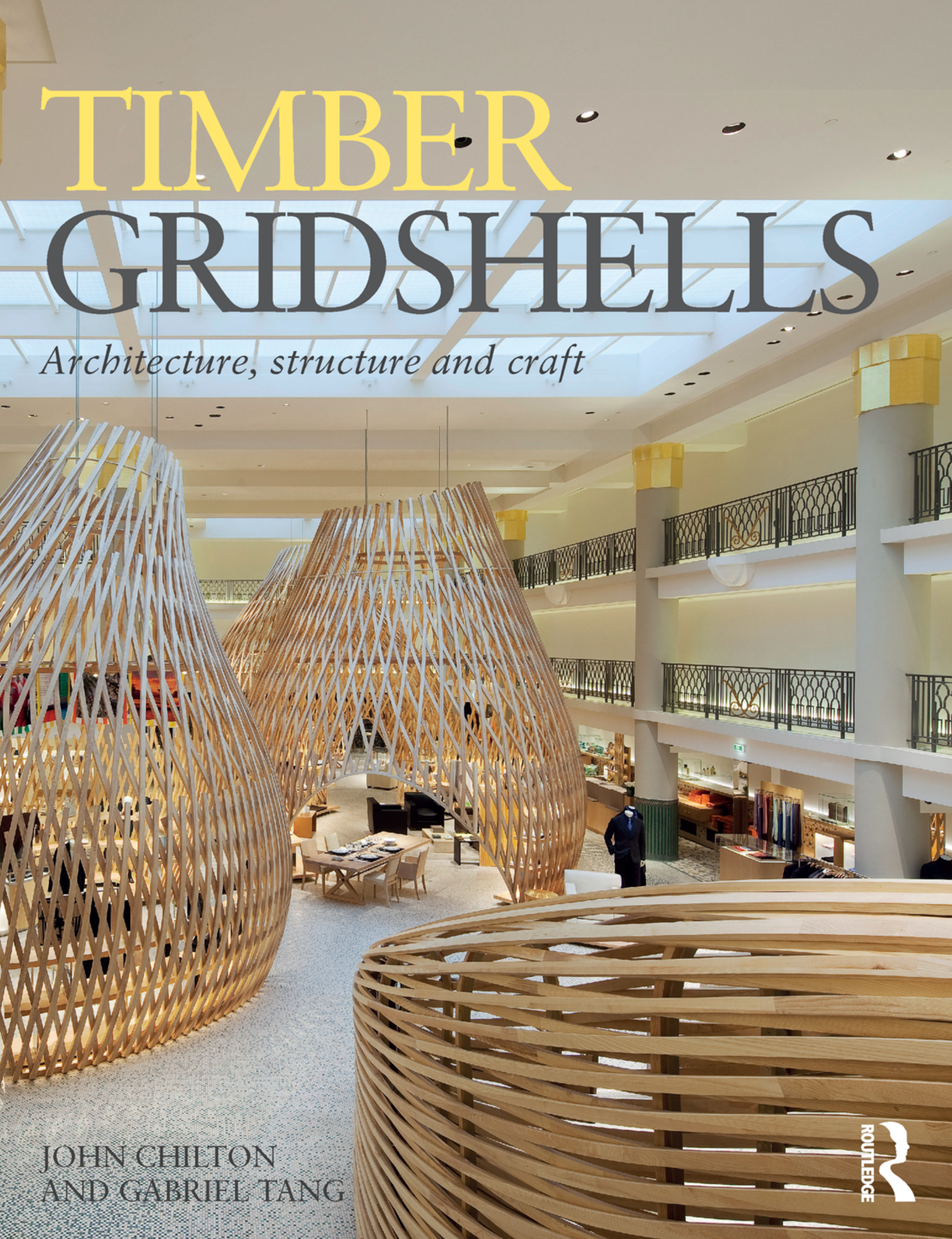
TIMBER GRIDSHELLS

Architecture, structure and craft



JOHN CHILTON
AND GABRIEL TANG

ROUTLEDGE

TIMBER GRIDSHELLS

THROUGHOUT history, people have constructed simple timber lattice shelters, such as the tepee or yurt, covered with animal skins, leaves, grasses and woven fabrics. Over the last fifty years, more sophisticated 'webs of wood' have emerged, with timber gridshells in particular becoming a structurally expressive form of architecture. Recent developments in digital design, 3-D modelling software and timber fabrication technologies, as well as trends towards low-carbon construction, have further reinforced architects' interest in the use of lightweight timber grids and lattice structures.

This timely book charts the origin and evolution of the timber gridshell and its relation to timber lattice architecture. Drawing on a range of international case studies, the authors trace the effect that advances in technology have had on design and construction in this field, providing a clear understanding of the structure, morphology, design process and construction technology, and examining both the application and constraints of timber gridshells in architectural design.

Timber Gridshells is a highly illustrated, up-to-date resource that provides detailed answers and inspires new ideas. As such, it is essential reading for students of architecture as well as professional architects.

JOHN CHILTON is Professor of Architecture and Tectonics at the University of Nottingham, UK. With a special interest in the history, design and construction of innovative and non-conventional structures, he is an active member of the International Association for Shell and Spatial Structures (IASS) and chaired their Working Group 12 – Spatial Timber Structures – from 1998 to 2015. He is the author of *Space Grid Structures* and *Heinz Isler: The engineer's contribution to contemporary architecture*, a book on the work of the Swiss reinforced concrete shell-builder Heinz Isler.

GABRIEL TANG is an architect and Senior Lecturer in Architecture at Sheffield Hallam University, UK. He trained at the Bartlett, University College London, UK, and worked in the offices of Foster + Partners, London. Currently completing a PhD at the University of Edinburgh, UK, on the novel use of deployable gridshells as formwork for concrete shell construction, his research interests lie in technology culture, material tectonics and the innovation synergies between architecture, structure and construction processes.

‘*Timber Gridshells: Architecture, structure and craft*, a well-written and illustrated book, takes readers on an informative journey through the origin, evolution and application of timber gridshells alongside the development of technology. The book will inspire creativity in architects and engineers alike.’

Abdy Kermani, Director of Centre for Timber Engineering, Edinburgh Napier University, UK

‘Anyone interested in the technology of structures and architecture will enjoy *Timber Gridshells*. Written with clarity and elegance, readers will find delight in the architecture presented through the series of beautifully illustrated and carefully designed case studies of this book.’

Remo Pedeschi, Professor of Architectural Technology, University of Edinburgh, UK

TIMBER GRIDSHELLS

ARCHITECTURE, STRUCTURE AND CRAFT

JOHN CHILTON

AND GABRIEL TANG

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PREFACE

TIMBER GRIDSHELLS

Everyone who has seen a timber gridshell will have experienced their delightful uniqueness and spellbinding magic. Their beauty lies in the way the 'bones' of the structure are exposed to express their form. The assemblage of filigree components creates a strong sense of materiality and tectonic understanding.

The curved nature of the gridded surface also allows the titillating play of light and shadow to accentuate the changing perspectives of the structural system, bringing about a visually stimulating surface rich with variations in daylight. Come nightfall, with imaginative lighting schemes, the structural net comes alive with spectacular visual drama. Gridshells depict structural logic, reveal construction technique and showcase the hand craftsmanship of the carpenters or digitally-controlled precision of the machines that have brought them into existence. These structures are most commonly applied as roof and/or wall enclosures, where structure

Figure 0.1 The inverted undulating surface of Savill Garden timber gridshell strongly projects the interlinking notions of architecture, structure and craft
Source: © John Chilton.

and building envelope exist in union as a single entity. In common with reinforced concrete shells, the form dominates the architecture. Imbuing these qualities and being visually striking, the architectural experience offered by timber gridshells is instant, powerful and instinctive.

ARCHITECTURE, STRUCTURE AND CRAFT

While researching this book, the changing relationship between architecture, structure, craftsmanship and technology has emerged as a recurring theme. As the evolution of timber gridshells has paralleled the development of technology, the story of timber gridshells also narrates, in part, the influence of technology on architecture.

Apart from their aesthetics, timber gridshells embody the close interlinking relationship between architecture, structure and craft, which results from the intimate collaboration of the architect, the structural engineer and the craftsperson/fabricator. From conversations with professionals involved in all aspects of timber gridshell realisation, these recurring themes have emerged in every project.

This tripartite notion of the complex overlap between architecture, structure and craft was acknowledged by Richard Harris, John Romer, Oliver Kelly and Steve Johnson in their paper, in 2003, which reported on the design and construction of the Weald and Downland Jerwood gridshell, near Chichester, UK. Completed in 2002, this was designed by Edward Cullinan Architects, now Cullinan Studio, and engineers Buro Happold, and represented the culmination of the ever-improving development of timber technology, form-finding methods and construction techniques. The designers learnt from and built on the lessons imparted by previous timber gridshells, such as those at the Earth Centre Forest Garden, near Doncaster, UK, and the cardboard tube Japan Pavilion at the Hanover Expo 2000. These projects and the technological developments that led to their realisation stimulated a renewed interest in timber gridshells as an architectural/structural typology.

Materially, technology is redefining the structural role and changing the physical appearance of timber gridshells. Problems faced by the early generation of gridshells such as breakages due to knots in the timber no longer have an impact on the possibilities.

Technological development is also changing the important role of the craftsperson from the thinking artisan to a mechanical assembler of pre-fabricated parts with tight tolerances. In a way, the role of the designer and the maker – one previously borne by the craftsperson – has now been replaced very much by the computer and the originator. This new way of realising digitally generated timber gridshells is casting a new light on the relationship between the architect, the engineer and the craftsperson – posing a timely question of how technology has affected gridshell design and construction.

During our research for the book, the criteria for classification of a timber grid structure as a gridshell was a common question both in discussions between ourselves as authors and in conversation with other professionals in the field. It remains a difficult question due to the multifarious nature of timber gridshell construction. There are 'purists' who accept as gridshells only those timber structures that fulfil the classic definition in *IL10 Gridshells – Gitterschalen* – i.e. those formed from initially flat deployable grids of thin timber laths. However, nowadays the term is also freely and widely applied by many to free-form timber grids assembled from sometimes relatively massive, single- or double-curved, engineered timber components, connected by sophisticated metal jointing systems. All are encompassed in this volume to enable the reader to decide for themselves.

STRUCTURE OF THE BOOK

In Chapter 1, we briefly review the historical precedents for timber gridshells and present aspects of their design including morphology, form-finding, materials, structure, fabrication and installation.

The birth of the engineered timber gridshell as building typology is outlined in Chapter 2 through an historical account of early timber gridshells attributed to the late Frei Otto (1925–2015). These range from a small pavilion at the Deubau exhibition, in Essen, in 1962 to the construction of the inspirational Mannheim Multihalle, in Germany, in 1975, which still stands today although facing an uncertain future. His first experimentations resulted in the coinage of the term gridshell or *Gitterschale*.

A second generation of large deployable gridshells, constructed over 25 years after the Mannheim Mulithalle, is described in Chapter 3. These developed from the collaborations between architects and engineers to improve on experience gained from the Multihalle, and were similarly constructed on the principle of deforming a flat deployable timber gridmat. The Weald and Downland gridshell, the seminal case study that embodies the spirit of the collaboration and respect between various agents of design, is featured here.

Ribbed gridshells are described in Chapter 4. Proposed by Julius Natterer, the method, which laminates alternating orthogonal layers of thin timber planks, creates a rigid single-layer gridshell and reduces (practically eliminates completely) the number of timber lath breakages typically sustained during the deployment of early gridshells.

Chapter 5 introduces alternative materials and construction methods through case studies of small-scale projects while in Chapter 6 further small-scale and experimental timber gridshell projects are presented. Undertaken by academics, practitioners and research groups around the world, these inform their teaching and practice and extend the knowledge boundaries of timber gridshell design and construction.

Chapter 7 spotlights larger-scale gridshells that are now frequently 'made to measure' using digital design and fabrication. As digital form-finding and structural analysis have become increasingly sophisticated, and fabrication technology, such as CAD, CAM and CNC machining of new, more stable, engineered timber products, has become more widely used, timber gridshells are becoming more adventurously free-form. This represents a major departure from the original deployable flat grid method first proposed in the 1960s.

The final chapter, Chapter 8 presents case studies of high-profile timber gridshell projects that are either recently completed or under construction at the time of writing. They demonstrate the increasing application of timber as the primary construction material and the growing acceptability of the gridshell typology for large-scale structures.

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CHAPTER ONE

Introduction

Shells with holes

WHAT IS A GRIDSHELL?

> The grid shell is a spatially curved framework of rods and rigid joints. The rod elements form a planar grid with rectangular meshes and constant spacing between the knots [nodes]. The form of a grid shell is determined by inverting the form of a flexible hanging net. To invert the catenary so that it becomes the thrust line of an arch free of moments is an idealisation. Analogously, inverting the form of a hanging net yields the support surface of a grid shell free of moments.
>
> (Hennicke and Schaur, 1974: 26)

THIS CLEAR DEFINITION of what the researchers considered a gridshell to be was set out in the introduction to the first and very comprehensive source of information on gridshells (or *Gitterschalen*), *IL10: Gitterschalen – Grid Shells* (Hennicke and Schaur, 1974), published by the Institute for Lightweight Structures (IL), University of Stuttgart, in 1974. The publication reported on work carried out initially under a joint Japanese-German research project 'Equal meshed compression stressed gridshells', which ran from 1971 till 1973, and was called S.T.I. after the partners Seibu Construction Company Ltd, Tokyo; Kenzo Tange + Urtec, Tokyo; and the IL, Stuttgart. It also described research under *Sondersforschungsbereich* 64 (SFB 64) 'Weitgespannte Flächentragwerke' (wide-span lightweight structures) which continued the initial research from June 1973, onwards.

One might take the above as the purist description. However, a wider, simpler and perhaps more generally accessible description was given by Steve Johnson of Edward Cullinan Architects in his article for the Weald and Downland Open Air Museum, describing the construction of the Jerwood gridshell (described in detail in Chapter 3): 'A shell is a natural, extremely strong structure. A gridshell is essentially a shell with holes, but with its structure concentrated into strips' (Johnson, 2000). In this definition it is important to note the last phrase – 'structure concentrated into strips'. In this book we shall initially consider timber gridshells that fit the original IL10 description – here referred to as 'classic' or 'traditional' gridshells – before exploring more recent interpretations of the term gridshell, which fit the latter definition, and the wider applications assisted by the availability of engineered timber products and digital design and manufacture.

PRECEDENTS

SEEN AS A modern structural form, the gridshell in its simplest form has been used by the human race to construct a shelter throughout history. The simplest of shelters consists of a network of bent and intersecting flexible twigs and branches. The basic grid can then be covered with animal skins or woven fabric. A more refined version of this is seen in modern camping tents, which use flexible fibre-reinforced rods to tension their covering fabric.

In the Mongolian desert, the yurt has evolved as a foldable and portable shelter for the nomadic peoples of that region. The key element consists of an, essentially flat, trellis lattice that can be deployed and bent to form a circular perimeter wall. This is stabilised by fixing to the ground and installation of the roof structure, before covering with felt blankets (Figures 1.1 (a) and (b)).

Figure 1.1 (a) Mongolian yurt, showing the folding trellis grid, single-curved, shell; (b) covered yurt at the Earth Centre, near Doncaster, UK
Source: (a) © By en:User:Tkn20 (en: Image:68530028.JPG), GFDL (www.gnu.org/copyleft/fdl.html), CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/) or CC BY 2.5 (http://creativecommons.org/licenses/by/2.5), via Wikimedia Commons; (b) © John Chilton.

BASKETRY WEAVING

THE HUMAN RACE has practised the art and craft of basketry weaving for millennia. Through the use of thin, flexible, usually natural grass stems, canes, twigs or poles, one can create an almost infinite variety of flat, curved and double-curved containers and load-bearing forms (Figure 1.2). The association between woven basketry and the classic timber gridshell is clear; however, there are also clear differences. In basketry there is generally no connection between the interwoven stems apart from direct contact friction and the stems are free to slide and rotate relative to each other. Conversely, although there

Figure 1.2 Woven grids of traditional baskets form double-curved load-bearing surfaces
Source: © John Chilton.

are some examples of woven timber grids – for instance, the bamboo grid used in Shoei Yoh's Naiju Community Center shown in Figure 5.7 on p. 105 – the vast majority of timber gridshells consist of two or more unwoven intersecting layers of timber laths that are physically connected at their crossing points or nodes.

Perhaps one of the most common gridshells (although not usually made of timber) is the food sieve (Figure 1.3). This is fabricated from a flat woven wire mesh, which is forced into a hemispherical shape by being pushed through a circular perimeter ring former. Close inspection reveals how the originally orthogonal grid deforms to achieve this change of shape. The mesh at the centre of the sieve remains orthogonal. However, close to the perimeter it can be seen that the mesh deforms in different ways according to location around the ring. In some areas, the square mesh shears, creating a pronounced diamond/lozenge pattern, with all wires intersecting the perimeter at a steep angle. However, in the intermediate areas this effect is far less pronounced, with the mesh remaining almost orthogonal, wires in one direction intersecting the perimeter almost perpendicularly, while the others form gentle, almost parallel, curves, which intersect the boundary at an acute angle. A similar deformation mechanism is required for all gridshells that are created from initially orthogonal meshes (the IL10 definition) to enable them to fit a double-curved surface.

Figure 1.3 Typical wire mesh food sieve. Note the variation in angle of the mesh where it meets the ring
Source: © John Chilton.

CLASSIC GRIDSHELL DESIGN

A CATENARY OR funicular curve is generated when a flexible linear element, resistant only to axial tensile forces, such as a rope or chain, is suspended between two support points and loaded only by its self-weight (Figure 1.4 (a)). The principle of inversion of the hanging funicular chain profile to create a structure under pure compression, when subject to the same loading, was known in the late seventeenth and early eighteenth centuries. Robert Hooke (1635–1703) is recognised to have solved the problem in 1671 while working with Christopher Wren on the rebuilding of St Paul's Cathedral, London, and Giovanni Poleni (1683–1761) used the principle in his work on the dome of St Peter's in Rome, in 1748 (Figure 1.4 (b)). It was famously applied for three-dimensional networks by Antoni Gaudí in the design of the Colonia Güell Church, Santa Coloma de Cervelló, near Barcelona (1898–1914). With these precedents, from 1946 onwards, German architect and engineer Frei Otto (1925–2015) experimented with nets of fine chains, as a method for determining the form of potential double-curved spatial structures. His innovation was to perceive that the three-dimensional form generated by a quadrangular network of hanging chains could be constructed using an initially flat, semi-rigid lattice of timber rods or steel bars (Happold and Liddell, 1975: 99).

