Evening meeting

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The Savill Garden gridshell: design and construction

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Synopsis
The paper describes the design and construction of the roof and supporting structures to the Savill Building. The structure is a timber gridshell, a technique described in detail in previous papers[1,2]. The timber for the Savill Building was harvested from the surrounding woodland. The form of the roof was derived from a simple geometric shape; the analysis and design checks were carried out using the Eurocode. Construction details and process, which developed from the techniques established on earlier buildings, are described.

Introduction
The competition

The aspirations for the Savill Building Project were set by the client, the Crown Estates. The brief was for '*an environmentally sensitive building that would nevertheless leave a dramatic mark on the landscape*'. From a shortlist of three practices, Glenn Howells Architects won the commission for the building in a design competition with a proposal for building roofed with a floating, oversailing curved roof formed using the timber gridshell technique.

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.

During competition interviews Glenn Howells took the client team to visit the Downland Gridshell in Sussex, which had been designed by Edward Cullinan Architects. Here the client met Steve Corbett of the Green Oak Carpentry Company who was able to explain in detail how the building was constructed. This visit, although it was to a building quite different in concept, and designed by another architect, gave a graphic illustration of the dramatic effect created by a timber gridshell roof and gave confidence that, though an innovative form of construction, the roof could be built.

Concept design

The architectural concept was to create a building that melds into the landscape, with a more subdued exterior than interior. The story of the building is about the gridshell roof but there is more than the roof to the structure!

Figure 1 shows preliminary competition sketches of the building form. From these a building structure emerged. From early on it was necessary to keep the edge of the roof high off the ground on the west side to maintain views of the gardens. Structurally this was very relevant as all previous gridshells approaching this size were clamped at ground level to provide the perimeter stiffness that was essential to their performance.

The building developed with a single central entrance from the car-park. On either side of the entrance were two single storey structures housing the ancillary accommodation such as teaching rooms, kitchens, toilets and plantrooms (Fig 2).

The single storey structures were to have earth banked up against them and be planted over with grass. Passing

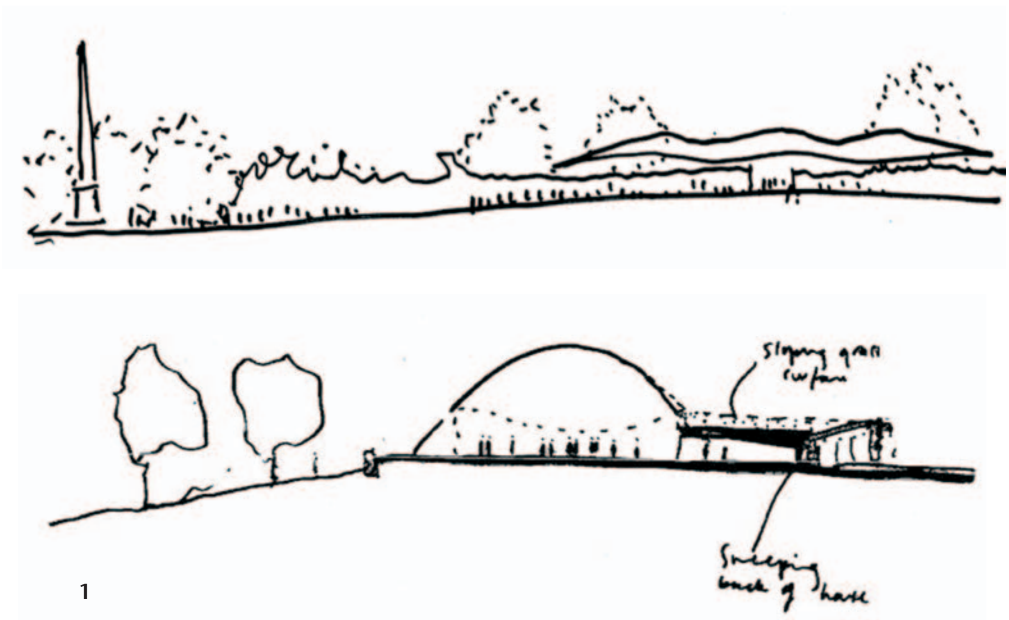

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Fig. 1 Glenn Howells Concept Sketches

through the entrance one would enter the main space, approximately 90m north to south and 30m across. This space was to house the restaurant, garden shop and ticketing booths. A single gridshell roof with a glazed façade was to enclose this volume. The east edge of the gridshell was to be directly clamped to the single-storey structure on the car-park side, providing an element of stiffness and longitudinal stability.
Engineer HRW was Glenn Howells competition partner and the client's appointed engineer but two important factors led to the early involvement of the Green Oak Carpentry Company (GOCC) and Buro Happold.

