.

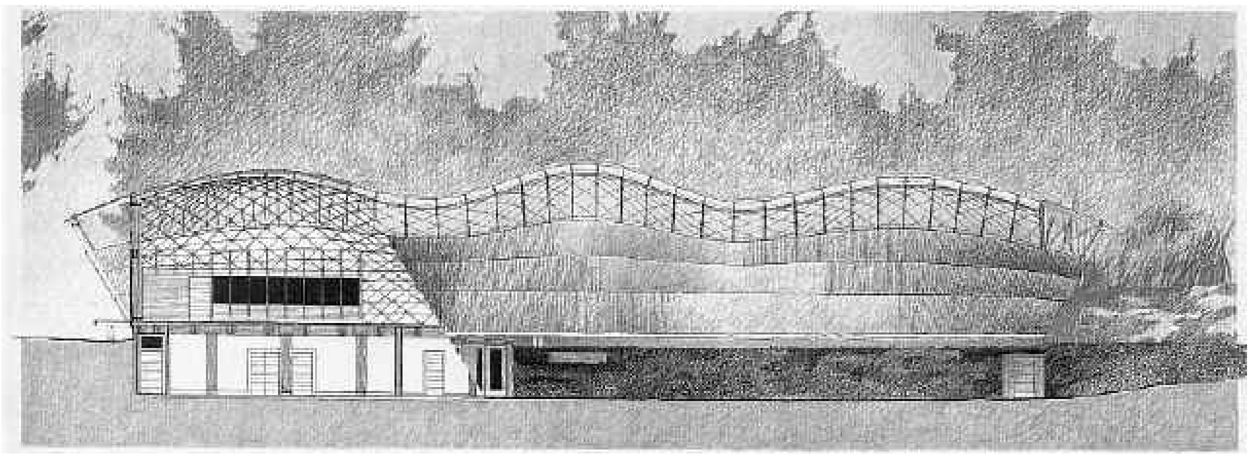


Figure 13: Architect's North Elevation. (Image: Edward Cullinan Architects)

The workshop roof is a doubly curved, four-layer oak gridshell, of a triple bulb hourglass shape, 48 metres long, 16 metres across at its widest points and 11 metres wide at the waists. The internal height varies between 7 metres and 10 metres. The lath spacing is 1 metre reduced to 500mm in areas where additional strength and stiffness is needed.

2.1.3 Improved Timber

A significant problem noted was the variability of the bending strength of oak due to “short grain”. To overcome the problem, the latest jointing technology was utilised to cut out the defects and use finger joints to join the lengths together, forming laths of the required length and of a consistently high quality, produced from normal grade timber. The technical term for this process is “optimisation”.

Finger jointing was performed using the GreCon Dimter finger-jointing machine. This is a continuous feed system. Collano Purbond HB 530 polyurethane adhesive was used.

The gridshell lattice required 6000 linear metres of lath; considering that individual pieces of graded lath averaged 0.6m in length this represented 10,000 finger joints. Although the timber had to be transported to the specialist machine the total weight was only 6 tonnes. Such a small quantity is easy to transport in one load.

The advantage of using ‘improved’ oak laths was that the quality of the material was maximised very quickly and cheaply with minimum wastage.

Figure 14: Finger Joint

2.1.4 Site Jointing

The next stage in the process was to join the 6m lengths of ‘improved‘ timber to produce continuous laths up to 37m long for the lattice laths and 50m long for the longitudinal rib laths. This work was carried out on site under the protection of a polytunnel. The 6m lengths were joined using scarf joints with a slope 1 in 7.

Figure 15: Site jointing

2.1.5 Nodal Connection

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

To form the shape from a flat mat, the nodes must allow rotation. Also, with a double layer system, because of their difference in the curvature and thus relative lengths, the upper and lower layers must be able to slide relative to one another. At Mannheim the problem was overcome with the use of slotted holes in the two outermost layers. Cutting slotted holes is not only an expensive and time consuming exercise, it also reduces the cross sectional area of the laths and makes them weaker.