If the node joints between the layers of the grid permit rotation relative to each other in plane, the flat assembly is deployable. It is a mechanism with one degree of freedom. This means that, in the idealised situation where all the joints are assumed to be totally frictionless and all the members in the grid totally rigid, deformation of any of the grid meshes will result in a similar distortion of all the remaining meshes of the grid. As can be seen by moving one point in a square grid (Figure 1.5 (a)), one diagonal of each mesh shortens while the other extends and a diamond or lozenge pattern of parallelograms is generated (Figure 1.5 (b)).

If the lattice is constructed using flexible rods, the grid may be bent out of its original flat plane into a

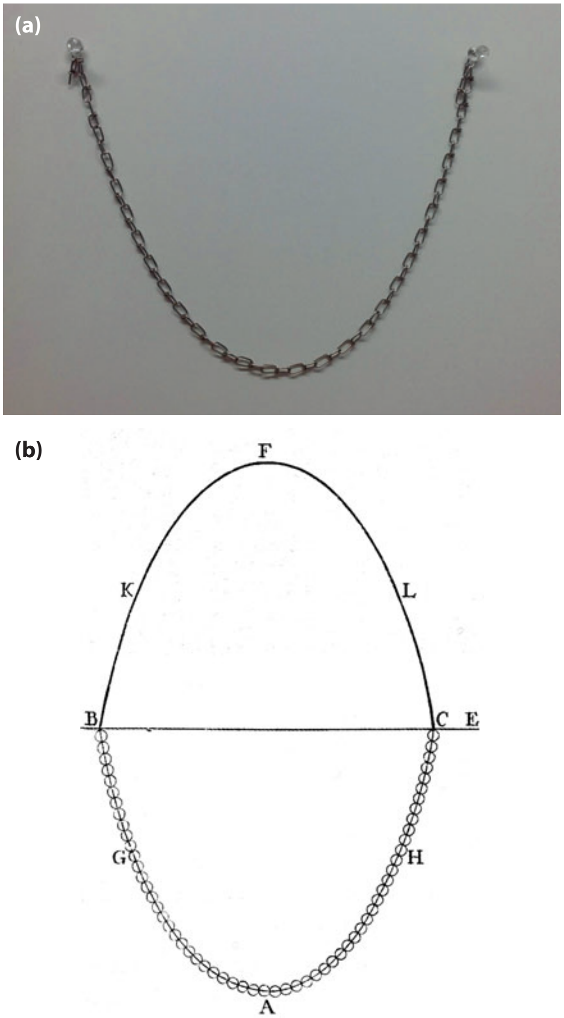

Figure 1.4 (a) Catenary or funicular curves formed by chains suspended between two points and loaded by self-weight only; (b) Hooke's hanging chain and the inverted rigid catenary arch, as depicted by Giovanni Poleni (1748)
Sources: (a) (© Gabriel Tang; (b) Adriaenssens *et al*. (2014).

single- or double-curved surface in which the shape of each mesh is slightly different from its neighbour.

This method appears at first to be deterministic, as the form is self-generating once the mesh is attached at the boundary. It is created by a unique balance of geometry, applied loads, internal forces and reactions, which apply only to the configuration under consideration. However, this is just one of an infinite number of possible solutions and there are many opportunities for the architect to influence the final form

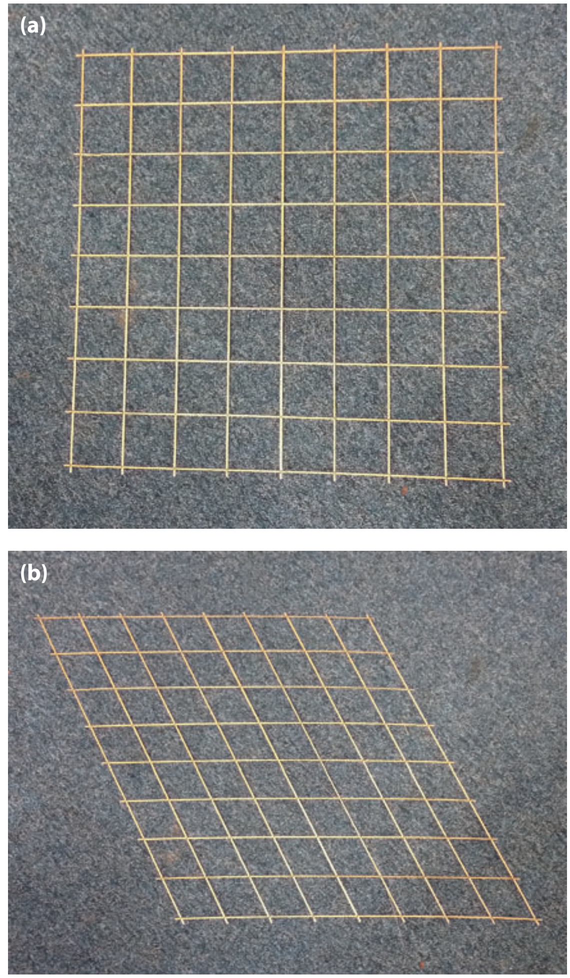

Figure 1.5 (a) Regular square lattice grid; (b) distortion of the grid
Source: © John Chilton.

from an aesthetic or functional perspective. For instance, for a given plan form, the rise of the gridshell may be altered by varying the overall dimensions of the mesh. One or more arched ribs may be introduced within a larger grid, being represented by individually shortened chains in the hanging model. The height of individual suspension points above the general boundary plane may also be varied.

It should be noted that a full chapter in *IL10 Grid Shells – Gitterschalen* (Hennicke and Schaur, 1974: 64–130) is devoted to revealing the complexities and numerous possibilities for surface forms generated from uniform chain and element nets with square meshes. Examples are shown in Figure 1.6.

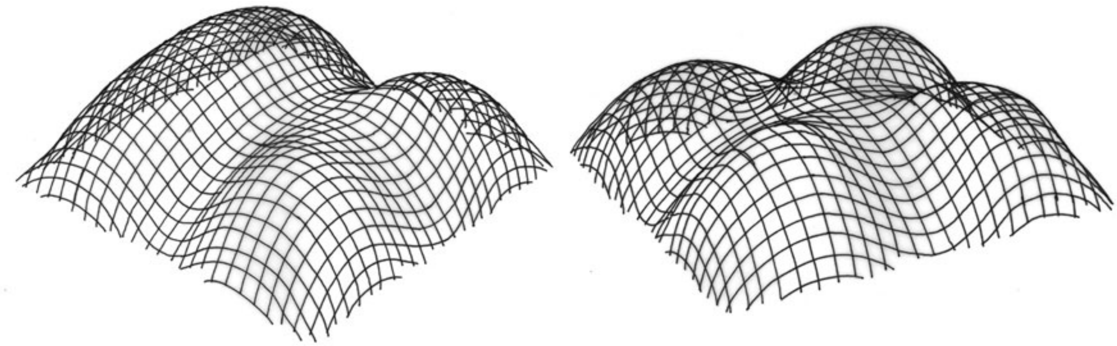

Figure 1.6 Examples of hanging chain grids
Source: © Gabriel Tang, redrawn from Hennicke and Schaur (1974: 81).

An alternative method, by numerical analysis, developed, as ever more powerful computers and software became available at around the time the Mannheim Multihalle and Restaurant gridshells were designed. The technique known as the force-density method (Schek, 1974) was applied to generate the form which the uniform mesh takes up under its own weight. The force density of a rod within the structure is defined as the force within the rod, divided by its length.

In more recent times the generation of three-dimensional forms has become far simpler using computer-aided design (CAD) software such as Rhino 3D® (Rhinoceros 3D, 2016). Although this has allowed the architect to experiment with free-form surfaces, unlike forms generated by physical and/or numerical modelling, these are not necessarily structurally efficient or economic forms.

Further information about the form-finding of shell structures in general, including gridshells, can be found in *Shell Structures for Architecture: Form Finding and Optimization* (Adriaenssens *et al*., 2014).

STRUCTURAL BEHAVIOUR

THERE IS A hierarchy of structural behaviour which relates to efficiency in resisting applied loads. In order of most to least efficient, these are: tension, compression, bending and torsion. In a structural element in pure tension, the full cross-section is generally equally stressed, in tension, and the element becomes straighter as more load is applied. Its capacity is limited only by the ultimate tensile strength of the material. On the other hand, a slender structural element in pure compression potentially suffers from an instability phenomenon known as buckling and requires more material to resist similar loads. For structures in bending, the stress is not uniform across the section – for instance, in a simply-supported beam in bending – stresses vary linearly from maximum compression at the top to maximum tension at the bottom, including a stress of zero at the neutral axis. This means that much of the beam material is underutilised.

In the traditional gridshell the overall form of the structure is designed to minimise bending and torsion and thereby enhance its structural efficiency by using the full structural section. They are often designed to have a funicular shape under their own weight, which in theory induces pure compression forces in the shell; however, any variation from that load distribution will generate bending and torsion. The structural efficiency of the gridshell, as a compression surface, will generally be determined by its resistance to buckling. The magnitude of forces in the laths will be influenced by the rise of the ribs relative to their span as well as loading.

MATERIALS, FABRICATION, INSTALLATION AND SUSTAINABILITY

Materials

Timber is a natural material that has good strength and stiffness to weight ratios roughly equivalent to those of steel (Harris, 2011: 110). However, the low density of timber (typical mean density 350–550 kg/m^3 for softwoods and 570–1050 kg/m^3 for hardwoods depending on the species) compared to steel (7850 kg/m^3) means that for equivalent structural performance components usually have to be bulkier. Physical properties of different timber species vary considerably and this influences their suitability for use in timber gridshells. Species used in some gridshells are shown in Table 1.1. Additionally, timber may have imperfections such as knots, splits, insect holes and damage from fungal attack that adversely affect its performance.

Because the timber used in classic gridshells is generally initially straight, although the final gridshell surface is single- or double-curved, an ability to bend without brittle fracture is desirable. For this, the low Young's modulus of timber is beneficial as it allows sections to be bent more easily. Creep – a gradual increase in deformation when subject to long-term loads – is quite pronounced for timber. When load is maintained over a long period on a piece of timber, the initial elastic deflection will slowly increase. On removal of the load there will be some recovery but there will also be a permanent deformation. For classic gridshells the effect of creep can be beneficial as bending stresses, induced when the flat grid is initially deformed into a curve, will relax with time under long-term loading. A consequence is that the initially straight laths would tend to remain curved if ever removed from the structure.

Fabrication

In the fabrication of a traditional gridshell three fundamental elements need to be considered: (1) the timber laths (or battens) that will form the grid; (2) the method of connection at the nodes; and (3) the means of stabilising the grid once deployed.

Table 1.1 Timber species choice and reason for use

Project	Reasons
Mannheim Multihalle, Germany (1975)	Western Hemlock Available in long lengths, normally straight grained, due to the tree growing up to 60 m with a straight bole
Silk Road Expo, Nara, Japan (1988)	Sugi (Japanese cedar) Symbolically the national tree; associated with sites of religious significance; reduction of embodied energy in construction; efficient use of locally grown natural resources; social benefits of employing local craftspeople
Weald and Downland Jerwood, near Chichester, UK (2002)	Oak Durable, available from sustainable sources in the UK and with a better performance than the other species on the shortlist
Savill Garden, Windsor, UK (2005)	Larch Available at the client's commercially managed and certified woodland of "exceptional quality".

Source: Adapted from Dragos, Harris and Williams, 2014.

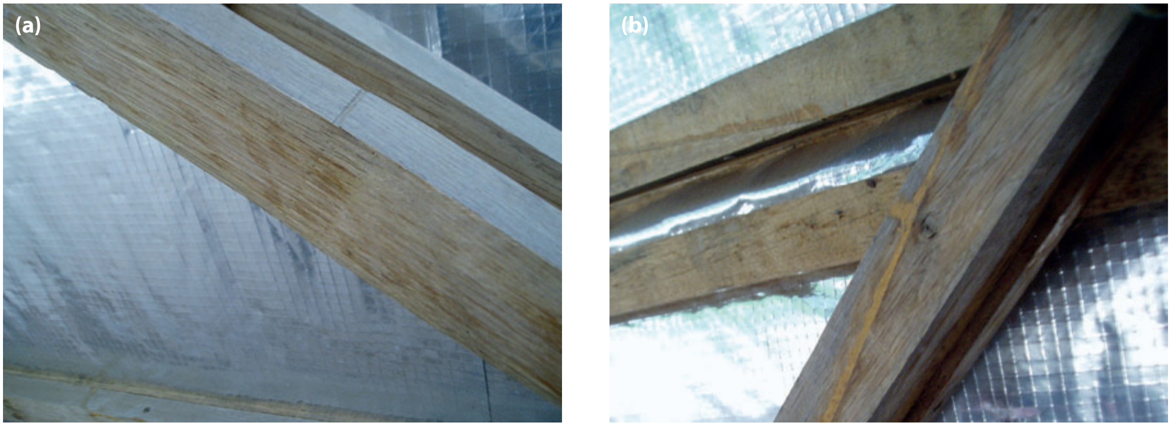

Figure 1.7 (a) Left: typical lath finger joint; (b) right: typical lath scarf joint
Source: © Gabriel Tang.

Laths and battens

Laths and battens used in classic gridshell construction are frequently bent to quite tight radii during the formation of the curved surface. To accomplish this more easily, ideally it requires a wide, thin timber section with the minimum of imperfections, in particular knots, that might induce fracture. On the other hand, even if the gridshell has a funicular form for self-weight, when it is subjected to applied loads such as wind, snow or point loads, the laths will be called upon to resist local bending of the surface. For this, a narrower but deeper section is more efficient. Clearly these are conflicting requirements and a compromise solution has to be found according to particular circumstances. Typically, this is resolved by using a double-layer grid.

With modern fabrication techniques it is possible to eliminate many imperfections by pre-processing the timber. Mechanical testing of continuous lath lengths enables bending strength and elastic modulus to be assessed and optical inspection can detect imperfections. Once detected, weak and imperfect sections can be cut out. Sound sections of timber can then be glued and finger-jointed together to make the longer pieces necessary for gridshell construction (see Figure 1.7 (a)). This procedure was used to manufacture the laths for the Weald and Downland, Jerwood Gridshell, where continuous oak laths composed of short pieces averaging 600 mm in length were assembled into 6 m lengths for transport from the processing plant to site. On site where longer lengths of lath are required, shorter lengths may be connected by scarf joints, as for the Jerwood Gridshell, see Figure 1.7 (b), or using mechanical connectors, as for the Nara Silk Road gridshells. The slope of the scarf joint in the Jerwood Gridshell is 1:7 to provide the same glued contact surface as used in the finger joints (Harris and Kelly, 2002: 169).

Node connections

Where grids are fabricated flat and then deployed to form a curved surface, it is essential that connections between grid layers at the intersections (or nodes) are able to accommodate the movements involved. This will normally include rotation, torsion and, in double-layer grids, some sliding of the different grid layers relative to each other. For simple small-scale grids, a single bolt at each intersection is generally sufficient (Figure 1.8). For larger and double-layer grids, more sophisticated arrangements may be necessary.

Once the gridshell has been deployed, the connection is required to clamp the layers together to limit further movement. In double-layer grids the node also has to transmit shear between the parallel grid layers to generate the expected increased stiffness of the surface (Happold and Liddell, 1975: 124). In the first large

Figure 1.8 Simple bolted intersection and longitudinal lath connection used in gridshells at the Earth Centre, near Doncaster, UK
Source: © John Chilton.

Figure 1.9 Typical node joint of the Multihalle, Mannheim
Source: © Gabriel Tang.

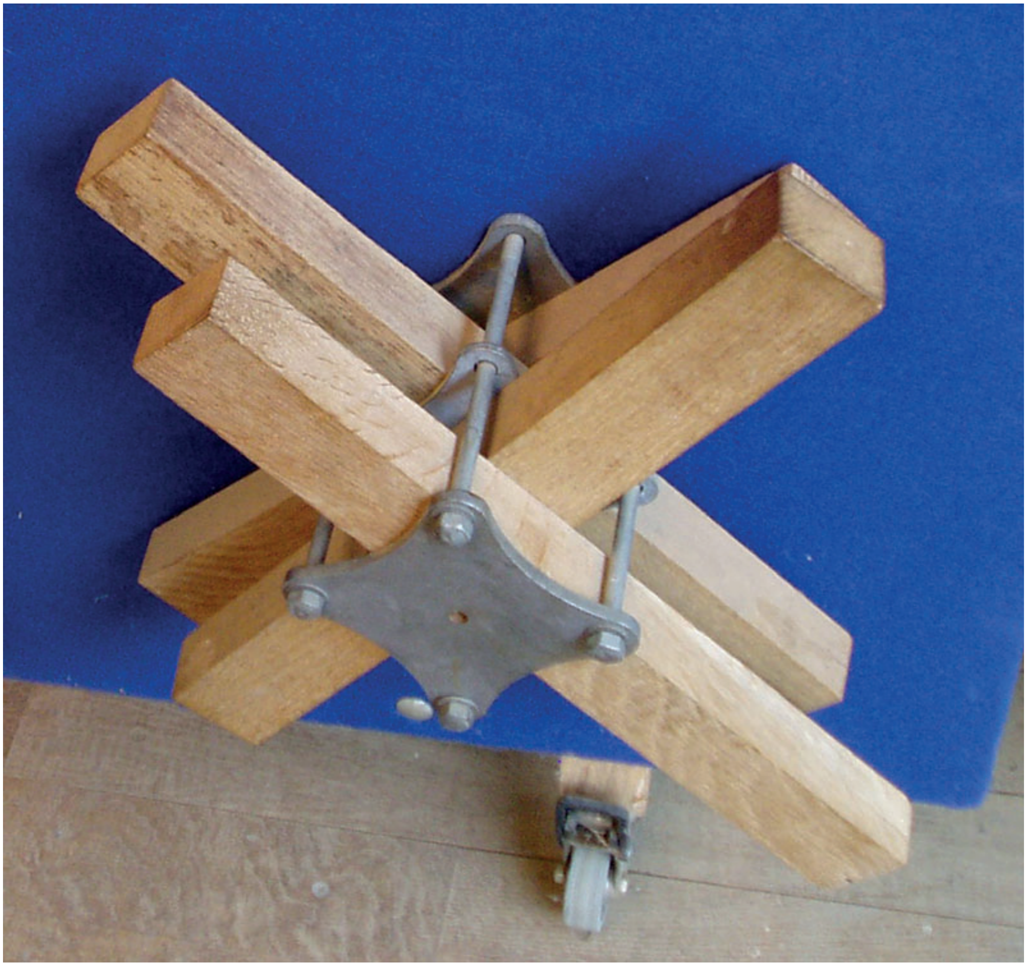

Figure 1.10 Typical node joint of the Jerwood Gridshell
Source: © Gabriel Tang.

gridshell at Mannheim this was achieved by means of a single 8 mm diameter threaded steel bar at each node, which passed through slightly oversized holes slotted in the outer two grid layers (Figure 1.9). To maintain a consistent clamping force at each node, four 35 mm diameter spring washers were employed (Happold and Liddell, 1975: 125; Burkhardt, 1978: 112), three at the top and one at the bottom.