The first was that with such a specialist form of construction, where method and design were so inter-linked, the procurement route suggested a performance specified approach, with the sub-contractor taking responsibility for the structural design. GOCC, working with Buro Happold, had clearly demonstrated this ability. The difference from the normal performance-specified approach in this case, was that the advice and design were required from pre-planning, right through to tender and construction. Secondly the Crown Estates required the design team to adopt standard fee scales at competition stage. A timber gridshell requires substantial engineering design input, the cost of which could be included in the cost of the roof. After the competition was won GOCC was invited on to the design team, employing Buro Happold as sub-consultant specifically to provide structural engineering design services for the gridshell roof.

Gridshell roof

The 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. Timber has small torsional stiffness and timber gridshells can be made by laying out a lattice as a flat mat, which is then manipulated into shape. The very long timbers needed to make timber gridshells are fabricated by splicing shorter, defect-free pieces together. The word 'lath' has been coined for these long timbers. During forming, the timber lattice must allow rotation at the nodes and bending and twisting of its constituent laths.

Bracing

Once formed, shell action is accomplished by bracing, which triangulates the structure and provides in-plane shear strength. The first double layer gridshell was erected for the Bundesgartenschau in Mannheim, Germany, in 1975. For this gridshell, crossed steel tension cables provided this bracing[3]. For the Downland Gridshell, the bracing was formed with timbers, acting as struts or ties that also supported the cladding. To save cost and make a more elegant structure for the Savill Building, the cables were omitted and the plywood covering, which is needed to support the raised seam roof, was used to provide in-plane strength and stiffness. The timber gridshell is 90m-long by 25m wide and is the biggest in the UK. It is a three-domed, double curved structure of sinusoidal shape, and is expressed architecturally on the inside of the building (Fig 3).

Setting out

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.

Dr Chris Williams at the University of Bath carried out the initial form-finding for this project. Dr Williams has worked in the field of non-

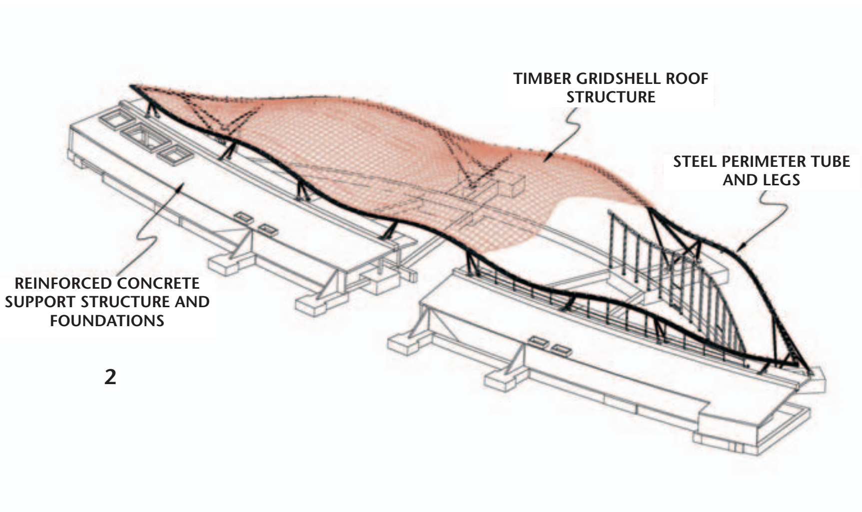

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Fig 2. Building structural layout / Fig 3. Timber gridshell roof

linear analysis of structures for many years; whilst working with Ted Happold at Ove Arup and Partners in the 1970s, he used both physical and computer models to carry out the analysis of the Mannheim shell.

The parametric modelling behind the shape of the Savill gridshell is quite simple: on plan, the perimeter is set out using arcs of two intersecting circles (Fig 4). The curved centreline on plan is the midline between the circles. The centre line of the roof, in section, is generated by a sine curve of varying amplitude, with its peaks and troughs at the tops of the domes and the bottoms of the valleys. The cross-section is then set out across the sinusoidal centre line as a series of parabolic curves of varying shape. This was achieved by means of a program written to define the shape as $z = f(x, y)$ with a damped cosine wave in the x direction and upside down parabolas in the y direction (Fig 5).