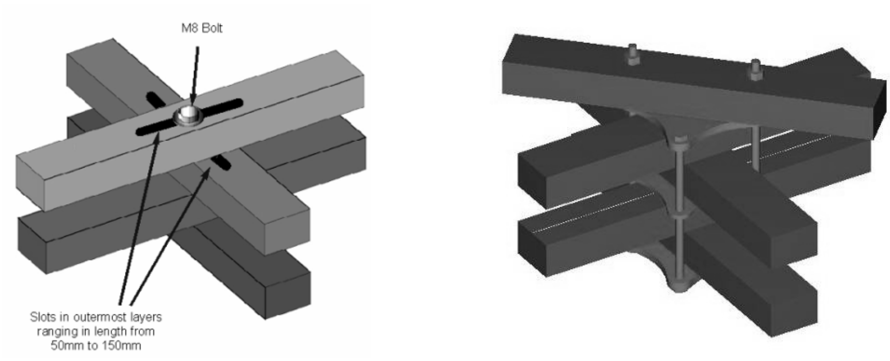


Figure 16: Nodal connection

The Downland Gridshell team developed an alternative method. This resulted in the patented nodal connection. The central plate has a pin that inserts into the central layers. This fixes the central layers in position so that the nodes are a constant 1m apart, and also enables rotation.