A completely different approach was taken for the Jerwood Gridshell. Here there are no holes through the timber laths at the node, thereby avoiding a potential weakening of the grid. Instead, the connectors enclose the joint, with four 8 mm diameter steel bolts passing through three steel spacers consisting of top and bottom plates 6 mm thick and middle plate 4 mm thick. The patented node connector in Figure 1.10 is devised so that the middle two orthogonal layers are held, to maintain the grid geometry, while the outer and inner layer laths are able to move relative to these during deployment (Harris and Kelly, 2002: 165).

Stabilisation

Unless restrained appropriately, a pin-jointed, two-way, lattice grid is foldable in the plane of the grid. Attachment to the foundations or support system provides some restraint although is usually insufficient to prevent excessive deformation of the surface under applied loads. Other restraint methods employ some form of diagonal bracing elements, for instance, galvanised or stainless steel wires attached at nodes to triangulate all or part of the grid. The Mannheim Multihalle used steel wire cables, see Figure 2.27 on p. 33, making it stiff in plane. The Weald and Downland Jerwood gridshell used timber lath cladding rails, whereas the Savill Garden gridshell used plywood to achieve this, see Chapter 3.

More recently, with advanced engineering and pre-fabrication possibilities, gridshells have achieved stability through their geometry, such as the three-way grid of the Centre Pompidou-Metz. Stability has also been achieved through using other methods of connection such as the Zollinger/lamella/reciprocal principle seen in the Bad Sulza and Bad Orb shells (see Chapter 7), as well as from the ribbed shell method developed by Julius Natterer (see Chapter 4).

Installation

A variety of installation methods have been employed since Frei Otto's first realisation of a full-scale gridshell pavilion for the German Building Exhibition, in Essen, in 1962.

The key methods are:

- crane lift of the flat grid assembled on the ground;
- crane lift of full or part grid assembled on profiled former;
- push-up of the flat grid assembled on the ground;
- gravity/pull-down of the flat grid assembled at high level;
- direct installation of grid using pre-drilled and dimensioned laths.

Crane lift of grid assembled on the ground

A crane lift was used for the Essen gridshell, described in Chapter 2, see Figure 2.2(a) on p. 18. It has the advantage that the grid can easily be assembled at ground level where there is easy access and control of dimensions. On large sites this might occur adjacent to the shell's final location but on a congested site it might be necessary to assemble the grid over its final position. It should be noted that, depending on the rise of the shell relative to its span, the un-deformed flat grid may not be much larger than the final plan footprint. However, there are disadvantages involved in crane-lifting. The size of the grid is necessarily limited to that which can be lifted safely by the available (usually mobile) crane. This may be restricted by site access and/or the maximum permitted reach of the crane jib, as this is limited by the load it can carry at a given radius. If this method is used, lifting the shell has to be considered as a separate load case in the structural analysis of the grid. The completed, initially flat, grid has a (normally braced) double-curved surface and it is primarily subject to distributed loads, such as self-weight, snow and wind forces. Conversely, during lifting, the grid is initially flat and is inevitably subject to a limited number of concentrated loads at the suspension points, which are unlikely to be the final support locations. Therefore, there has to be very careful assessment of the appropriate lifting points, the distribution of the suspension forces into the grid, and means of attachment to avoid overstressing nodes, etc.

Another consideration is the deformation of the grid under its self-weight during the lifting process. With careful selection of lifting points, this can greatly assist the shaping of the curved form. However, this draping may not be sufficient to bring the grid to the required final plan profile (or may be excessive). In either case additional jacking may be required to enable the shell to be attached to the foundation points.

Crane lift of full or part grid assembled on profiled former

The gridshells at the Nara Silk Road Expo' 88, see Chapter 5, were pre-assembled in 4 m-wide pre-curved modules that were subsequently craned into position and bolted together to form the shell. As an example of pre-assembly of a full shell, described in Chapter 4, the 'hypar' gridshells of the Hanover Expo-Dach were prefabricated on formwork to the required profile before being transported to site as complete 19 m x 19 m units, each weighing 37 tonnes (Herzog, 2000: 45) see Figures 4.19(a) and (b) on p. 93.

Push-up of the grid assembled on the ground

The excessive cost of required cranage led to the push-up of the grid assembled on the ground being adopted as the preferred installation method for the Multihalle Mannheim, described in Chapter 2, see Figures 2.28 (a) and (b) on p. 34. Here the grid was too extensive to be built adjacent to its final location and it had to be assembled across the final plan footprint. The method potentially allows better control as the push-up points can be more numerous and can be moved once the grid starts to rise. However, the weight of the grid may be seriously heavy and there are site safety issues as operatives necessarily need to work under the heavy moving structure. Also, in order for it to rise, the flat grid must slide on the ground at its perimeter as its plan area diminishes. An alternative method proposed in the original IL10 and currently being researched at the Department of Structural Design and Technology, University of Arts, Berlin, is to use a pressurised membrane inflated to lift the gridshell (Figures 1.11 (a)–(d)).

Gravity/pull-down of grid assembled at high level

Where the grid is assembled at a high level, it has to be at a height close to (or even above) its final maximum rise above the foundation and supported on temporary scaffolding which has to be movable to allow the grid to deform under gravity. However, this may restrict site access for other activities. In the case of the Weald and Downland, Jerwood gridshell, the grid was assembled at the height of the 'valleys' in the final form, and the areas between rose as the grid was deformed. As was found during its construction, gravity loads may not be sufficient to fully distort the grid into its final form, see the case study in Chapter 3, Figures 3.17 (a)–(f) on p. 58.

Direct installation of grid using pre-drilled and dimensioned laths

For small-scale gridshells, such as those at Flimwell, UK, the fabricator, Cowley Timberworks, Lincoln, created a precise CAD model of the final roof and rib geometry. Using CNC techniques, it was then possible to dimension, cut and pre-drill fixing holes to enable the shells to be assembled directly (Figure 1.12).

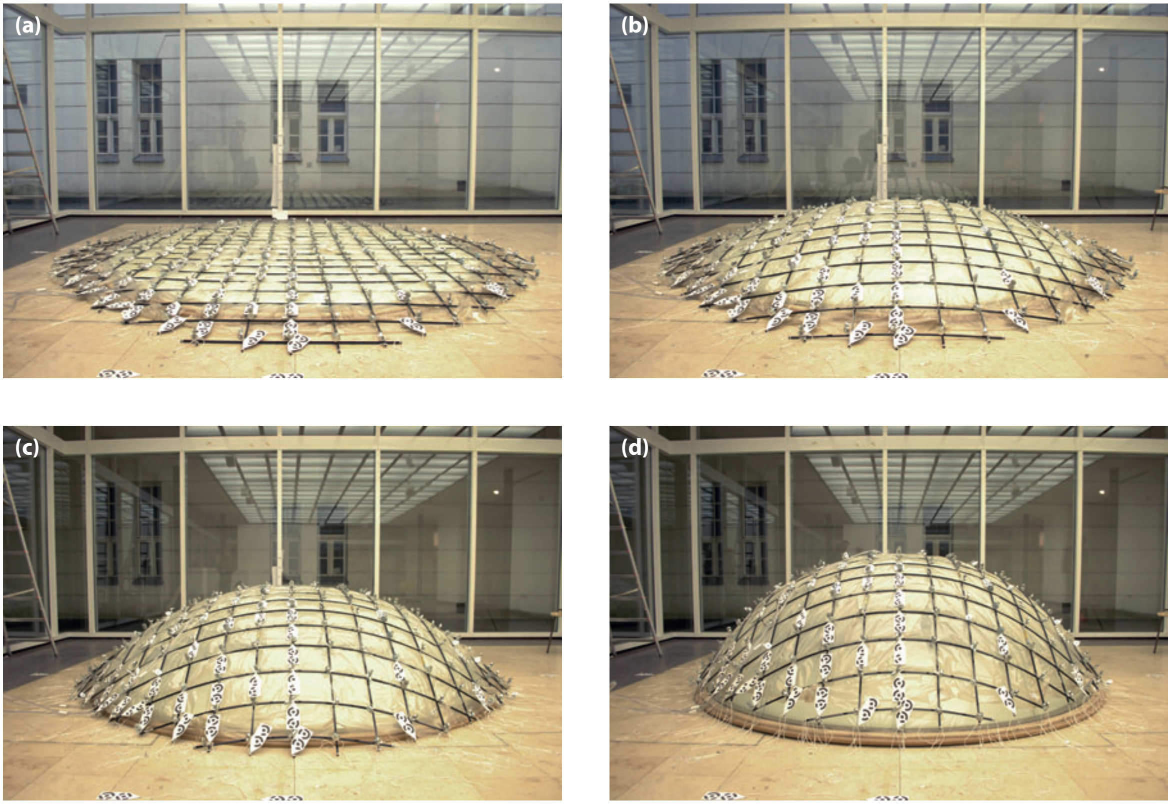

Figure 1.11 (a)–(d) Raising of gridshell using an inflated membrane
Source: © Gregory Quinn MEng/Professor Christoph Gengnagel/Department for Structural Design and Technology (KET)/University of Arts, Berlin.

Figure 1.12 Site assembly of Flimwell gridshell
Source: © Woodnet.

Cladding

An essential characteristic of most gridshells is their double curvature, which influences the type of external cladding that can be used. Many cladding materials are manufactured in flat sheets. Depending on their thickness and profile, it is usually possible to bend these to a curve in one direction. However, it is generally more difficult (and therefore expensive) to form a flat sheet to fit a double-curved surface, although this depends very much on the radii of curvature to be accommodated. This difficulty may be compounded in some timber gridshells due to the variable curvature across the building envelope, which would necessitate the manufacture of many different cladding components.

For the first large-scale gridshell at Mannheim, the problem was solved by using a flexible grey-tinted, open weave, PVC-coated, polyester mesh fabric. The fabric could be easily pre-cut to fit the varying shape of panels between grid lines and then heat gun-welded and tensioned on site to form a smooth surface (see Chapter 2, Figures 2.31, 2.32 and 2.33 on pp. 37–38). This was later replaced by a white membrane cladding (Figure 1.13). Although, inevitably, there must be some limited structural interaction between the gridshell and the membrane surface, at the design stage it was not considered to contribute to the stiffening of the grid.

Cladding elements may also interact structurally, more strongly, with the gridshell. This is the case for the Jerwood Gridshell, where an alternative rigid cladding was used, namely large timber shingles. As the shell grid was arranged so that the main structural laths ran diagonally at approximately 45˚ to the main axis when viewed in plan, when additional laths were connected, running longitudinally, they stiffened the grid by

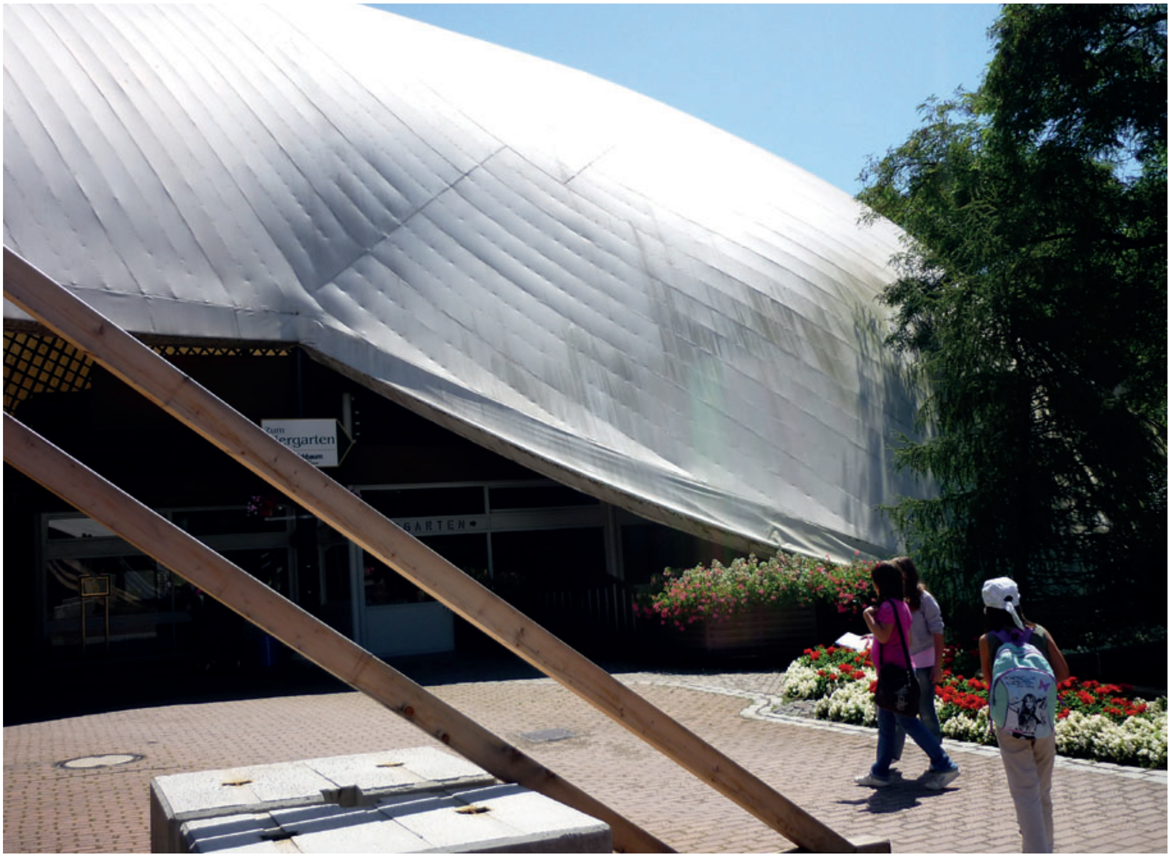

Figure 1.13 Smooth replacement white, PVC-coated, polyester fabric membrane as external cladding of the Mannheim Multihalle gridshell
Source: © Gabriel Tang.

triangulating the mesh and provide support for the overlapping shingles. In this case, the gridshell was also insulated using flexible, multi-layer, foil material between the main structural grid and the outer cladding laths, as seen in Figure 1.14.

At the Savill Garden, where curvatures were not so pronounced in the undulating form, the grid was covered with a 12 mm-thick plywood decking (Figure 1.15), which stiffened the grid and provided a platform for the installation of insulation, waterproofing, steel-profiled decking and an oak board rain-screen.

Later technologies see the use of other materials applied as cladding to gridshells. These include ETFE cushions in the case of Waitomo Glowworm Caves Visitor Centre in New Zealand and Canary Wharf, CrossRail station, London; metal sheeting in the SUTD plywood gridshell in Singapore, more sophisticated membranes at the Solemar Therme Baths as well as the roof at Bad Sulza and Bad Orb, as well as the Centre Pompidou-Metz. Surprising solutions come in the form of paper membranes used in the Japan Pavilion in 2000. Chiddingstone Castle saw the use of glass as cladding, while concrete clads the Naiju Community Centre in Japan. These show the versatility of possible ways of cladding the double curvatures but specific to their location and climatic context.

Sustainability

There are two important aspects of timber gridshells as sustainable architectural structures. First, timber, the primary material used for their construction, is sustainable in the sense that it is a natural renewable resource, which sequesters carbon dioxide (CO_2) from the atmosphere and encapsulates it as cellulose in the structure (Herzog, 2000: 64–5). Second, there is the sustainability of shells as efficient structural forms that

Figure 1.14 Internal view of Jerwood Gridshell showing flexible multi-layer foil insulation
Source: © Gabriel Tang.

Figure 1.15 Internal view of the Savill Garden gridshell showing plywood decking
Source: © John Chilton.

use the minimum amount of material to carry imposed loads using primarily membrane action, gaining strength through form rather than mass.

With gridshells, shorter and thinner section timbers often deemed inferior could be used, instead of being discarded. The Hooke Park Westminster Lodge used roundings, usually rejected thinnings, to construct the shell roof (Burton *et al*., 1998). 'Thinnings' are by-products of timber production. To ensure that trees grow straight and tall, the forests are densely planted. Weaker specimens are removed after 10–15 years. These removed specimens or 'thinnings', with a diameter of between 50 mm and 150 mm, are often worthless and or have limited use as firewood. Within this forested setting, these by-products were used in the experimental design and construction of the roof structure at the student house at Hooke Park.

Later examples also saw timber planks arranged and dowelled differently following the Zollinger principle seen in the timber gridshells of Bad Sulza and Bad Orb.