By having a clear geometric basis to the surface shape, the architects and engineers could work together to adjust and agree a shape that met the aesthetic aspirations and practical constraints. Onto this surface a grid of equal length elements is generated. The fitting of the equal mesh net on the surface is done using the fact that it is known where two opposite diagonal nodes of a little rhombus lie on the surface, the other two can be calculated. This problem is known as constructing a Tchebyshev net[4].

Analysis

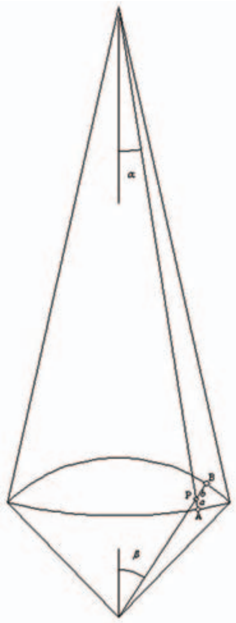
Once the formfinding model was agreed with the architect, the nodes were imported into a structural analysis model. Structural analysis was carried out using Robot 3D (Fig 6). The Eurocode for Timber Structures (BS EN 1995) was used to check the structural elements. The 3D model was then used by the fabricator to detail the structural elements.

The analysis required an interactive period of design between the roof designer (Buro Happold) and the foundation designer (Engineer HRW). The stiffness of the foundation would be fed into the roof model, the results determined and information fed back on whether or not the foundation needed to be stiffened. The foundation would be modified and the new stiffness studied in the roof model, the process being repeated until both the foundation and the roof were performing well.

Structural design

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 (Fig 7).

The Savill gridshell is made up of a regular 1m grid of 80mm × 50mm sections of larch timber. In construction, the height of the roof was adjusted at 200 points across the plan area to bring it to the desired shape. 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 bracing 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.



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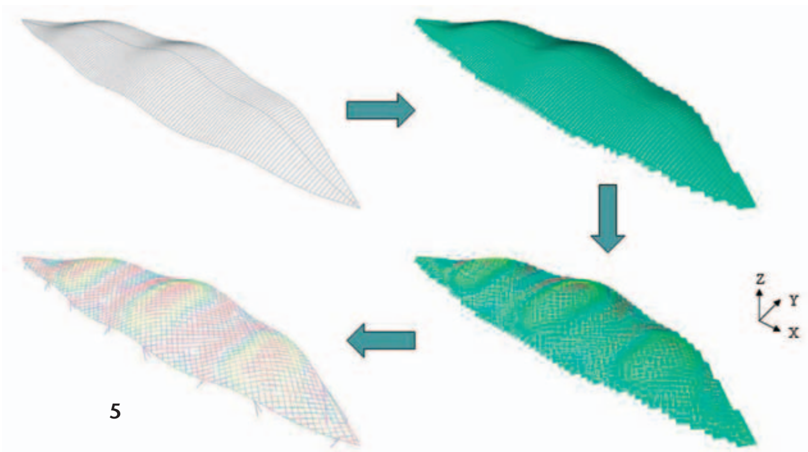

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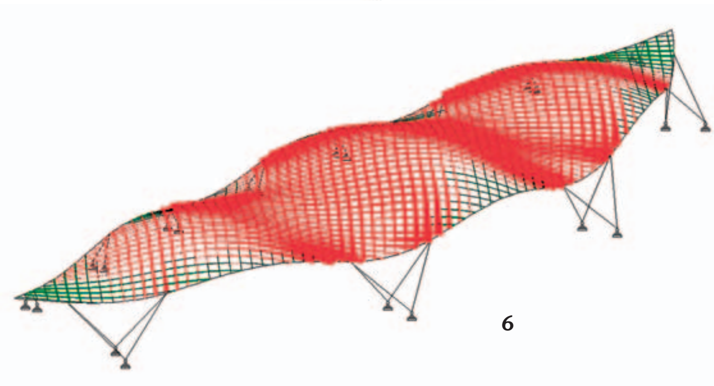

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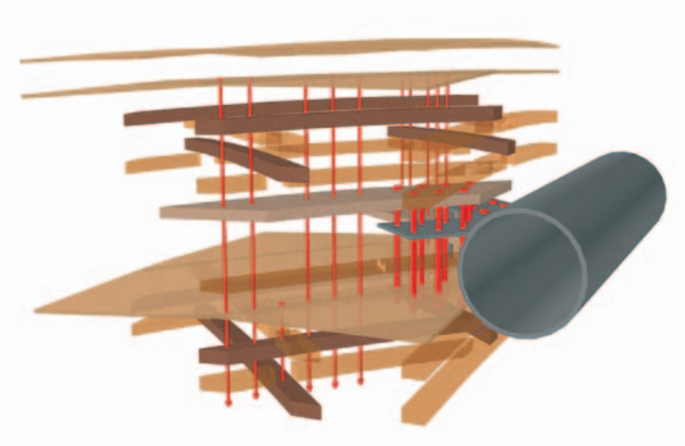
Fig 4. Setting out plan / Fig 5. Form finding and analysis model / Fig 6. Structural analysis model / Fig 7. Connection to perimeter tube