2.1.6 The forming procedure

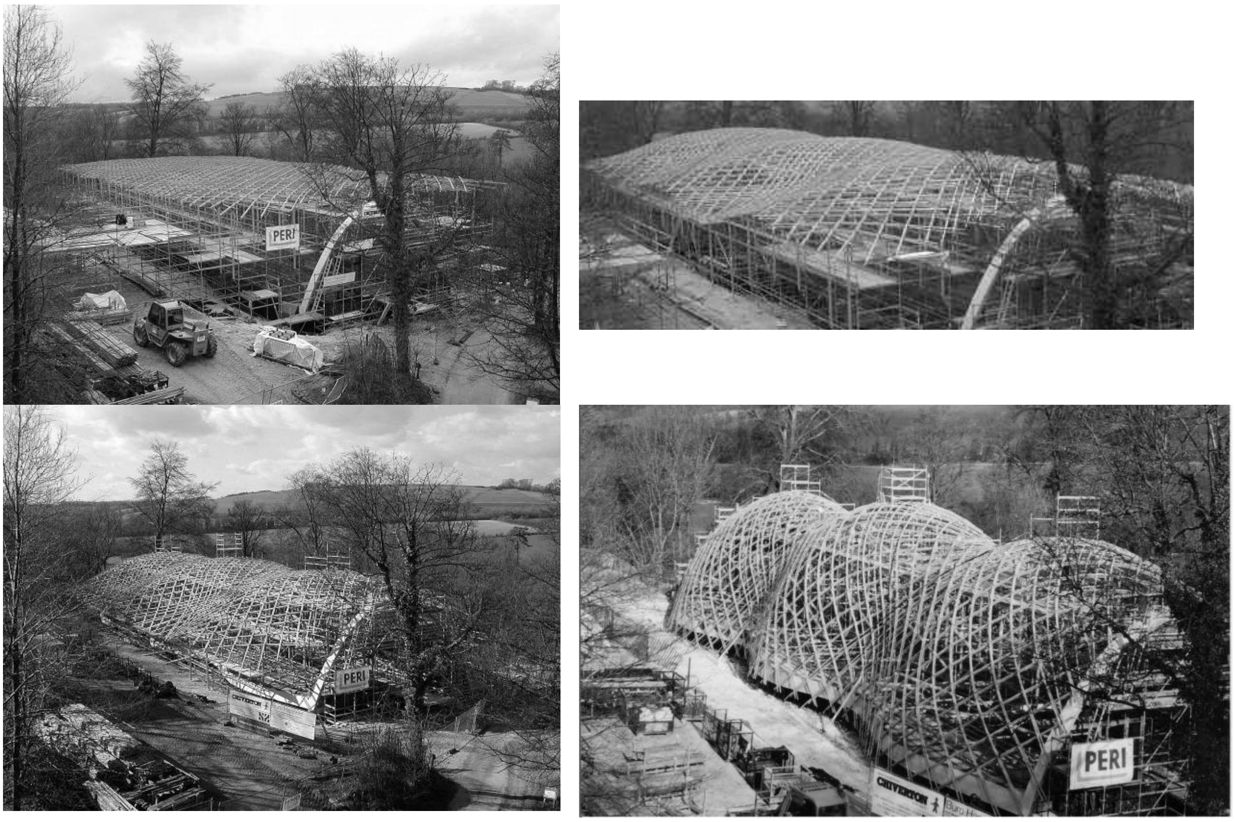


Figure 17: The downland Gridshell

Figure 18: Downland Gridhell - The Completed Building
Photo: Buro Happold / Adam Wilson

2.2 The Savill Garden Building Roof

The Savill Building roof is 90m-long by 25 metres wide timber gridshell – the biggest in the UK. It is a three-domed, double curved structure of sinusoidal shape, and is clearly visible on the inside of the building.
Buro Happold also worked closely with HRW Engineers, the structural engineers for the whole building.

Figure 19: The Savill Garden Building Roof

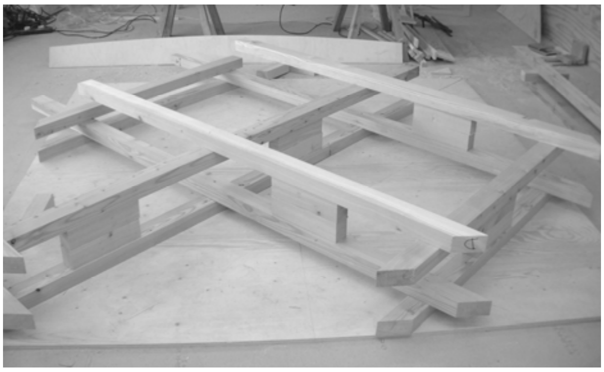
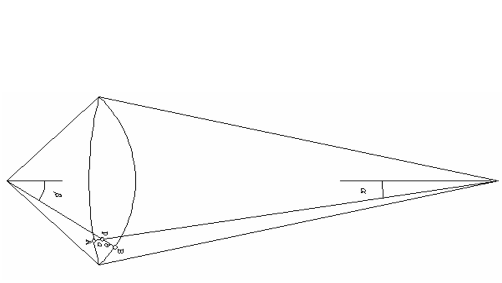


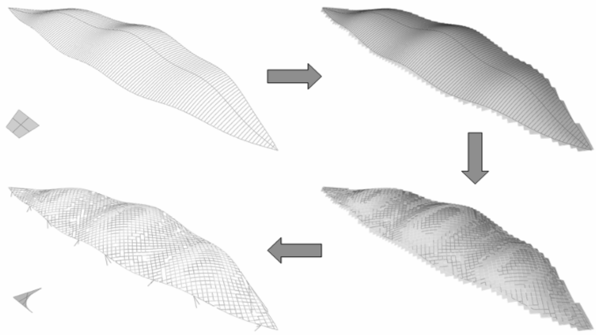
Figure 20: The Design

The design for the Savill Garden Gridshell was developed with the Green Oak Carpentry Company (GOCC). Buro Happold had worked with GOCC on the Downland Gridshell.

The Savill gridshell is made up of a regular one metre grid of 80mm x 50mm sections of larch timber. The three-domed shape is clad in oak.

There is a rigorous form underlying most structures in nature and, although this roof is not a natural organic shape, it has a clear underlying logic to its geometry.