Of course, more recent timber examples, under strong digital influence, featured engineered timber products that also used timber that was previously deemed low value. Glulam timbers can now be precisely machine routed, milled and sectioned to produce dimensionally stable three-way curved sections. Although glue might not be the most sustainable material, the ease of creating sections of milled timber, as opposed to steel or concrete, means that precise curved forms are now possible. With new material like laminated veneer lumber (LVL), the challenge of joining smaller sections of timber together is solved as laths can now be fabricated with predetermined curve and twists, as seen in the Waitomo Glowworm Caves Visitor Centre gridshell in New Zealand and the Hermès Rive Gauche gridshells in Paris, completed in 2010 and 2011 respectively. In the case of Waitomo, the grid size was unprecedentedly large. The mild climate of New Zealand rendered their open-air application appropriate. Additionally, ETFE film cushions were a material that allowed the grid sizes to be as large as 4.25 m.

DEVELOPMENT OF GRIDSHELLS

FROM THE EARLY experimentations by Frei Otto (1925–2015), first realised in the lightweight Deubau Pavilion, in Essen, in 1962, engineered timber gridshells were designed largely by highly intricate physical hanging chain models. These examples pertain to a purist's view of a timber gridshell – where gravity and structural principles interact to create a highly optimised form constructed with relatively simple technology.

The following decades saw the flourishing of alternative methods of constructing timber gridshells. To improve and reduce the time-consuming and space-consuming erection process, sections of gridshells were pre-fabricated and assembled on-site as large pre-assembled sections, as illustrated by the Silk Road Exhibition, Nara, Japan in 1988, see Chapter 5. Other variations of this include the use of ribbed shell and screwed rib plank gridshell construction techniques developed by Julius Natterer, see Chapter 4. This idea was most memorably expressed in the construction of the canopy roof of the Expo-Dach World Exposition in Hanover in 2000.

Subsequent developments, resulting from the advances in digital design, analysis, parametry and fabrication, have seen the creation of built structures, that previously were impossible to build. Brought about by computer-based design and construction, timber gridshells are beginning to take on forms quite different from their predecessors. Timber gridshell geometry is now determined by computers and is beginning to have a greater variation of grid dimensions. New materials such as laminated veneered lumber (LVL), which are stable under different weather conditions and reduce the effect of knots, are beginning to take on an increasingly non-timber-like characteristic in the creation of timber gridshells.

All these developments have encouraged the use of timber, a sustainable material in structural applications that encapsulate architecture, structure and craft.

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CHAPTER TWO

Early gridshells

INTRODUCTION

ALTHOUGH THE RUSSIAN structural engineer Vladimir Shukov (1853–1939) constructed the world's first lightweight metal gridshells at Vyksa near Nizhny Novgorod, Russia, in 1897, the German architect Frei Otto (1925–2015), who was awarded the Pritzker Architecture Prize posthumously in 2015, is considered to be the father of modern timber gridshell architecture. Using methods similar to those employed by Antoni Gaudí, for the form-finding and design of the Church of the Colonia Güell, Santa Coloma de Cervéllo, near Barcelona (Tomlow, 1989), Frei Otto had been experimenting with nets of fine chains, as a means of determining the form of potential double-curved spatial structures, since the late 1940s (Otto and Rasch, 1995: 136). His particular insight had been to perceive that the three-dimensional form generated by a quadrangular network of hanging chains could be constructed using an initially flat, semi-rigid, lattice of timber laths or steel bars (Happold and Liddell, 1975: 99). He referred to this lattice structure as a *Gitterschale*, which is translated into English as gridshell.

DEUBAU, ESSEN, GERMANY, 1962

FREI OTTO HAD previously led a student project to construct a square plan, corner-supported, 52 m^2 gridshell made from steel reinforcing bars, when visiting the University of California, Berkeley, in 1962 (Hennicke and Schaur, 1974: 270). However, his first realisation of a timber gridshell structure was for a 15 m x 15 m pavilion at the German Building Exhibition, Deubau, in Essen, also in 1962.

Developed by Frei Otto with Bernd Friedrich Romberg (ibid.: 26) using hanging and physical models (Figures 2.1 (a) and (b)), the 198 m^2 'squircle' – superelliptical – was a cross between a square and circle in plan. It had a maximum span of 16.82 m across the corners and rose to 4.85 m at the centre. Timber rods were glue-laminated from three 60 mm x 13 mm laths of hemlock pine and

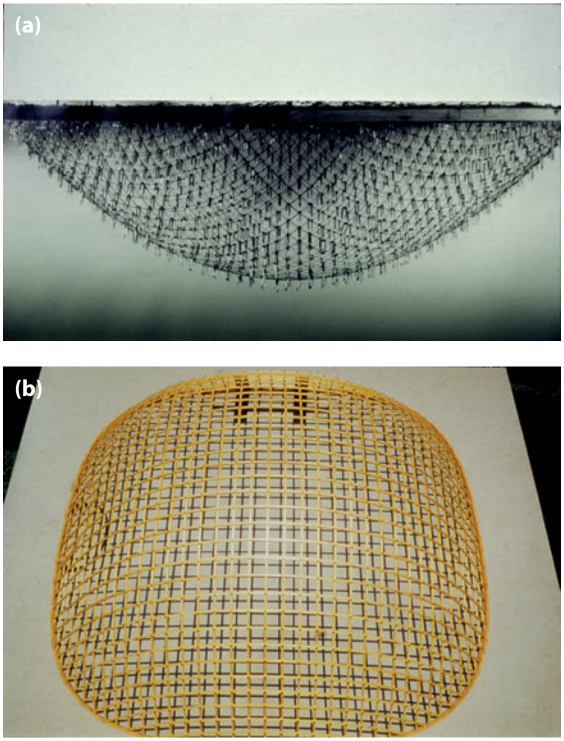
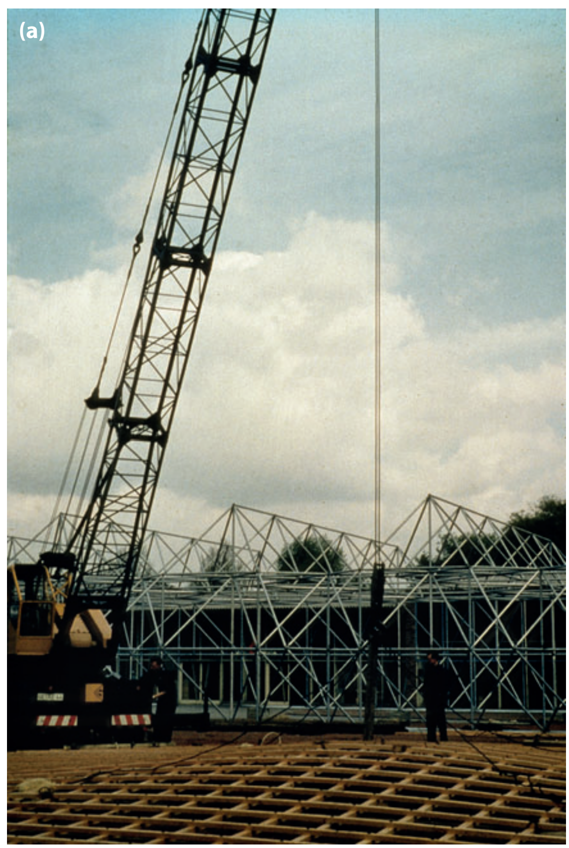


Figure 2.1 (a) Hanging model; (b) plan view of physical model of gridshell for Deubau, Essen, 1962
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

assembled on the ground on a square grid of 482 mm centres, by bolting at the nodes. Once complete, the full grid of approximately 1140 m of rods was lifted by mobile crane and coaxed into the shell form (Figures 2.2 (a) and (b)). It was then fixed with galvanised steel straps to a pre-set timber base ring, secured with ground anchors (Figure 2.3).

Door access to the pavilion was created by cutting an opening into the grid and reinforcing the adjacent meshes. Subsequently, the grid was clad with a transparent plastic foil fixed by timber cover strips nailed to the top layer bars (Figures 2.4 (a) and (b)) (Hennicke and Schaur, 1974: 272–273).



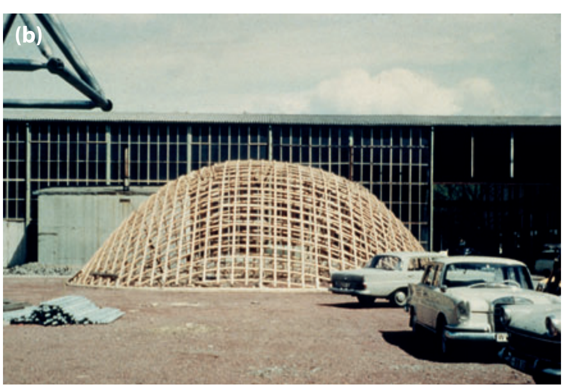


Figure 2.2 (a) Crane lift; (b) external view of Deubau gridshell, Essen
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.3 Internal view of edge fixing Deubau gridshell
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

MONTREAL EXPO, CANADA, 1967

THE SUCCESS OF this demonstration project of relatively simple form led to more ambitious proposals for the use of timber gridshells, for instance, in the German Pavilion at the World Exposition, held in Montreal, in 1967. This pavilion is best known for its dramatic and extensive use of mast-supported cable nets and tensile membranes. However, it is less well known for the innovative timber gridshells that were used to form the vestibule roof of the main auditorium within the tensile enclosure. Designed in 1966, the two interconnected timber gridshells were the result of extensive exploration by architect Rolf Gutbrod, with Frei Otto and his team at the Institut für leichte Flächentragwerke (Institute for Lightweight Structures, IL), at the University of Stuttgart, to determine the ideal forms for the two irregular plans, linked along a common valley beam. Demonstrating their model-making craft, first, a suspended model was constructed and measured precisely to determine the shell profiles (Figures 2.5 and 2.6), then a 1:10 scale model was made using 2 x 3 mm timber strips (Figure 2.7).

At 365 m^2 the whole structure was about double the area of the Essen gridshell. Its double irregular plan forms, having a maximum span of 17.5 m and maximum rise of 4.0 m, were made of 151 timber laths configured on a 500 x 500 mm grid. Figure 2.8 (a) shows the two contoured plans and Figure 2.8 (b) the

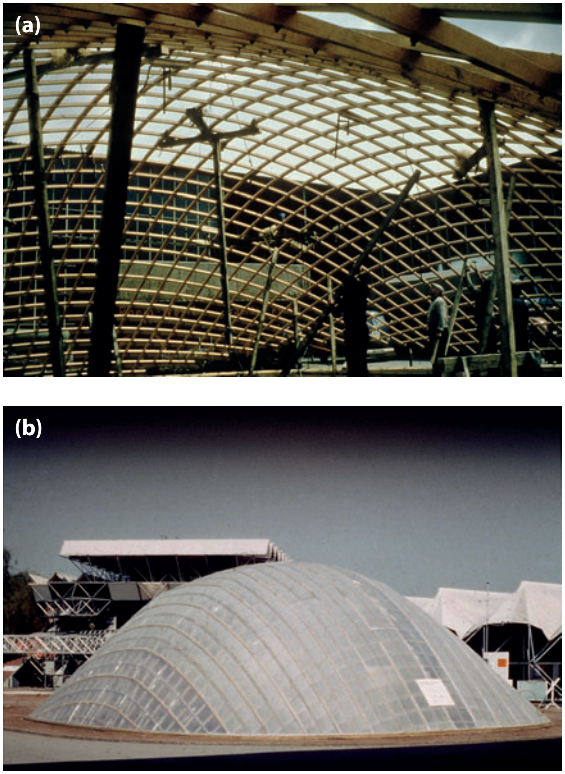


Figure 2.4 (a) Internal and (b) external view of Deubau gridshell, Essen, with cladding
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

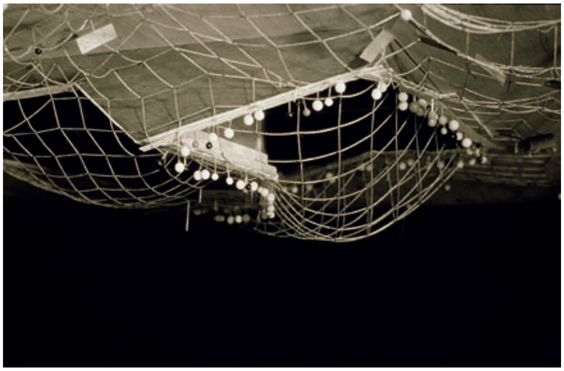


Figure 2.5 Hanging model for Montreal Expo'67 gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

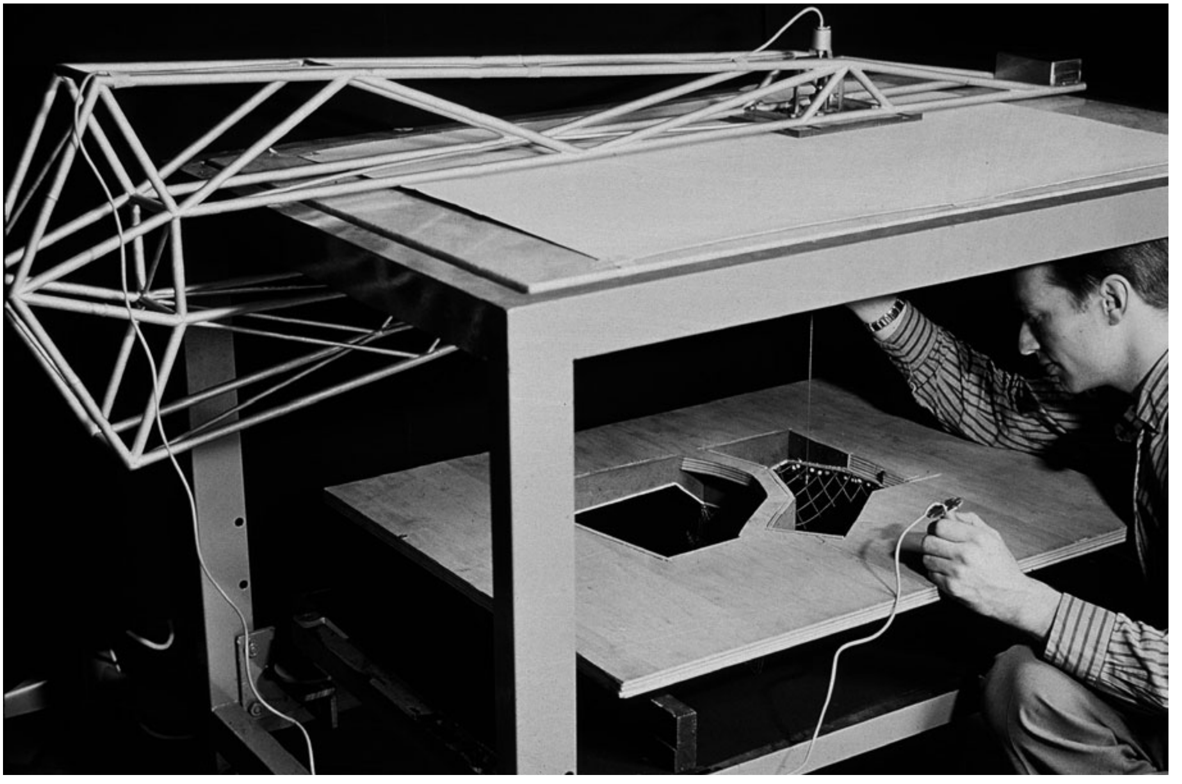


Figure 2.6 Measuring the form of the hanging model for Montreal Expo'67 gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

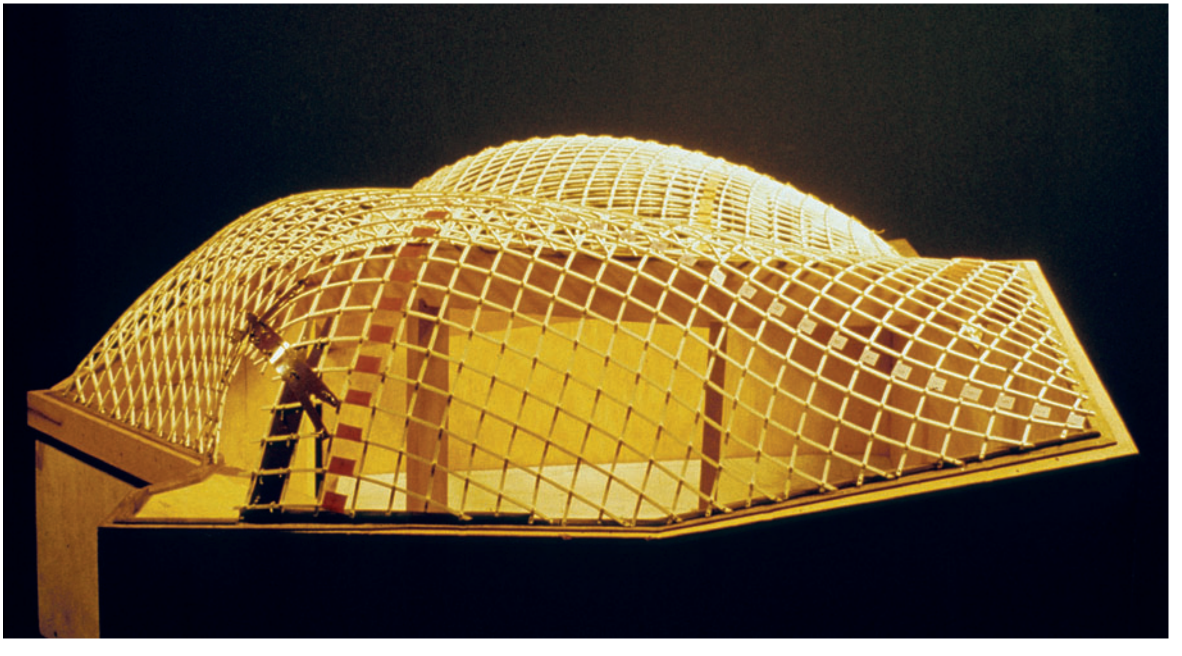


Figure 2.7 Physical model for Montreal Expo'67 gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

regular-meshed flat grids from which the double curved shells were formed. They incorporated approximately 1580 m of timber connected at 1620 bolted nodes. A timber perimeter beam supported the grid shell. For the common support line along the valley between the two gridshells, this was carried on a reinforced concrete beam and for the remaining perimeter, on reinforced concrete walls. Engineers for the project were Leonhardt and Andrä, Stuttgart.