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Together, the 20km of 80mm × 50mm larch timber and its birch plywood covering weigh some 30t – much less than a similar roof in concrete, reducing the loads on the quadruped legs and foundations.

Nodal connection
There are limitations on the tightness of curvature to which laths of a particular cross section can be bent. Hence the depth of lath required in a single layer gridshell, to achieve relatively large spans, may be too deep to permit bending of the flat lattice to a final shape that has tight radii of curvature.

The solution to this problem is to utilise a double layer gridshell. For a lattice composed of four layers, effectively two single layer mats sitting one upon the other, the laths are of sufficiently small section to permit bending of the lattice into the desired geometry. Upon completion of forming, timber shear blocks are positioned between the lath layers and fixed with screws. These transfer horizontal shear between parallel layers and endow the lattice with the properties of a deeper section.

For the Downland and Mannheim gridshells all four laths were bent together[5,6,7]. For the Savill Building, the bottom two laths were bent into shape, then the shear blocks were screwed into position. The upper two laths were positioned over the shear blocks and screwed into place. This technique enabled greater spacing of the layers than achieved on previous gridshells, leading to greater out-of-plane strength and stiffness.

Edge connection (Fig 8)
The timber structure springs from the perimeter tube. Steel brackets are welded to the tube in fabrication. On site flat steel gussets, made to the setting out geometry of the shell lathes, are bolted (Fig 9). Kerto LVL (Laminated Veneer Lumber) fingers are bolted to the steel plates. These carry load from the shell to the steel plates and are used to pick up load from the larch laths and progressively transfer it. They are tapered and are bolted between the layers of timber laths. 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.

Timber sourcing and material properties

Timber selection and testing
Various species of timber were considered. It quickly became apparent that Douglas Fir, Larch and Oak were all available from the Crown Estate's commercially managed (and Forest Stewardship Council-certified) woodland in Windsor Great Park. Samples of all three were examined; the larch was clearly of exceptional quality and was chosen for use in the gridshell. It was very carefully selected to ensure the quality and quantity of timber was sufficient.

The sourcing process, which began in 2003, was carried out in parallel with structural tests of the wood which informed the structural design process. The information was critical in determining lath size and spacing as well as the quality of the bolted joints and screwed shear blocks. Further selection of the wood, into high- and low-grade timbers, was made to ensure the critical structural members, such as the long lengths which carry the internal loads to the perimeter, are of necessary strength. Other elements, such as the infill blocks, are safely made of lower grade timber.

The timber was improved off-site by cutting out defects and finger jointing. Each length of larch was visually inspected by a skilled carpenter to identify knots, unacceptable slope of grain and other defects.

The laths and finger joints were tested in a four point bending test in accordance with sample dimensions given in the Standard[8]. The samples were tested green and not conditioned to the specifications generally required. Testing examined a range of variables, including capacity about both axes, performance of different adhesives and the effect of different production processes. In production a quality control system was implemented to ensure the effectiveness of the finger joints.

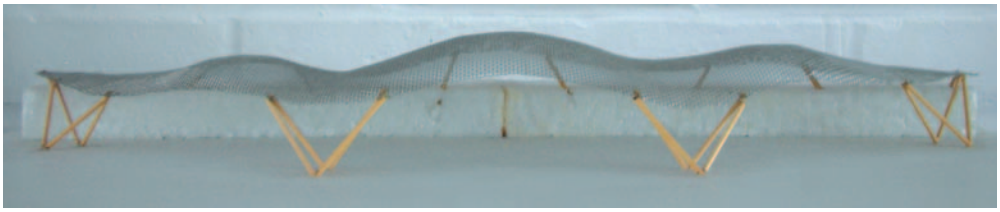
This testing enabled two grades to be identified, with the material properties needed for the structural design. Both grades were specified by the usual criteria with limits on knots and slope of grain; the differentiation between the grades was by ring spacing. By grading the timber into Savill Grade 1 and Savill Grade 2, the utilisation was maximised. The higher grade material was destined to be jointed into 36m lengths to form the major lengths that transfer the structural loads and make up the grid. The lower grade timber was used for shear blocks and packing pieces. The result was very little wastage and efficient use of the 400 larch trees felled for the building structure.