The geometric form of relates back to a single setting out line, which is very near to the building's centre line and is an arc in plan.

Figure 21: The Structure

Load concentrations on the structure had to be carefully considered. Proposals for an all timber structure were considered but, in being true to the design competition concept and creating a dramatic structural statement, the long, high openings into the garden led to the introduction of steel tubes for the perimeter ring and the quadruped legs.

The timber structure springs from the perimeter ring. Kerto LVL ("Laminated Veneer Lumber") fingers, bolted to the steel perimeter, are used to pick up load from the larch laths and progressively transfer of load from the shell to the legs. In general the LVL fingers are hidden behind a soffit of plywood which extends beyond the glazed perimeter walls but, in places of very high load concentration, they can be seen pointing into the interior gridshell space.

Figure 22: "Laminated Veneer Lumber"

To act as a shell, the structure must be strong and stiff in its plane. Initially the concept included steel cables to triangulate and thus brace the shell in its plane.

The plywood covering, which is needed to support the raised seam roof, was used instead. In supporting roof loads, this in-plane structure is just as important as the more visibly obvious laths.

Figure 23: The Plywood covering

The structure's own weight is easily carried by the timber and, with no other loads applied, the stresses in the laths and the plywood bracing are very small. More critical are the forces induced by severe wind and snow. In these design situations, the structural plywood helps transfer the forces through the domes or valleys of the roof, to the steelwork and foundations.

When snow collects on the roof, the plywood in the valleys acts in tension, inducing compression in the larch laths of the domes, which carry the load to the perimeter. When the wind blows through open doors (in a very strong wind it is possible that a door may blow open), the roof tends to lift off; the valleys go into compression and the domes into tension. In either state the timber shell works with the perimeter ring to carry the load to the quadruped legs.

Figure 24: The domes or valleys of the roof

The timber used in the structure has all come from the Crown Estate's commercially managed (and Forest Stewardship Council-certified) woodland in Windsor Great Park. It was very carefully chosen to ensure the quality and quantity of timber was sufficient. This sourcing process, which began in 2003, was carried out in parallel with structural tests of the wood which informed the structural design process and was critical in determining lath size and spacing as well as the quality of the bolted joints and screwed shear blocks.

Figure 25: Photo:Steve Corbett – GOCC

The same jointing method as that used at the Downland Gridshell was used for the Savill Building Gridshell; the Windsor Great Park larch being sawn, finger jointed and planed off-site. The total quantity of material was 10,000m of high quality larch and another 10,000m of lower grade timber, all in six-metre lengths. The result was very little wastage and efficient use of the trees.

Figure 26: Fixing shear blocks
Photo: Buro Happold / Adam Wilson

Unlike the Downland Gridshell, at Savill, because the shell did not have to wrap around to form the walls, it was erected by manipulating the bottom two layers into position and then screwing the shear blocks down before adding the top two layers over the top. In this way it was possible to create extra depth to the overall shell.

More than 20km of 80mm x 50mm larch timber is used in the gridshell. The roof structure weighs 30 tonnes – much less a similar roof in concrete, reducing the loads on the quadruped legs and foundations.

On top of the gridshell is 160mm of insulation, covered by an aluminium roof system and a profiled standing-seam skin which is the waterproof layer and support for the oak rain-screen. Oak was specified for its natural resistance to the elements and for the silvery-grey look it will assume as it weathers.

Figure 27: Insulation cover by aluminium

The confluence of the structural engineering knowledge and analytical and detailing capability of Buro Happold, the design flair of the architect, Glenn Howells Architects and The Green Oak Carpentry Company's remarkable three-dimensional understanding of wood, combined with very high levels of organisational skill and the application of years of craft-based experience, has enabled this structure to be realised.

Another winner of a Wood Awards Gold Award and a shortlisted project for the 2007 Stirling Prize, this building has proived to be another success for the timber industry.

Figure 28: Savill Building - The Completed Building. Photo: Warwick Sweeney