Unlike the Essen gridshell, in this case, solid Hemlock Pine sections were used, 42 mm x 35 mm in the case of the auditorium and 42 mm x 28 mm for the vestibule space. However, to facilitate their bending and reduce the possibility of breakage, laths used in areas of acute shell curvature were split in two along their length

(a)

(b)

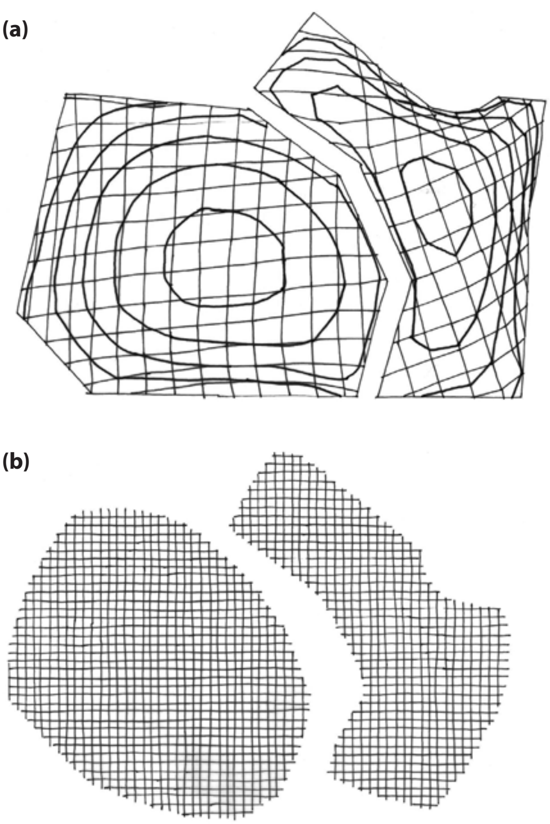


Figure 2.8 (a) Contour plan; (b) developed flat grids for Montreal Expo'67 gridshells
Source: © Gabriel Tang, redrawn from Hennicke and Schaur (1974: 275).

(Hennicke and Schaur, 1974: 274). The grids, which were manufactured in Germany, were trial-assembled there (Figures 2.9 and 2.10) before being folded, much as one might fold a garden trellis into a long thin strip, and transported to the Expo site in Montreal as complete sections. Frei Otto's enthusiasm for the new structures can be seen in Figure 2.11, which shows him proudly standing on the summit of the trial assembly.

Once there, the folded lightweight timber grids (Figure 2.12) were carefully deployed (Figure 2.13) and winched into position using cable hoists suspended from the main roof cable net (Figure 2.14). Plywood decking was then nailed to the grids to support insulation boards and a final covering of PVC-coated fabric (Figure 2.15) (ibid.: 274–277) An interior view is shown in Figure 2.16.

A step change in scale was proposed in an unbuilt project for a wave pool roof on the North Sea island of Borkum, also designed in 1966. This had a plan and corrugated form similar to a scallop shell and was supported on edge arches. With a maximum span of 72 m and rise of 11.4 m, the proposed single-layer timber grid of 50 x 40 mm glue-laminated laths was to be clad with plywood, insulation board and waterproofing (ibid.: 272–279).

THE S.T.I. EXPERIMENTAL MODEL AT IL, STUTTGART, GERMANY, 1973

THE 37.5 M² experimental grid shell built at the IL during the S.T.I. project, in 1973 (ibid.: 298–301) deserves a special mention. Its initial form was created using a flexible hanging net. Under its own weight, a hanging net is a unique self-formed structure, with all forces in equilibrium at each node. Its shape is affected solely by the mesh geometry, support locations and gravity. All elements are in tension and the same structure inverted about the horizontal plane, under the same loading, will have all the elements in compression.

The x, y and z co-ordinates of the mesh nodes were determined using the IL measuring table (ibid.: 132) to an accuracy of ±0.1 mm and were then analysed

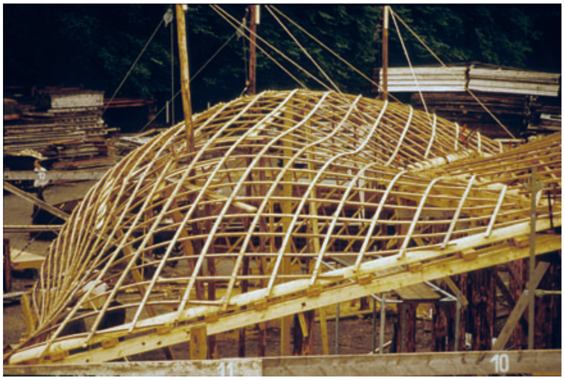


Figure 2.9 Trial assembly in Germany of Montreal Expo'67 gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.11 Frei Otto standing on top and admiring the trial assembly of Montreal Expo'67 gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.10 Interior view of trial assembly in Germany of Montreal Expo'67 gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.12 Fully folded lattice ready for deployment Montreal Expo'67 gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.13 Unfolding the grid in Montreal
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

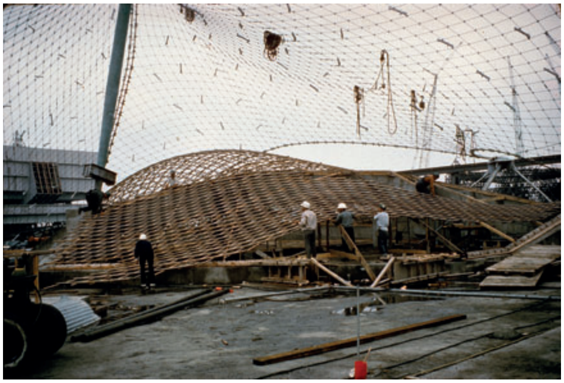


Figure 2.14 Lifting the gridshell suspended from the cable net
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.15 View of the Montreal Expo'67 Pavilion showing the exterior of the gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

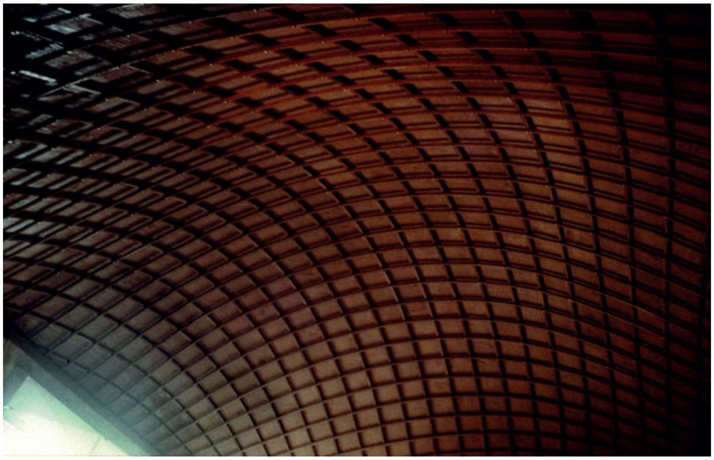


Figure 2.16 Interior view of the Montreal Expo'67 Pavilion gridshells
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

statistically by the Institut für Anwendungen der Geodäsie im Bauwesen (Institute for the Application of Geodesics in Building (IAGB)) at the University of Stuttgart. From these measurements it was possible to calculate the node spacings which were found to vary by up to 5 per cent from the actual rod length (ibid.: 190). Subsequently, techniques developed by the IAGB and first used in the analysis of the cable nets of the Munich Olympic Stadium roof were applied to numerically generate the geometry for the original 7 x 7 mesh of the model and denser mesh configurations of 14 x 14 and 28 x 28.

Before construction of the full-sized experimental gridshell, a 1:10 scale model was fabricated from 2 mm x 3 mm pine strips connected with 1 mm diameter brass bolts and load tested. The full-scale model consisted of a 14 x 14 mesh grid assembled from 15 mm x 15 mm Hemlock Pine laths, spaced at 500 mm centres and connected by M4 bolts at each node (with a 2 mm thick plywood spacer attached to each rod) (Figure 2.17 (a)). It had a maximum span of 6.68 m and rise of 2.68 m (ibid.: 298). The model was used to validate load-deflection behaviour predicted by finite element analysis (ibid.: 210–217).

Jürgen Hennicke, who conducted the tests, recalled what fate befell this experimental gridshell. Not wishing to leave the thin timber ribs exposed to bad weather, it had been covered with protective plastic sheeting. However, over the Christmas holiday in 1973 there was a heavy snowfall which accumulated on the cover. When the researchers returned to work in the New Year, they found that the shell, which had never been intended or designed to resist snow load, had failed under the unanticipated loading (Figures 2.17 (b), (c) and (d))!

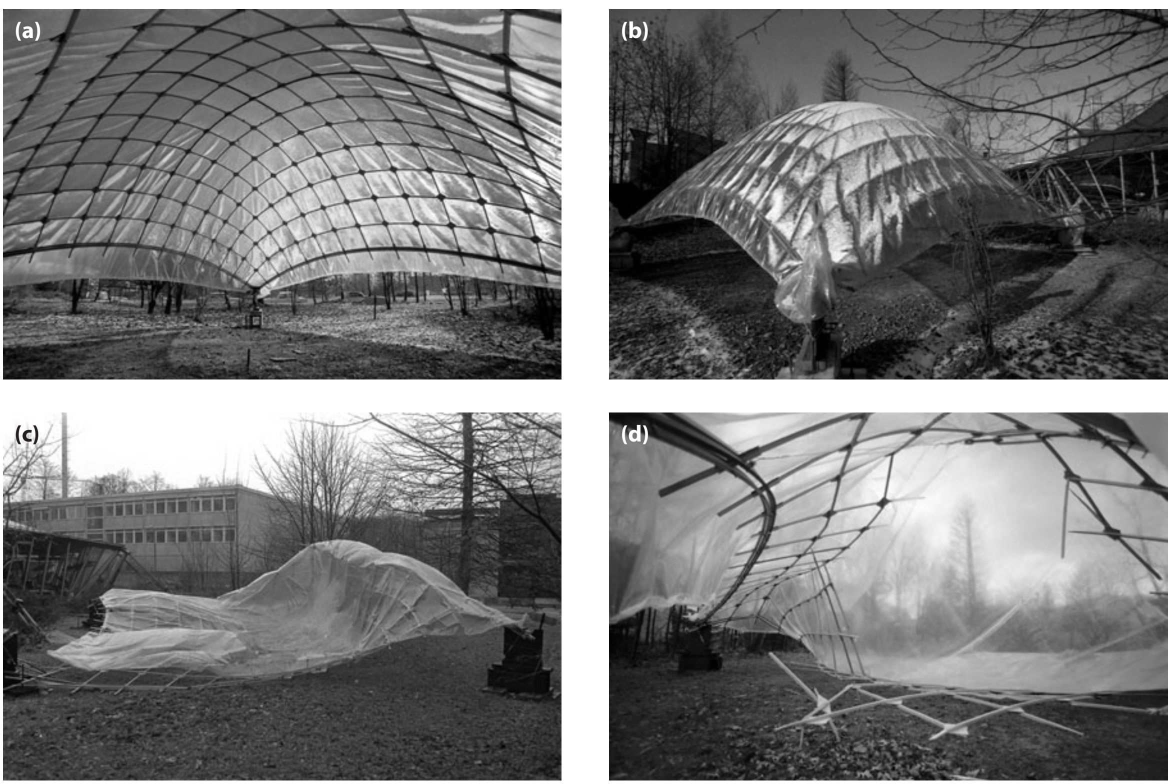


Figure 2.17 (a) The S.T.I. experimental gridshell; (b) the gridshell covered in light snow; (c) (d) destroyed by excessive snow load over the Christmas/New Year holiday 1973
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

MULTIHALLE AND RESTAURANT, BUNDESGARTENSCHAU, MANNHEIM, GERMANY, 1975

THE MULTIHALLE (MULTI-PURPOSE hall) and restaurant, for the Bundesgartenschau (German Federal Garden Festival), held in Mannheim, in 1975, marked the acceptance of the timber gridshell as a new typology for long-span architecture. At the time it was the boldest and most extensive example of timber gridshell construction. Here Frei Otto and Ewald Bubner of Atelier Warmbronn, working with the architects Carlfried Mutschler and Partner, Mannheim (Joachim Langner, Dieter Wessa and Winfried Langner) and the Structures 3 group at engineers Ove Arup & Partners, London (Edmund 'Ted' Happold and Ian Liddell) contrived one of the most innovative spatial grid structures of the twentieth century. Designed between 1972 and 1974, the project also involved as consultants the Institut für leichte Flächentragwerke (IL) and the Institut für Anwendungen der Geodäsie im Bauwesen (IAGB), at the University of Stuttgart. Engineers for the substructure of the gridshell were Bräuer and Späh, Mannheim.

Completed in 1975, the gridshell (Figure 2.18) covers an area of around 7400 m² with a roof surface area of approximately 9500 m². The larger Multihalle spans up to 60 m and the Restaurant 50 m, with the gridshell rising to 20 m and 18 m respectively (Hennicke and Schaur, 1974; Burkhardt, 1978: 58).

Initially using catenary hanging chain models to derive the building's form, the measurement techniques of the day were used to derive its geometry. Subsequently, newly developed computer-aided form-finding techniques, as used on the S.T.I. experimental structure, were implemented to determine the precise geometry required to enable accurate structural calculations to be made, and for the gridshell, which contains about 34,000 nodes and around 72,000 m of timber, bars up to 100 m long, to be constructed.

Figure 2.18 Aerial view of the gridshell for the Bundesgartenschau (German Federal Garden Festival), Mannheim, 1975
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Architectural design development

Every two years the German Bundesgartenschau is hosted by one of the country's major cities, which compete for the honour of holding the show. In 1970, Mannheim and Ludwigshafen were selected as joint winners of the design competition for the landscaped Herzogenriedpark. The following year, local architects Mutschler + Partner were appointed to design that part which included the multi-purpose hall and restaurant (Happold and Liddell, 1975: 106). However, as Carlfried Mutschler has written, the original concept for the Multihalle was not a gridshell but consisted of 'large umbrellas arranged in a row, on which gas-filled balloons … were to be hung' (Burkhardt, 1978: 21). Following the rejection of this proposal by the building authorities, the architects enlisted the help of Frei Otto to explore alternative solutions. Rejecting various tented, pneumatic cushion and air-supported alternatives, the design team opted for two gently rounded lattice shells to cover the multi-purpose hall (Multihalle) and restaurant respectively (Happold and Liddell, 1975: 106; Burkhardt, 1978: 23–29), like low hills blending with the landscape. A similar lattice was used to form a curving annex to the Multihalle and over various linking and entrance tunnels and walkways.

Before the design of the Mannheim Multihalle, Frei Otto's techniques had been applied in only a few and relatively much smaller gridshell structures. Although other projects had been proposed and designed but not built, the proposed Mannheim Multihalle could be seen as a great leap into the relatively unknown. It was approximately twenty times more extensive in area than any gridshell built previously, with longer spans and much greater rise.

The Multihalle project is a classic example of hand-crafted physical models being used in both architectural and structural design. Initially, as the outcome of joint design work between Mutschler & Partners and Atelier Warmbronn, a 1:500 scale wire mesh model was made at Frei Otto's studio to determine the preliminary architectural/spatial form of the gridshell (Figure 2.19). As described by Ewald Bubner, to determine the size of net required a larger scale model to be made, and the approximate dimensions of the curved mesh model were obtained by measuring the length of fine threads stretched across the surface at regular intervals (Burkhardt, 1978: 33). These measurements were then used to establish the pattern for the chain net of a suspended model constructed at 1:98.9 scale (Happold and Liddell, 1975: 106).

Figure 2.19 Wire mesh scale model (1:500) used to determine preliminary architectural/spatial form
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

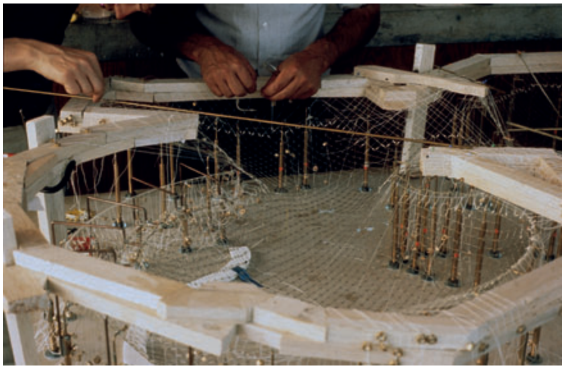


Figure 2.20 Assembly of hanging model
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

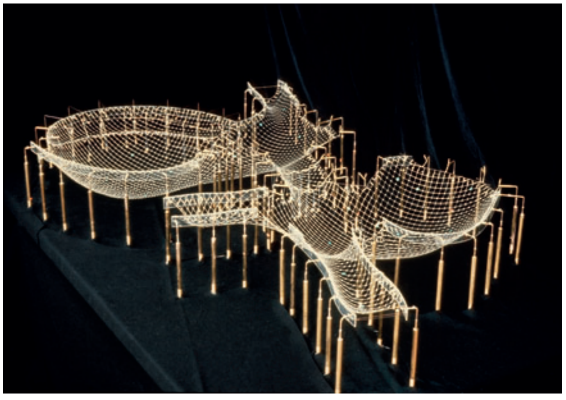


Figure 2.21 Completed hanging model
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.22 Detail of hanging model showing wire links connected by rings
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

An important decision had to be made by the design team at this stage. What were the most appropriate directions for the principal lines of the mesh to follow? If, as initially thought, one grid line should follow the main axis of the building with the other perpendicular to it, then it became apparent that any irregularities in the surface would have been more obvious. The second grid direction would also have attracted higher forces. To avoid these disadvantages, the grids were set at 45° to this axis (Burkhardt, 1978: 35), as can be seen in Figure 2.24 on p. 29. This is similar to the technique in tailoring and dressmaking where fabric is cut 'on the bias', that is at 45° to the warp and weft directions of the fabric weave, so that it moulds itself more closely and fluidly to the curves of the human body.