Site jointing
The next stage in the process was to join the 6m lengths of 'improved' timber to produce continuous laths. Some of the secondary trimming timbers were as much as 100m long. 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.

The gridshell lattice would require 20 000m of lath, which were finger jointed into 6m lengths and then scarf-jointed into 260 continuous single pieces each up to 35m long. 10 000 finger joints and 1000 scarf joints comprise the structural jointing. There were two fractures during the construction process, easily repaired.

The advantage of using 'improved' timber laths was that the quality of the material was maximised very quickly and cheaply with minimum wastage. The result was 10 000m of high quality (Grade 1) larch and another 10 000m of lower grade (Grade 2) timber, all in 6m lengths.

Fig 8. Edge detail / Fig 9. Edge plate fitted on site



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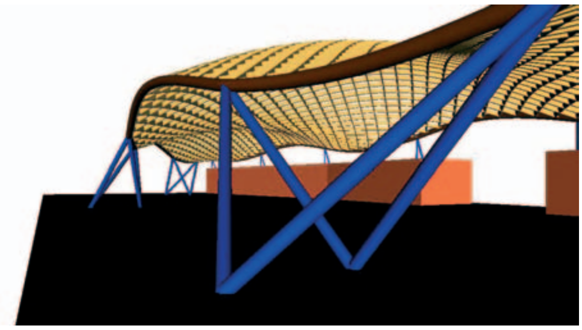

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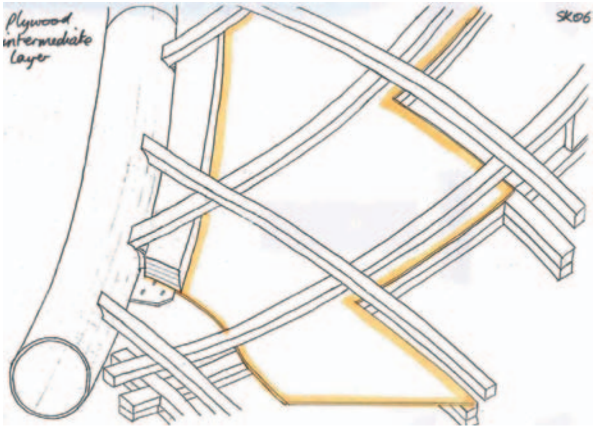

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Prototyping

The design process utilises several stages of modelling

Small scale development models were made using woven wire mesh (Fig 10). These are quick and easy to make in the scheme design stage and give indicative information about both the buildability (by estimating curvature) and appearance. The next stage is computer modelling (Fig 11).

The development of the grid model is explained above. Conversion of this to both analysis models is obviously essential. There was also the opportunity to create visual models for presentation to the client and the team. In developing details, the carpenters produced sketches of suggested practical details. These were invaluable in creating the final solution (Fig 12), especially the complex detail connecting the shell to the perimeter tube.

Towards the end of the detail design period, the carpenters rented a medieval barn in West Sussex and in it constructed a small, full-size section of the shell. This enabled a client review of the structural appearance (Fig 13). There was a choice of the layout of shear blocks and the one preferred by the architect and client was selected. The client chose to upgrade the quality of the plywood surface to the shell, from spruce to birch, which gave an improved appearance.

Roof and glazing finishes

Glazed façade

The gridshell roof is a long-span structure and deflects significantly under load. With full drifted snow load in the valleys, deflection on the glazing line the roof could be 150mm. In wind reversal (with a strong wind and dominant opening) deflection upwards could be 70mm at the same point. Thus the glazing head needs to accommodate movement of 220mm. The horizontal restraint forces from the glazing head must be applied into the gridshell along its neutral axis, to the centrally located LVL fingers used to transfer the gridshell loads into the perimeter beam. None of the connections could clash with the gridshell lath members.

This range of design parameters led to a purpose designed and fabricated solution, developed with the glazing contractor, Haran Glass. It involved a top bar linking the mullions and a double-slotted sliding connection. The torque bar at the top enables the connections to be positioned to avoid the laths (Fig 14). On the entrance elevation a structural connection with the roof was avoided by cantilevering the mullions.

Fig 10. Wire mesh model / Fig 11. Computer model / Fig 12. Sketches of details (© *Green Oak Carpentry Company*) / Fig 13. Full size prototype Fig 14. Glazed façade

Roof finishes

The structural roof finish uses two layers of plywood to resist vertical loads and to brace the roof (Fig 15). A timber finish to the roof was proposed from the start, but it was never intended to be water-tight.

There was much debate about this roof covering. It was clear that the competition had proposed a timber finish and, with high quality material available from Windsor Great Park, there was a strong desire that this finish should be oak, which has good natural resistance to decay and can weather to silvery-grey.

Initially the design team proposed a sarnafil type roof membrane laid over the insulation, over the ply. This meant the rainscreen needed to be supported off the roof on long stools, which would have led to over 2000 holes through the membrane. Even with careful flashing, this would have created an unacceptably high risk of water ingress and the main contractor, William Verry, proposed a standing seam zinc roof which when investigated, offered many advantages. It was far more robust and able to withstand site abuse and the standing seams where ideal fixing points for the rainscreen. The final build up on top of the plywood is 160mm of insulation, covered by an aluminium profiled standing-seam skin which is the waterproof layer and provides support for the oak rain-screen.

Cantilever eaves bracket

To form the leading edge to the roof, tapered cantilevered oak arms extend from the top of the perimeter beam to permit the rainscreen to sail over, with the edge terminated by one continuous mechanically laminated edge timber linking the ends of all the cantilever arms. This timber, spliced on site from finger-jointed lengths, is over 100m long.

Foundations and steel structure

Ground conditions

The site is at the top of a rise with the ground dropping down to the west but fairly level to the east. The initial site investigation showed there to be a soil profile of medium dense sands to a depth of approximately 10m overlying stiff fissured clay; average N values in the sands were 17 at 2.0m and a net bearing pressure of 140kN/m^2 was adopted.

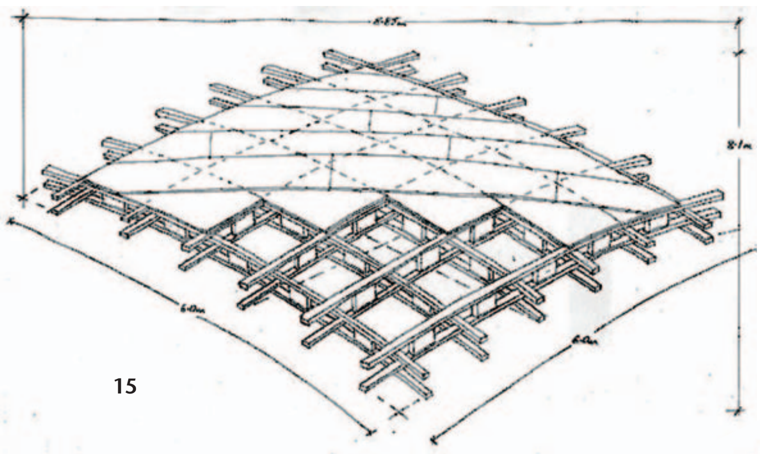
A number of settlement calculations were carried out, the values ranged from 8mm using an empirical calculation derived by Schulz and Sherif[9] to 25mm using the conservative Terzaghi and Peck graph of N values against foundation width. With these estimated settlements a spring stiffness was derived for the soil and a finite element analysis carried out to evaluate the settlement characteristics of the base as a whole and as previously mentioned, these results were fed back into the gridshell analysis.

Settlement of the bases was important, as a 5mm drop below the main compression leg base would result in a 20mm lateral movement in the perimeter beam, which in turn would increase bending stresses and decrease axial stresses within the gridshell. In this ground there is the potential within the sand strata for soft clay lenses to exist and these could have had serious settlement implications. Four cone penetration tests to 8m depth, two on each side of the main garden side foundations were carried out as a precaution but no soft lenses were found. Using the Schmertmann method[10], settlements of approximately 4.0mm were calculated under full loading, about half that previously calculated.

Foundation loads

To understand the foundation design it is necessary to understand the primary loads that are acting on them. The foundations were designed in balanced groups.The net vertical loadings are not significant. For each group of four legs the load is approximately 700kN. However, the high internal axial forces generated in the gridshell and the lack of alignment between the legs bases and these forces, generate large overturning moments. This resolved as a base reaction under the forward legs of approx. 1850kN and an uplift on the back legs of 1150kN.

The foundation groups are arranged to balance the loads (Fig 16). Group 1 links the east and west elevation forces normal to the perimeter beam and Group 2 resolves the forces tangential to the perimeter beam. All the loads on the east elevation had to be directed through the concrete superstructure. This structure consists of a raking curved flat slab supported off a retaining wall at the lower end and an *in situ* concrete ring beam spanning 12.4m between columns at the upper end.