Assembled flat, by hand, the flexible chain element mesh was then suspended from a temporary rigid boundary cut to the external plan profile of the whole building (Figure 2.20), and supported by and above a flat marble slab 1.2 x 1.7 m marked with an orthogonal grid. Marble was chosen as the base material due to its flatness, its dimensional stability under variations of temperature and humidity and its solidity. The ends of the individual chains in the mesh were then carefully transferred, one-by-one, to the permanent model edge support suspended by threads attached to bolt nuts in order to tension the mesh slightly (Figure 2.21). This chain net did not consist of fine chains but of an 'element' mesh of straight thin wire links connected by small ring nodes on a 15 mm two-way grid (Figure 2.22). Here each chain line in the model represented every third mesh line in the full-size structure, where the grid spacing was at 500 mm centres. The chains represented the system lines and overall net the system area or thrust surface, i.e. the surface at the mid-depth of the grid shell construction.

Ewald Bubner remarks that the full-sized gridshell was supported on four different foundation types: reinforced concrete wall foundations, double glue-laminated timber edge beams, timber arches and paired double steel cables (Figures 2.23 (a)–(d)) (Burkhardt, 1978: 37). These different support conditions were represented in the model by a perimeter profile made from either curved

2 mm-thick Plexiglas strips (concrete), brass wire rods (edge beams and ropes) or chains (arches) and allowed adjustment to find the optimal shape. Each was slightly roughened and had a thin layer of glue applied to minimise the horizontal slipping of threads. Small feather springs (supplied by the Black Forest watchmaking industry) were also incorporated to measure strains/forces at the perimeter (Hennicke and Schaur, 1974: 309; Happold and Liddell, 1975: 106).

Various adjustments had to be made to the chain mesh and this led the designers to the realisation that a 35˚ or 55˚ grid deviation from the main building axis might have been preferable to the 45˚ chosen. Also they found that the self-determining hanging chain form did not always behave as anticipated when compared to the more rigid wire mesh model. In particular, at the mouths of the entry tunnels, small hemispherical domes had to be introduced to maintain sufficiently large headroom at the opening (Burkhardt, 1978: 39).

Definition of geometry

The technology for measuring and defining the geometry of the double-curved surfaces was, at the time, in an early stage of development. However, Frei Otto had previously worked with Klaus Linkwitz in the design of cable net structures for the German Pavilion at Expo' 67, in Montreal, and on the stadium roof for the 1972 Olympics, in Munich. Büro Linkwitz working

Figure 2.23 Different foundation types (a) reinforced concrete wall; (b) double glue-laminated timber edge beams; (c) timber arches; (d) paired double steel cables
Source: © Gabriel Tang.

with the Institut für Anwendungen der Geodäsie im Bauwesen (IAGB), at the University of Stuttgart, first used stereographic photographs of the final 1:100 scale model to obtain the three-dimensional co-ordinates of all nodes. However, this revealed that the hand-made links were not necessarily all exactly the same length and in some places the surface was actually found not to be in tension. Therefore, the geometry determined from the model was then refined using force density form-finding software developed by the IAGB (Burkhardt, 1978; Linkwitz, 1994; Wendland, 2001: 7) (Figure 2.24). This produced a set of node co-ordinates commensurate with a net of ideal hanging chains, having the same distance between all nodes and with forces in equilibrium at each node when loaded by self-weight (Happold and Liddell, 1975: 108). Without this refinement, as Lothar Gründig, Ulrich Hangleiter and Hans D. Preuss have commented:

> Any purely geometric transfer of a mistake – independently of whether it is due to the construction of the model, the measuring of the model, or to a discrepancy between the model and actual building – would be enlarged one hundred times in the building itself.
>
> (Burkhardt, 1978: 41)

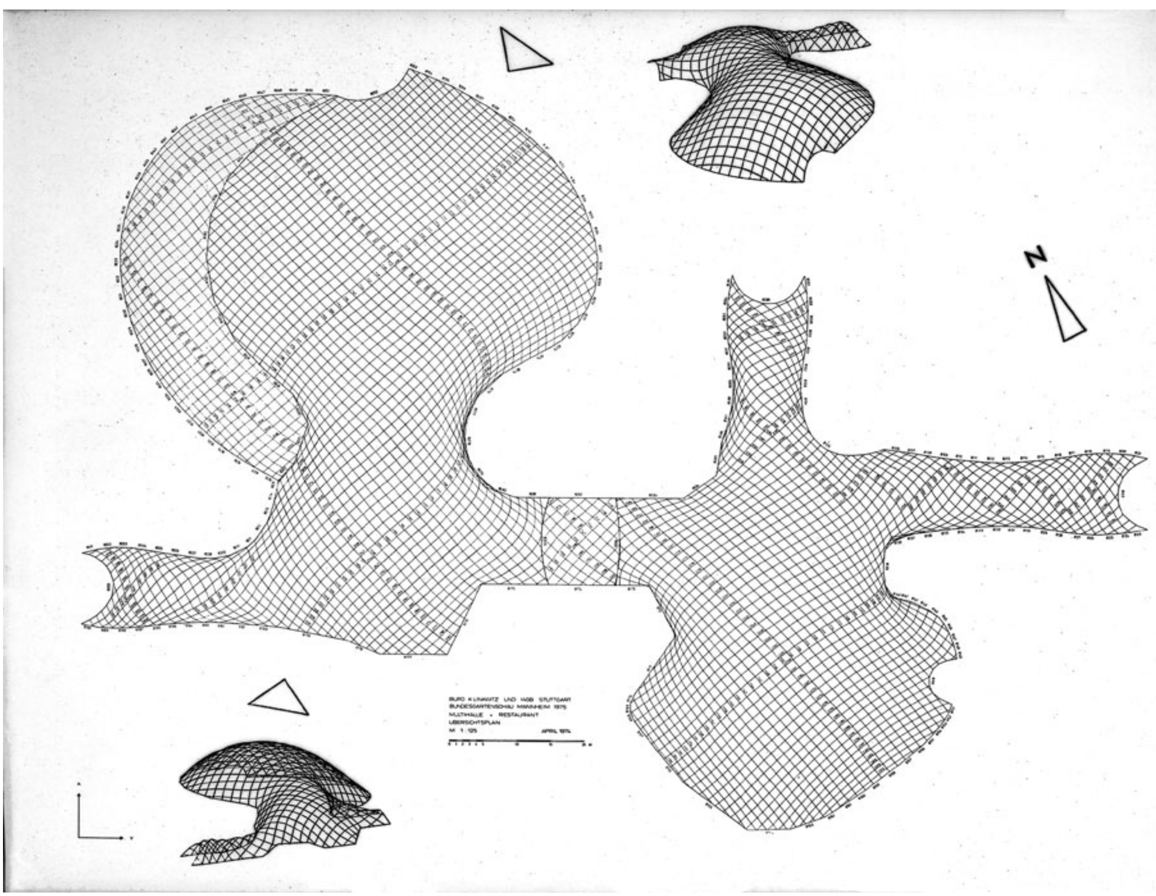


Figure 2.24 Plan of Multihalle and Restaurant gridshell geometry
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Structural design

In May 1972, the Mannheim practice Bräuer and Späh were appointed as structural engineers for the Herzogenried section of the Bundesgartenschau site, which included the multi-purpose hall and restaurant. However, as Heribert Späh recalls (Burkhardt, 1978: 55), in October 1973, following the production of the physical model and digital form-finding, at the suggestion of Frei Otto, responsibility for the design of the timber gridshell was assumed by the Structures 3 group, at Ove Arup & Partners, London. Bräuer and Späh retained responsibility for the reinforced concrete and steel of the substructure.

The Structures 3 group was at the time headed by (the later Sir) Edmund (Ted) Happold (Walker and Addis, 1997: 89), who founded his own practice Buro Happold with seven colleagues from Arup, in 1976, shortly after the completion of this project. Taking on the structural design of the Multihalle at this relatively late stage – just 18 months before the scheduled opening date of 18 April 1975 – was a risk for Arup because, as Happold remarked: 'there was no previous engineering experience in this field' (Happold and Liddell, 1975: 106).

To gain some appreciation of lattice shell behaviour, the team started with something simpler than the complex Mannheim form. They load-tested a 1:16 scale model of the Essen dome, which had been constructed in 1962. Using the original construction data obtained from Atelier Warmbronn, they used 3.0 x 1.7 mm Perspex strips spaced at 50 mm centres, drilled and connected with small pins at all intersections and taped to a profiled baseboard (ibid.: 115).

A key issue in the structural stability of gridshells is restraint of the initially deformable mechanism of the mesh. (For an explanation of the behaviour of a lattice grid, see Chapter 1.) To explore the effect of different restraint methods – pinned joint, glued (i.e. assumed rigid) joint, pinned with loose ties, and pinned with diagonal ties at all joints – the Arup team applied increasing point loads to the model (using bundles of 12.5 g nails as weights) at three grid locations in turn – centre, side and corner. This test was performed repeatedly with increasing uniform load applied to all joints in the grid. It was found that, by applying diagonal stiffening, grid deflections were reduced and the load at which collapse occurred was higher but happened more suddenly. These model results were compared with the actual properties and behaviour of the Essen shell, using appropriate scale factors and dimensional analysis, and 'to try to predict the failure loads of the Mannheim shells' (ibid.: 115). As a result of these tests and subsequent analysis, a double-layer grid (i.e. with two layers of timber laths in each direction) with diagonal ties was selected for the Mannheim shells.

A model of the Multihalle shells was also made, at a scale of 1:60, comprising a single layer of 1.40 x 2.60 mm-wide Perspex elements, connected by pins on a 50 x 50 mm grid. As the proposed grid spacing in the full size was 500 mm, each model element represented six gridlines of the double-layer structure. This was tested using a similar procedure to that applied for the Essen model, including some tests with linen thread diagonal ties at a spacing equivalent to 3√2 (4.24) m in the full-size gridshell. The tests suggested a collapse load of 63 kg/m^2 for the unbraced shell and 280 kg/m^2 for the shell with diagonal ties although subsequent computer modelling predicted a collapse load of approximately 100 kg/m^2 under uniform loading. The difference was believed to be due to the higher stiffness of the joints in the scale model relative to those in the actual structure (ibid.: 116–118).

Gridshell material

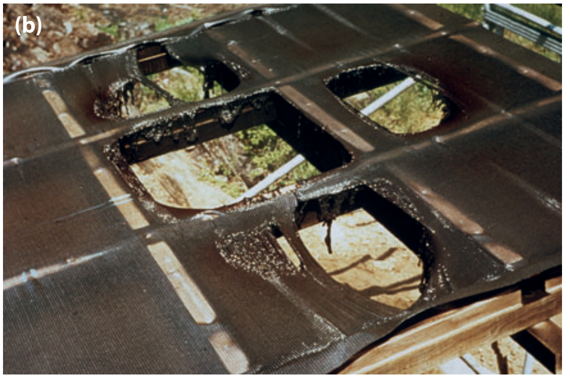
The Mannheim double-layer gridshell is composed of two connected orthogonal grids of 50 x 50 mm Western hemlock (*tsuga heterophylla*) spaced at 500 mm centres in each grid direction. Jürgen Hennicke has observed that a property of the 500 mm grid spacing – with a 450 mm gap between laths – was that it was considered relatively safe to walk on. In the event of anyone slipping, the rapid extension of both elbows would effectively minimise the possibility of falling through.

Western hemlock originates from the Pacific Coast of North America, where mature specimens achieve a height of 50–70 m with a trunk diameter of up to 2.7 m. It is usually straight- and fine-grained, non-resinous and available in long lengths. Given the large quantity of material in the grid and the large number of bending strength and elastic modulus tests carried out by others, it was decided to accept established properties for air dry hemlock (12.8 per cent moisture content), namely:

Bending strength: 83.0 N/mm^2
Modulus of elasticity: 10,400 N/mm^2

In the Mannheim gridshells the radius of curvature is 10 m over considerable surface areas and as tight as 6 m in some places. As a consequence, the engineers tested the timber at 6 and 12 m radius and found that initially high bending stresses soon relaxed due to creep (Happold and Liddell, 1975: 112–113). To reduce breakage the 50 mm laths were split into two 25 mm deep sections where the radius was below 10 m (Liddell, 2015: 44).

To comply with fire control requirements, the hemlock laths were impregnated with water-based flame-retardant salts. A sample panel of approximately 5 m^2, including the coated fabric mesh cladding, was tested to the fire officer's satisfaction (Figures 2.25 (a) and (b)). Tests carried out subsequently to determine whether this treatment affected timber properties showed a 20 per cent reduction in bending strength and 10 per cent



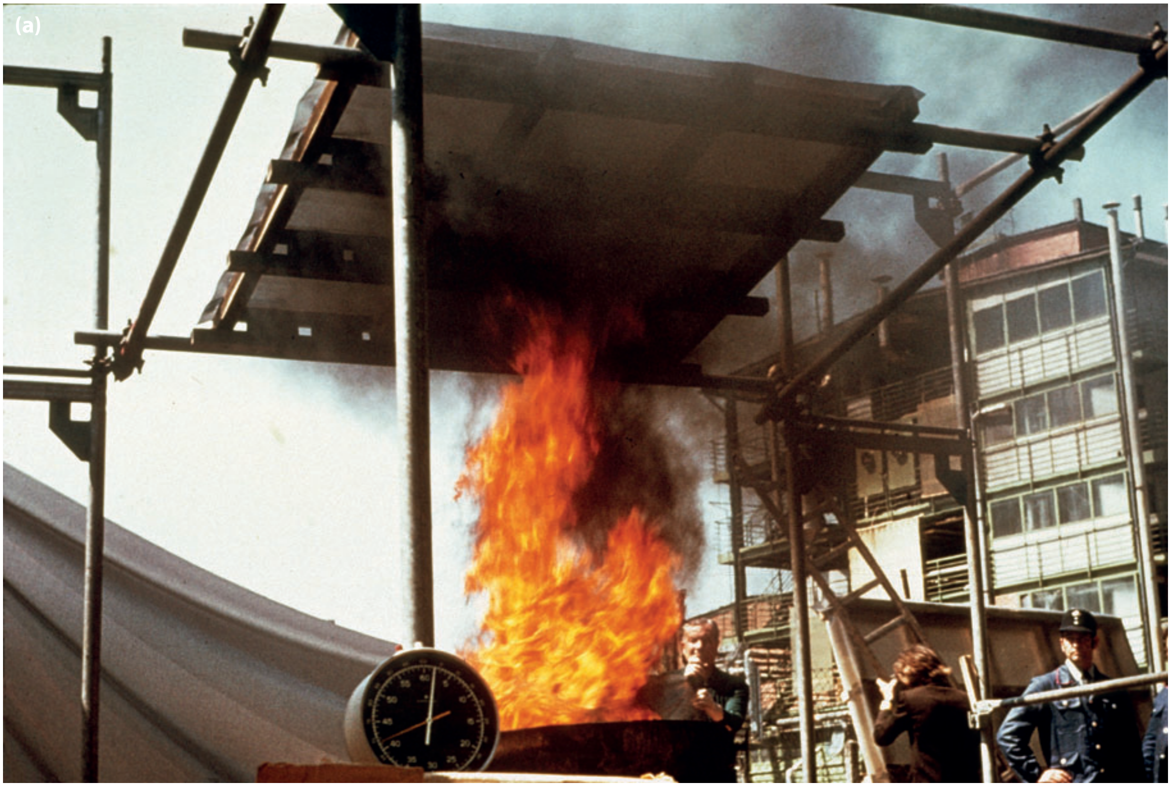


Figure 2.25 (a) Fire test on sample flame-retardant impregnated timber gridshell panel and membrane cladding; (b) the sample post testing
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

increase in elastic modulus (Happold and Liddell, 1975: 114–115).

To achieve the required DIN 4102, Class B1 fire resistance for the translucent, grey-tinted, open weave, PVC-coated, polyester mesh fabric, developed by Degussa, the base fabric fibre coating was heavily dosed with antimony trioxide flame retardant, and non-flammable softeners were incorporated in the self-extinguishing PVC coating (Burkhardt, 1978: 131–133).

Construction details

In a double-layer gridshell each node has to allow slip to occur between layers during erection but must transmit shear forces between layers in service. Working with the Timber Research and Development Association (TRADA) in the United Kingdom, Arup conceived and tested a joint, shown in Figures 2.26 (a) and (b), which would maintain a constant clamping load of 400 kg while allowing for 5 mm of shrinkage of the full depth of timber in the node. Connection was by an 8 mm diameter threaded steel rod, through clearance holes – slotted in the outer layers – with a 55 mm x 1 mm thick steel spreader washer at each end and a total of four proprietary 35 mm diameter Schnorr disc springs (three at the outer surface and one at the inner).