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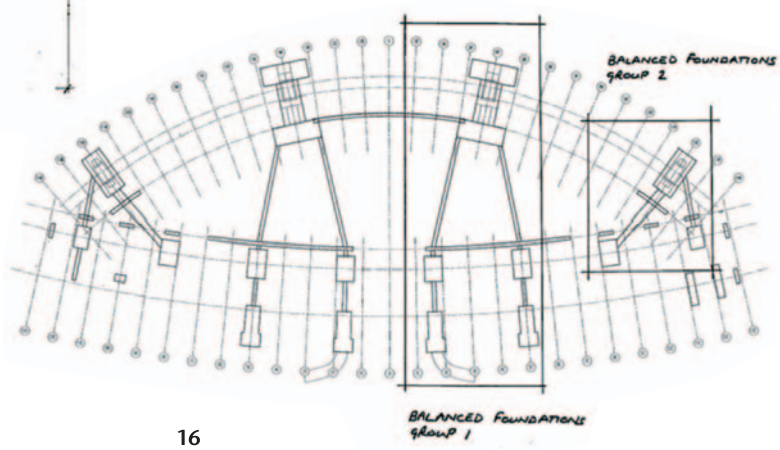

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Fig 15. Structural roof finishes (© *Green Oak Carpentry Company*) / Fig 16. Balanced foundation groups

The loads from the east elevation legs are similar to those on the west elevation, however, as they are shorter and stiffer the tangential forces are more evenly distributed between them. The central leg pairings carry the most load and each leg in the pair, forward pair and rear pair, carry similar loads under most loading conditions. When resolved at the bases the primary forces are therefore vertical and normal to the perimeter beam. The end leg pairings carry significantly less load, and most of the load comes from the side domes. When resolved at the bases the primary forces are vertical and tangential to the perimeter beam. Although the end legs carry very little load, in the thermal load condition they restrain the roof construction from expansion and, as a consequence, attract high tension loads. Luckily high temperatures and snow rarely exist together (!) and so the forces could be considered independently.

The foundation design adopted uses a foundation block to distribute the load under the front legs and an offset anchor block to the rear linked by two groundbeams. The offset anchor block has the double benefit of distributing some of the upwards load to the foundation block, reducing its size and, by using a lever arm, the size of the anchor block could be reduced. If the anchor block were located under the rear legs, with a Factor of Safety of 1.5, then 74m^3 of concrete would be required but the one constructed contains 24m^3. A similar principle was used on the east (entrance) elevation where a tension column was positioned away from the steel tension leg, the tension column is restrained at ground level by a cantilevered groundbeam.

Steel structure

The steel perimeter tube and timber gridshell roof are interdependent, the analysis of the gridshell had to include the perimeter beam as the relative stiffness of each determines the performance of the roof and the distribution of stresses. The finite element analysis of the roof was carried out by Buro Happold using over 30 different load cases. Following the first iteration, horizontal and vertical spring stiffnesses for the supports were calculated by Engineers HRW and fed back into the roof model.

The domes of the shell work in compression and the valleys hang between them. The primary axial compression forces meet the perimeter roughly where the curvature changes between dome and saddle, and this is where the leg connections are located. The leg connections are the stiffest points along the perimeter and will naturally attract load, the positioning was a case of responding to the natural needs of the structure. The heavy red colour of the roof finite element model (Fig 6) shows the concentration of load in the shell over the stiff support legs.

By generating a surface and cutting planes through to create the perimeter edge centre lines, the steel tube could be fabricated in two dimensions, making for increased buildability. Full moment continuity was required along the length of the perimeter tube, with site fabrication joints hidden from view. Axial loads from the gridshell roof need to pass through the centre of the beam.

Pre-tender meetings during the design stage were held with a number of steel fabricators, and the issues of the geometrical complexity and load transfer at the legs were discussed. SH Structures proved very helpful in resolving these issues and a number of meetings were held with GOCC, Buro Happold, Engineers HRW and SH Structures – even though it was pre-tender SH Structures were prepared to offer free advice at this stage.

The perimeter tube was to be segmentally cut and welded to form the curvature on plan and an agreed deviation from the centreline determined the lengths of the segmentally welded sections. The sections were delivered to site in lengths up to 13m and connected via internal end plates and tension control bolts. The site connections were also designed as points of rotation. Access holes cut into the tube enabled the on site bolting to be carried out, these were later sealed and once painted the connection joint was not visible.

The fabrication and erection detailing and method enabled an accuracy of ±6mm to be achieved on the erected steel structure, despite the complexity (Fig 17). The leg size had to be visually subservient to perimeter beam. It was initially proposed that all the legs have moment connections with the perimeter tube and pinned feet. On the east elevation, due to the very short leg length, these legs attracted very high moments. To get these legs to work with standard sections it was necessary in places to sleeve the tubes. Fortunately SH Structures was able to simplify this

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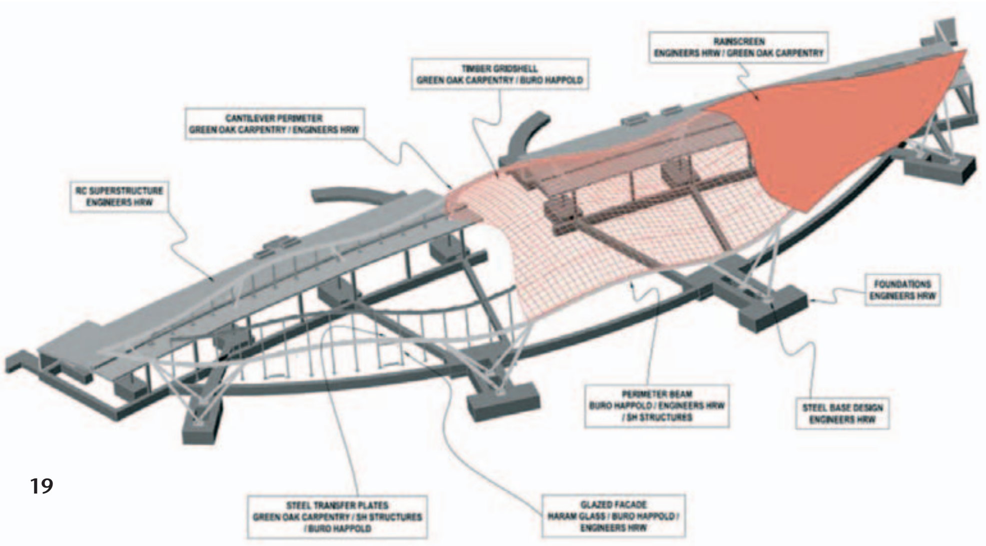
Fig 17. Steel perimeter tube during construction / Fig 18. Completed steel edge



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by sourcing non-standard circular sections with up to 30mm wall thickness.

The central garden legs are approximately 8.0m long and accommodate loads up to 980kN; to keep the section size below that of the perimeter beam pinned connections were required top and bottom. With a 20mm eccentricity allowed for at the connection and a further 20mm eccentricity allowed for in the rolling tolerance, and using grade S 355 steel, these legs are working at 98% capacity under full load. The rear legs to each set are normally working in tension and so are smaller sections. The leg to beam pins were later covered with steel cowlings to give the impression of a moment connection (Fig 18).

All the leg bases had to transfer large horizontal loads, compression and tensile loads. They are also visible to close inspection in the finished project and the connections had to be in proportion to the legs. In many instances the shear pins had to fabricated from FV 520 B martensitic stainless steel to avoid oversized connections. On the east elevation more freedom was permitted and the fin plates could exceed the width of the tube.

Conclusions

Only through collaboration was this project possible. First there was a client with consistent vision of a quality end product. Then there was the confluence of the structural engineering knowledge and ability of two structural consultants, Engineers HRW and Buro Happold. The design flair of Glenn Howells Architects, and GOCC's remarkable three-dimensional understanding of wood, combined with very high levels of organisational skill and the application of years of craft-based experience, enabled a successful realisation.

In addition, the collaboration of several specialist contractors (in particular Haran Glass and SH Structures) brought together by the main contractor William Verry provided further opportunities (Fig 19). The result is a succesful product for the client (Fig 20).

Credits
Client: Crown Estates
Architect: Glenn Howells Architects
Structural Engineers: Engineers Haskins Robinson Waters with Buro Happold
Building Services Engineer: Atelier 10
Cost Consultant: Back Group
Project Manager: Ridge and Partners
Contractor: Verry Construction
Timber Engineering Contractor: The Green Oak Carpentry Company
Forestry: Crown Estates
Timber Supply: English Woodlands
Structural Steel: SH Structures
Glazing Contractor: Haran Glass

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Fig 19. Collaborative design / Fig 20. Completed building (© *Warwick Sweeney*)