To stiffen the shell, a diagonal network of twin 6 mm diameter, 19-strand steel wire ties was installed at 4.5 m centres each way (Figure 2.27). It was initially hoped that these could be installed at the mid-depth of the grid but to ensure a simple fixing they were finally installed across the outer layer, connected to the main joint bar by an aluminium cable clamp substituting for the outer nut, and with the top plain washer replaced by a 50 mm diameter bulldog connector, as shear connector. It was also found to be necessary to increase the stiffness of some of the members carrying high axial load. This was achieved by inserting double (folding) wedge blocking

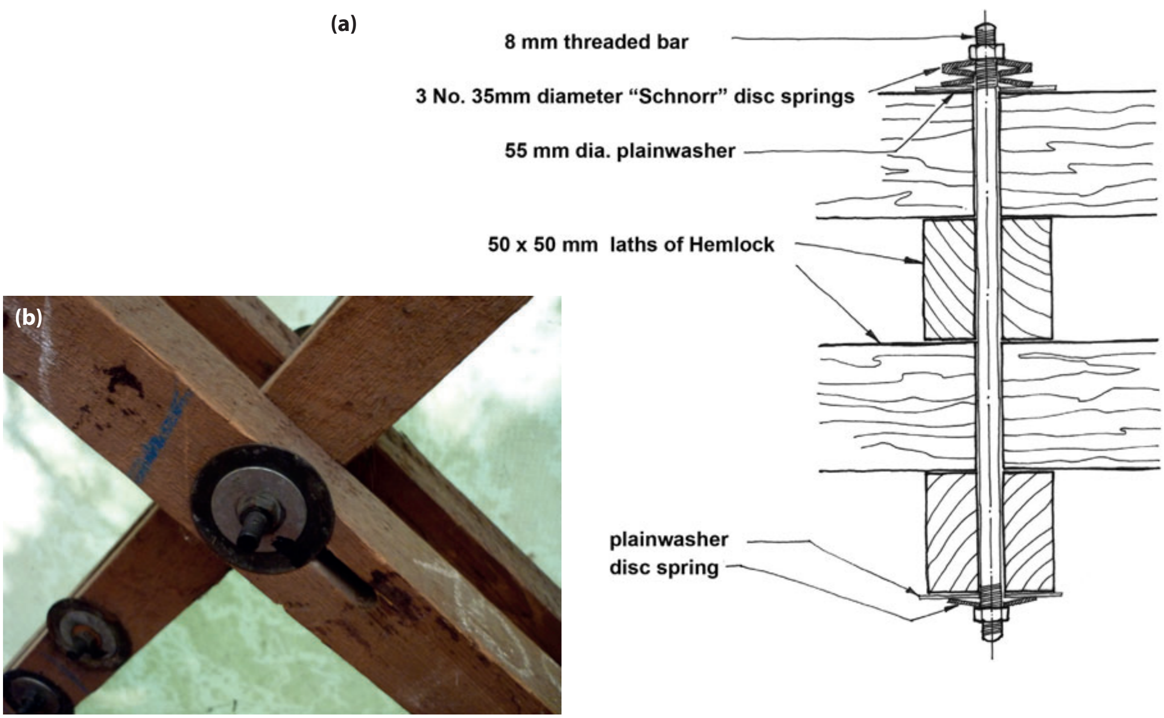


Figure 2.26 (a) Detail of the Mannheim gridshell node joint; (b) typical node as realised in the gridshell
Sources: (a) © Gabriel Tang, redrawn from Burkhardt (1978: 112); (b) © Gabriel Tang.

pieces between parallel grid layers once the full grid had been erected and all the joint nodes fully tightened. Each blocking piece was held in place using three of the standard 8 mm bar, washer and spring washer configurations. In certain areas of the gridshell surface, the bending stiffness had to be enhanced by 50 per cent, which was achieved by installing extra double laths, fixed in place after the erection of the main grid (Burkhardt, 1978: 113, 115).

Individual laths of up to 40 m long were made by end-to-end finger jointing of shorter lengths at the factory of the contractor, Poppensieker. However, the finger lengths of 20 mm and root of 6 mm were reported to have led to several finger-joint failures on site. These were repaired by nailing 50 x 25 mm lapping pieces to each side using 16 nails, the same technique that was used to join the long laths at the site (Burkhardt, 1978: 115; Liddell, 2015: 44). Two of the standard 8 mm bolt and spring washer connectors installed on each side of the join increased friction between the lath and lapping pieces and ensured rigidity (Happold and Liddell, 1975: 127).

INSTALLATION

AS NOTED BY Happold and Liddell (ibid.: 130), there are essential differences in behaviour between single- and double-layer gridshells, which affect their respective installation processes. A single-layer grid is flexible but is largely stabilised once fixed at its boundaries, and any surface irregularities caused during lifting tend to smooth themselves out as the surface strain energy finds a minimum. Double-layer grids, on the other hand, have lower relative structural stiffness until the layers act compositely, and this does not occur until

Figure 2.27 To stiffen the shell, a diagonal network of twin 6 mm diameter, 19-strand steel wire ties was installed at 4.5 m centres
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

the node joints are tightened and stiffening ties are added. Also the lack of stiffness means that deviations from the designed surface profile tend not to be self-correcting, requiring more lifting points to be used. In fact, at Mannheim, it was estimated that the gridshell self-weight and collapse load of the structure, unless temporarily propped during installation, would be practically identical (ibid.: 130).

Earlier gridshells, such as that built in Essen, had been shaped and lifted into place using cranes and this method had initially been proposed at Mannheim. However, the engineers at Ove Arup became aware that very large cranes would be needed and would have to be in position for several weeks until the grid could be fully stabilised. A physical wire mesh model was used to simulate the flexible double-layer grid during installation, to determine appropriate lifting points and anticipated loads. This indicated that cranes capable of lifting 16 tonnes at a radius of 40 m were necessary, requiring expensive 200 tonne capacity cranes. Excessive cost, therefore, led to the adoption of the alternative erection method – lifting with fork-lift trucks of scaffolding towers installed at 9 m spacing and supporting 2.5 x 3.5 m spreaders to carry the grid (Happold and Liddell, 1975: 131; Liddell, 2015: 46) (Figure 2.28).

As the flexible grid sagged by up to 200 mm between the temporary supports, its form subsequently had to be adjusted in order to conform, within an acceptable tolerance of ±50 mm between towers, to the shell geometry defined by Klaus Linkwitz. Adjustment proceeded in strips across the shell, first, in one direction, then at right angles to it, working from the centre towards the perimeter, with the node bolts being tightened as work progressed (Figure 2.29). Smoothness of the gridshell curvature was checked by eye (Happold and Liddell, 1975: 132).

Figure 2.28 (a) and (b) Fork-lift, scaffold towers and spreader beams used to push up the gridshell from below
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.29 Twisted arch support for gridshell under construction
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Testing

Although considered unnecessary by Arup's engineers, the proof engineer Professor Fritz Wenzel requested that a load test of 1.7 times the design load should be applied to approximately 500 m^2 of the Multihalle grid. The test load, applied using water-filled municipal dustbins weighing 90 kg each, suspended from every ninth node, amounted to 40 kg/m^2 (0.4 kN/m^2) and was equivalent to 2.5 times the imposed load (Figure 2.30). After a preliminary loading using 25 per cent of the test load, the vertical deflections measured at 14 points were found to agree well with those predicted by computer analysis, confirming the acceptable performance of the gridshell (Happold and Liddell, 1975: 133–134). The maximum recorded deflection at the centre point was 79 mm, 9 mm greater than predicted. However, a residual deformation of 10 mm once the load was removed was attributed to 'bedding in and joint slip' (Liddell, 2015: 47).

Roofing the gridshell

A very important architectural consideration is the external cladding of the gridshell, in this case, a translucent, grey-tinted, PVC-coated, polyester mesh fabric of around 0.9 mm thick, weighing about 1 kg/m^2. The open weave, polyester base fabric allowed a visible light transmittance of approximately 30 per cent. As only 60 working days were available to Koitwerk H. Koch KG for installation of the whole 9500 m^2 surface, alternative assembly methods were trialled on a smaller gridshell of approximately 80 m^2 to enable an efficient method to be established. These trials suggested that in order to avoid folds, the membrane strips of up to 50 m^2 should run parallel to the nailing laths from the perimeter to the crest, generally in the direction of rainwater run-off (Figure 2.31).

Nailing laths were fixed to spacers on top of the structural grid to avoid the coated fabric cover being

Figure 2.30 Load test of gridshell with water-filled dustbins weighing 90 kg to 2.5 times the design applied load
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.31 Installation of translucent membrane in strips of up to 50 m^2 running parallel to the nailing laths from the perimeter to the crest, generally in the direction of the rainwater run-off
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

damaged by the node bolts and diagonal bracing fixings (Figure 2.32). Purpose-built tools, adjustable to different tensions, were used to stress the fabric. Following the installation, clamping and pre-stressing of one section of fabric, subsequent sections were attached by hot air welding of the PVC coating (Burkhardt, 1978: 151). This permitted the welded seams to be loaded almost instantly, thereby speeding up the cladding process. After welding and pre-stress, the membrane was nail-gunned to the laths at approximately 160 mm centres – even closer at the perimeter – using 26 mm-long galvanised steel staples. Subsequently all exposed edges of the seams and all staple fixing points had to be sealed using an appropriately pigmented solution of the PVC coating in tetrahydrofuran (THF) (ibid.: 153) (Figure 2.33).

The fabric membrane cover also contributed to the environmental control within the Multihalle, including roof ventilators of 25 m^2 in both the multi-purpose hall and the restaurant and a PVC inflatable tube which can be used to close the 500 mm perimeter ventilation strip. An area of around 500 m^2 of the membrane cladding was replaced by 0.75 mm-thick transparent PVC film for the duration of the Bundesgartenschau and could easily be interchanged. Also PVC polyester fabric internal enclosures for the multi-purpose hall were tensioned under the gridshell. In total, 12,500 m^2 of PVC polyester membrane material was installed by just 25 workers in 60 days (ibid.: 153).

A common criticism of tensile fabric membrane-covered enclosures is that there is poor definition of objects within (Chilton and Lau, 2015: 208) due to the

Figure 2.32 Nailing laths were fixed to spacers on top of the structural grid to avoid the fabric cover being damaged by the node bolts and diagonal bracing fixings
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

predominance of diffuse light. However, in this case, the open weave of the mesh and relatively high translucency of the coated fabric introduced a greater proportion of direct illumination (Figure 2.34), creating the shadows required to better define the contents of the pavilions and giving 'a special feel that was different from most fabric structures' (Liddell, 2015: 48).

Reaction to the gridshell

At the end of their detailed description of the design and execution of the Mannheim Multihalle, Burkhardt (1978) included reactions to the new building form from fellow professionals and the public and these make interesting reading.

Winfried Langner from Büro Mutschler & Partner discusses the development of the architecture programme and the problems associated with the fact that the purpose of the hall was not well defined. The client was looking for 'an exhibition hall in which other events can be organised' (ibid.: 183). He summarised this as a space without internal supports; with large

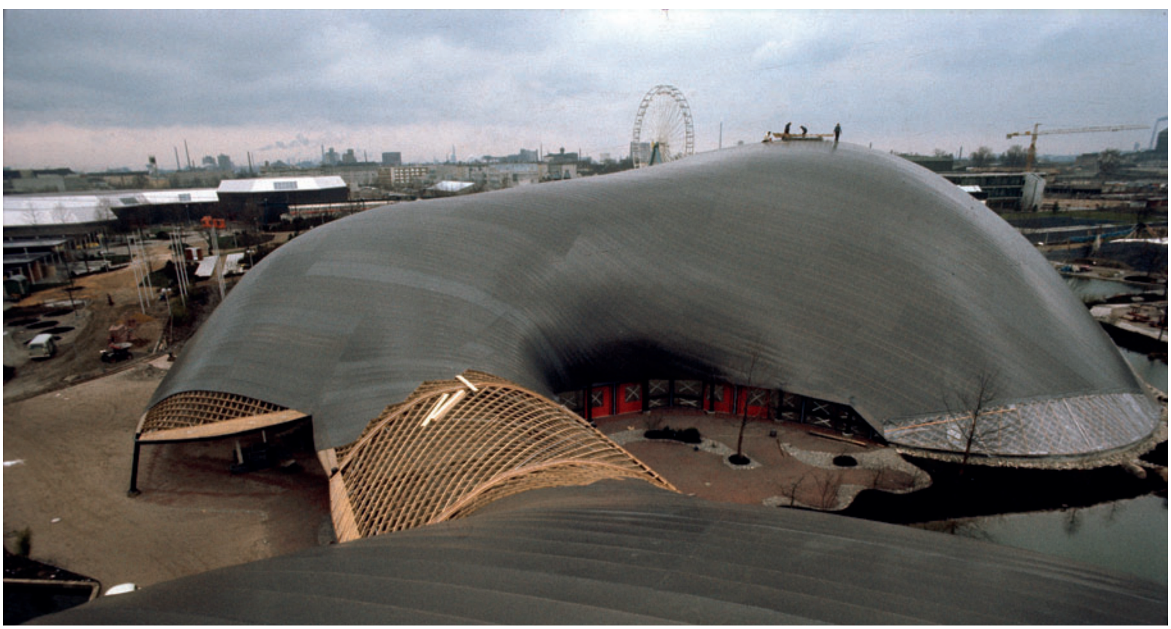


Figure 2.33 Roof view showing completed membrane skin (foreground)
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Figure 2.34 Interior view showing how the open mesh weave and relatively high translucency of the coated fabric introduced direct illumination to better define the contents of the pavilions
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

flat floor areas and with great flexibility. Compromises needed to be made between rectilinear and organic plan forms, a raked arena or flat floor, the overall area provided and material cost. For the roof, a desire for a non-conventional structure led to the adoption of the gridshell, the covering of which had to be translucent, low-cost and offer good lighting conditions for the exhibition.

At the opening of the flower show, it became apparent that the design intentions had been fulfilled with the creation of a light and airy terraced exhibition space. During the exhibition the presence of plants and soil softened the acoustics. However, it was reported that the acoustic performance was not so good when the Multihalle was used later for a conference on timber structures and for musical performances. Eventually, it was found better to limit sound sources to optimum locations within the multi-use space. Winfried Langner noted that around 120 events had taken place within the space by the end of the garden show. He concluded that: 'This structure fulfilled more than it has promised and is justly termed multiple purpose hall' (ibid.: 184–191).

Max Bächer's article, 'Freiräume hinter Gittern' (Free Spaces behind Gratings) reproduced from *Der Architekt*, is complimentary about what is described as a whale-like form (Figure 2.35), which effortlessly spans with 'a filigree fabric'. He comments on the 'hand-made air of do-it-yourself', the visible reference numbers used for assembly, '[the] scent of wood', 'signs of rapid inventive improvisation' and lack of perfection, which make the building human (Burkhardt, 1978: 193). The scale of the regular grid mesh is deemed very suitable to highlight changes in the curvature of the building envelope that result from its deformation from square to rhomb. His main criticism is of the restaurant enclosed by the gridshell, which he describes as being 'like a stone in the stomach', although he also draws attention to the difficulty of connecting vertical partitions to the curved profile of the roof.

Manfred Sack's article, from *Die Zeit*, describes the gridshell as 'the most complicated simple roof in the world' and 'like a thick satisfied snake after having devoured its prey'. He comments that the building is more pleasing from the inside from where the grey-tinted translucent mesh skin admits a pearlescent light and contrasts against the timber grid (Burkhardt, 1978: 208–213).

Figure 2.35 External view of grey-skinned 'whale-like' gridshells integrated into the landscape
Source: © Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart.

Unresolved questions

Unresolved questions relating to the gridshell construction are summarised in *IL13 Multihalle Mannheim* by Jürgen Hennicke (Burkhardt, 1978: 237–240), namely:

- the use of cables as edge support members;
- the effect of joints in the grid laths;
- the turning resistance of grid nodes;
- methods of stiffening the grid;
- the effect of point loads hanging from the gridshell;
- comparison of the 'as-built' with theoretical form and the impact of deviations;
- alternative methods of assembly and erection;
- improved thermal insulation (without loss of translucency);
- geometrical presentation of complex details;
- connection of internal walls and façade to the grid (including accommodation of movement);
- integration of window/door openings;
- control of acoustics;

- flexibility/utilisation of the space;
- maintenance (vandalism, decay, soiling/cleaning, heating costs, etc.);
- architectural design interrelationships (lightweight shell contrasting with heavyweight internal structures);
- scale of the interior space (human scale within a large envelope);
- efficiency of the enclosure (height, plan to volume ratio).

(Burkhardt, 1978: 237–240)

Several of these problems have been resolved in the past 40 years by the use of digital design and fabrication and the improved timber and construction technology described in the following chapters. However, others – for instance, architectural design interrelationships – still cause problems for gridshell designers and constructors.

Frei Otto's concluding remarks

Given its innovative nature and high profile, it seems surprising that no gridshell of similar size was built until over ten years later – those of the, now almost completely forgotten, Nara Silk Road Expo, Japan, in 1988, described in Chapter 5. However, concluding remarks by Frei Otto in the publication devoted to its design and construction, *IL13 Multihalle Mannheim*, shed some light on this. He says:

> If we had another project like this, we would certainly make things in a different manner. We would try to find a better shape, better details and a better skin – we could even render more services for the same money.
>
> (Burkhardt, 1978: 229)

He emphasises the public's reaction to the building's aesthetic qualities, suggesting that most visitors are either 'enthusiastic or … reject the building (frequently in disgust)' (ibid.: 229). Such contrasting public opinions are not uncommon towards new building typographies and frequently soften with time and familiarity. The Multihalle's survival well past its intended design life is witness to this.

Otto also asks the question 'What could be improved, if anyone else had to design and construct a hall under similar conditions?' In response, he highlights four areas: (1) form finding; (2) the skin; (3) the fixing of the skin; and (4) the air conditioning ducts. For form finding, he discusses, in particular, complications in incorporating an internal partition, eventually a fabric membrane, in the waisted entrance section of the Multihalle. This highlights a common design problem in double-curved roof structures – how to satisfactorily intersect vertical walls with the roof surface. Local deformation and buckling of the surface, the effect of grid orientation and the grid angle are also reviewed. For the skin, Otto says that he does not wish to discuss the weak points of the skin material but draws attention to the diverse and sometimes conflicting properties required. Factory-prefabricated and insulated fabric membranes attached to the grid by retaining bolts/washers are rejected on cost grounds. However, an important suggestion is to use fully vacuum-impregnated timber for the top laths of the grid with integral channels to lead condensate to the perimeter. Finally, he points out that transparent membranes might have been used for the air-conditioning ducts rather than the sheet metal ducts that were used, which seem to support the roof. (Burkhardt, 1978: 235–236).

Maintenance and repair

Ian Liddell, who worked on the project at the time as a member of Arup's Structures 3 group, has recently commented that 'The Mannheim project was an experimental structure that was a product of its time' (Liddell, 2015: 48). As one might expect from such an innovative and experimental construction, which has survived beyond its intended life, there has been and still is a need for maintenance and repair.

Unfortunately, the combined effects of ultraviolet degradation and excessive heating of the mesh yarns,

Figure 2.36 (a) Exterior of Mannheim gridshell recovered in a more durable, reflective, white PVC-coated, polyester fabric; (b) internal view showing the more diffuse nature of the transmitted light
Source: © Gabriel Tang.

due to their dark coating, induced shrinking and cracking of the PVC coating and the roof membrane began to leak. Subsequently, in 1981, it was replaced by a more durable, reflective, white PVC-coated, polyester fabric, produced by Sarnafil (Figure 2.36 (a)) (ibid.: 48). The replacement membrane diffuses light more strongly, resulting in less defined internal shadows (Figure 2.36 (b)).

Timber is a material that creeps (i.e. it suffers increasing deformation under long-term constant load). The Mannheim gridshell is still in existence 40 years after its construction. It has, therefore, been subject to long-term loading and it is reported that there has been some local deformation of the original shell profile at a few locations (Figure 2.37). Klaus Linkwitz, who was head of the IAGB in Stuttgart at the time the roof was designed and constructed, has surveyed the altered roof geometry and assessed its effect using the computer programs used at the time the roof was designed. In his plenary lecture at the Structural Membranes 2011 conference in Barcelona, he suggested that certain small areas of the gridshell were in need of reinforcement to ensure its long-term serviceability and stability (Linkwitz, 2011). In January 2014, the estimated costs of repair, including planning costs, were approaching €6 million (*Rhein Neckar Zeitung*, 2014).

Despite these problems, in recognition of the architectural and engineering innovation applied in

Figure 2.37 Local propping up of Mannheim gridshell in 2009
Source: © Gabriel Tang.

its design and construction, the Multihalle has been a protected monument since 1998. However, at the time of writing, December 2015, various options for its future are to be considered by the municipal authorities in 2016. It is hoped that, as the prototype for this long-span architectural typology, every effort should be made to retain it for posterity and that it should be restored if economically feasible.

This chapter is intended to give an overview of the early development of timber lattice gridshells and the design and construction of the Mannheim Multihalle. For a comprehensive report, readers are strongly recommended to refer to the publications that are still available from ILEK: *IL10: Gitterschalen – Grid Shells* (Hennicke and Schaur, 1974) and *IL13: Multihalle Mannheim* (Burkhardt, 1978).

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CHAPTER THREE

Second-generation deployable gridshells (post-Mannheim)

ALTHOUGH TIMBER GRIDSHELLS continued to be built after the Mannheim Multihalle, with newly improved methods of construction, the following decade saw the popularisation of steel and concrete as structural solutions, favouring exposed components and assemblies. As a structural solution, timber gridshells did not hold the appeal their competitors possessed. After all, timber is a natural material, one with imperfections, one which could fracture easily, making it a much less controllable material.

The way in which timber gridshells were designed and built was also rapidly evolving as digital form finding and structural analysis were refined. After a period of no construction of actively bent gridshells, the Weald and Downland gridshell, completed in 2002, became the epicentre in the revival of this new wave of timber gridshell interest.

EARTH CENTRE, NEAR DONCASTER, UK, 1998

THE FIRST LARGE-SCALE timber gridshell constructed in the twenty-first century was the Jerwood gridshell at the Weald and Downland Museum, near Chichester in Sussex, in the UK. Prior to its construction, Buro Happold, the engineers for the project, had worked with Shigeru Ban Architects in the design and construction of a cardboard tube gridshell for the Japan Pavilion at the Expo' 2000 in Hanover. They had also

Figure 3.1 Concept sketch for 'humped mound' landscape features with green oak gridshells in the Earth Centre Forest Garden, near Doncaster, UK
Source: © Grant Associates.

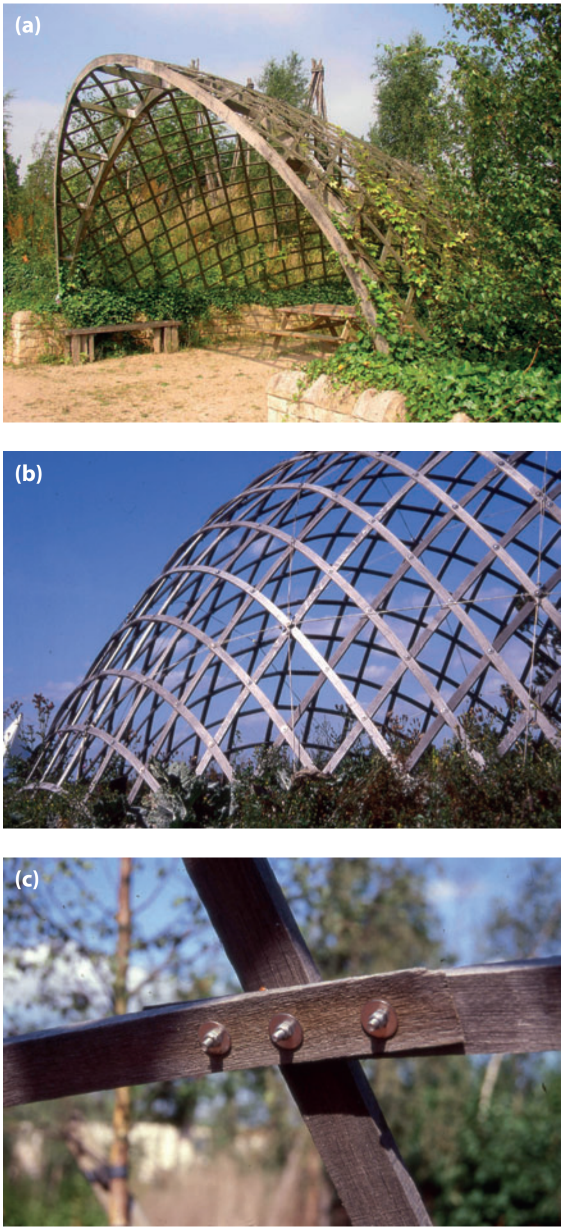

Figure 3.2 (a) One of the Earth Centre gridshells sitting in its naturalistic surroundings; (b) Earth Centre oak lath gridshell stabilised with thin diagonal stainless steel cables; (c) bolted lap joint and node connection
Sources: (a) © Carpenter Oak and Woodland Co. Ltd; (b) and (c) © John Chilton.

collaborated with architects Grant Associates in the design and fabrication of several small-scale gridshells at the Earth Centre, near Doncaster, in the UK. According to Grant Associates, the Earth Centre Forest Garden aimed to show how most natural resources required to support human existence (including those necessary to provide shelter) could be derived from managed woodland. Designed to echo the landscape, the 'humpback mounds' green oak lath gridshells, completed in 1998 (Figure 3.1) were proposed to demonstrate 'an efficient, elegant and structurally inventive way of creating habitable structures from timber' (Grant Associates, 2015).

Manufactured by Carpenter Oak & Woodland from thin oak laths, the flat single-layer grids were lifted by crane and bent into the final gridshell configuration before being stabilised with thin stainless steel cables, shown in Figures 3.2 (a) and (b). Lap joints in the laths and grid nodes were connected with stainless steel bolts, to resist chemical attack by the tannins in the green oak (Figure 3.2 (c)). These elegant small-scale structures informed the design of the Weald and Downland gridshell by providing information about the bending properties of the green oak and demonstrated the importance of deploying the gridshell before fully tightening the node connecting bolts (Harris and Kelly, 2002: 162; Grant Associates, 2015).

THE JAPAN PAVILION, WORLD EXPO, HANOVER, GERMANY, 2000

IT MAY BE surprising to find this project featured in a book about timber gridshells as this structure is made mainly from paper tubes, not exclusively timber. However, like the Earth Centre gridshells, this project was influential in the development of timber gridshells that followed.

> In accordance with the main theme of Expo 2000 – environmental conservation – I have designed a temporary pavilion that uses recycled materials

to a great extent. The building should produce minimum waste when dismantled and be highly reusable or recycled.

(Shigeru Ban, 1999)

Designed and built for the World Expo 2000 in Hanover, the pavilion, representing the land of the rising sun, remained one of the more memorable national pavilions, surprising visitors by the unexpected use of paper tubes (Figure 3.3). Responding to the Expo theme of Mankind, Nature and Technology, the pavilion was designed to 'touch the ground lightly' by being completely recyclable and removable from site.

The paper-tube gridshell measured 72 m long, 35 m at the widest point on plan, rising to a height of 15.5 m enclosing a space with a largely rectangular floor area of 3600 m^2 (Dickson *et al*., 2001: 1). Designed by Shigeru Ban Architects, the building, with the easily recognisable triple bulbous swellings, was commissioned by JETRO (Japanese External Trade Organisation) to provide exhibition and administrative spaces.

The novel idea of using paper tubes was developed and evolved with the collaborative involvement of Frei Otto. The paper tubes, 120 mm in diameter and 22 mm thick, were fabricated by Sonoco from three-ply spiral card tapes of specified structural strength and moisture content, into individual paper tubes each 20 m long and weighing 100 kg. The paper tubes were spliced and socket-jointed to form the desired lengths of up to 68 m (Davey, 2000). The intersections were then tied together with polyester webbing strips. The pavilion terminated at both ends with diaphragm walls of cable-braced cardboard honeycomb mesh (Figure 3.4).

Previously, the conventional use of paper tubes was in the form of straight tubes with nodal block connections, as seen in previous projects by Shigeru

Figure 3.3 Through the translucent envelope, the Japan Pavilion glows like a Japanese lantern hinting at the gridshell structure beneath and within

Source: © Jens Bludau (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons).

Figure 3.4 Inside, the Japan Pavilion defines a brightly lit environment. The end diaphragm walls of cable-braced cardboard honeycomb mesh are clearly visible at the far end.
Source: © Hiroyuki Hirai, www.flickr.com/photos/eager/17068464076.

Ban, such as in his proposals for a temporary community centre after the earthquake which struck Kobe, Japan, in 1995. Using paper tubes structurally in a curved form was unprecedented. Therefore, to gain an understanding of the erection process, prototypes had to be constructed at various scales to study the behaviour of node connections. Numerous physical models were made, including a life-sized bay 1/6 of the actual pavilion fabricated to investigate the entire process of construction (Dickson *et al*., 2001: 2).

Based on form-finding and buckling analysis, changes in the triple-hump geometry were reiteratively revised, resulting in a self-supporting shape with a safety factor of 3 against buckling.

Originally designed as a gridshell structure made solely from paper tubes, the imposition of stringent building regulations meant that the structure had to be stiffened by curved and trussed glulam 'ladders' made from 60 mm-deep timber laths with 'rungs' sandwiched in between (Figure 3.5). Low in environmental impact, these timber 'ladders' allowed the paper membrane to be easily attached across the gridshell. Obviously, 60 mm-deep hoop trusses were not sufficiently stiff, therefore, stainless steel tension cables had to be used to increase the effective structural depth and hence its in-plane stiffness.

Longitudinally, a purlin spaced every 3 m proved useful for attaching the paper membrane onto the structure. The space between the glulam timber 'ladders' provided access and acted as a gutter for rainwater drainage. This arrangement resulted in the space acting as a ventilation gap which allowed any condensate to drip off without coming into contact with the paper tubes, or compromising their structural integrity.

The foundation system consisted of a series of A-frames placed at the base of each arch with a trapezoidal profile corresponding to the plan of the pavilion at ground level. These frames were fitted with timber boards and filled with sand to provide deadweight that prevented gridshell uplift and sliding. The sand was recycled afterwards.

The paper tubes were laid on a diagonal grid on the bias at 1 m spacing and connected to each other and to the timber above by fabric bands.

Pushing up the gridshell

The modular scaffold system PERI-UP saw the paper tube lattice first being arranged flat on a scaffold bed at low level before being pushed upwards into position by the use of a precise proprietary jacking system called the MULTI-PROP system.

The contractor, Takenaka, methodically planned the erection in seven major stages, with each stage subdivided into seven further secondary stages. In-plane webbing restraints were used to allow for the sliding of the paper tubes and to control the change in direction from a flat lattice mat into a three-dimensional form, resulting in tolerances within +50 mm (Dickson *et al*., 2001: 5). The structure was then covered with a recyclable paper membrane specially developed in Japan which provided fire- and water-proofing. After the Expo, the entire pavilion was taken apart and reused.

The Japan Pavilion saw the innovative use of a man-made material – paper – to construct a structure sustainably. The project also was the precedent for the 9-tonne paper tube gridshell arch, with a 26.5 m span, that Ban designed for the Abby Aldrich Rockefeller

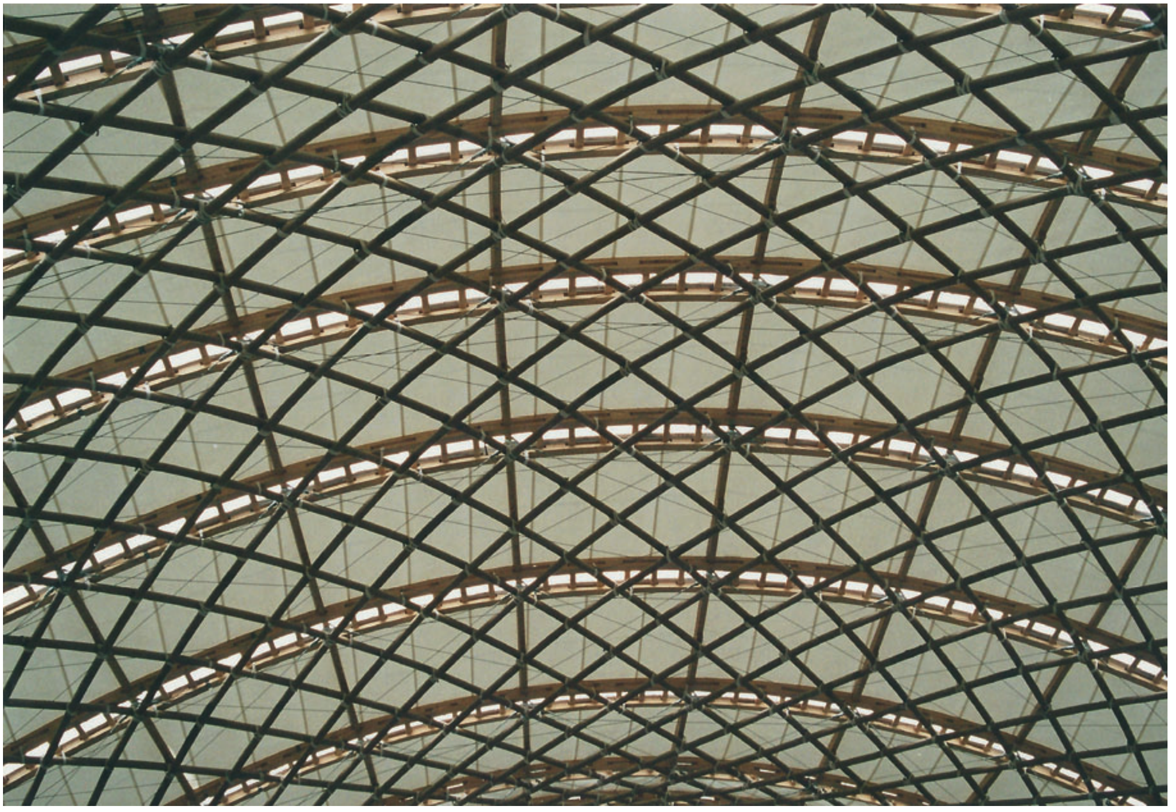

Figure 3.5 Timber ladder trusses traverse the shell, meeting the paper tube gridshell beneath
Source: © Nicolas Janberg.

Sculpture Garden for The Museum of Modern Art in New York in 2000. This arch, constructed on the same principles as the Japan Pavilion, saw the reductive substitution of timber ladder trusses with paper tube trusses (Shigeru Ban Architects, 2015).

Most significantly, following the construction of the Japan Pavilion, PERI was invited to submit a tender that was pivotal in the construction of the Weald and Downland gridshell, where the construction safety and erection process were refined. The experimental and pioneering use of PERI scaffolding led to the gravity drop-down construction innovation at the Weald and Downland gridshell – an ingenious departure from what had been done before in construction terms (Harris *et al.*, 2003: 444).

THE WEALD AND DOWNLAND GRIDSHELL, SINGLETON, UK, 2002

AS WE HAVE learnt, the words *timber gridshell* conjure up visions of woven timber roofs defining a sinuous curved space within. Many of us would have understood the term from images of the Weald and Downland Gridshell, often quoted as a contemporary example being completed in 2002. With its distinctive triple hourglass shape (Figure 3.6), the timber gridshell nestles within the woodland in Singleton near Chichester, England. From the outside, the structure is not perceivable, being cloaked in a timber board and polycarbonate cladding. It is only upon entering the cathedral-like interior that the timber gridshell becomes clear, revealing all its glory and structural logic to magically celebrate the seamless union between architecture, structure and craft (Figure 3.7).

Figure 3.6 The undulating silhouette of the Weald and Downland gridshell nestles within the woodland of Singleton, UK
Source: © Richard Learoyd.

The Weald and Downland gridshell, also known as the Jerwood gridshell, measures 50 m in length on an east–west axis. On plan, it measures 16 m across at its widest points, decreasing to 12.5 m at its narrowest (Figures 3.8 (a) and (b)). It rises to a crest height of 9.5 m falling to 7.35 m in the valleys (Harris *et al.*, 2003: 442). This gridshell is formed from two layers of oak timber laths 50 x 35 mm deep, running diagonally from the perimeter.

Similar to the Mannheim Multihalle, the formation of the gridshell was developed from an initially flat lattice mat. However, this project incorporated revised thinking and many improvements on the deployable timber gridshell construction process and detailing experienced in earlier gridshells.

The design brief

The project was commissioned in 1996 by the Weald and Downland Museum whose mission is to rescue and restore historic English timber buildings that would otherwise be left in disrepair and be subject to further deterioration. Since its opening in 1970, the open air museum has restored more than 45 such buildings in South-East England by transporting them to museums where they are repaired, reinstated and restored (ibid.: 429).

The clients had requested a new open-air workshop space with sufficient spatial clearance for large-scale wood working, which involves working on large-sectioned building parts. This space had to be sufficiently large for timber frames to be laid out and be moved around. It was also imperative that this space had stable temperature, constant humidity level and good ventilation, whereby workshop doors could be left open to provide good air flow. A smaller enclosed workshop area, planned at the eastern end, was designed with these conditions in mind without disrupting the larger workshop space.

Figure 3.7 The light-flooded interiors of the Weald and Downland gridshell display the seamless union of architecture, structure and craft
Source: © Richard Learoyd.

Also required was an artefact store for iron and wood articles. This space did not need to be a specially controlled environment. Due to the slope of the site, the

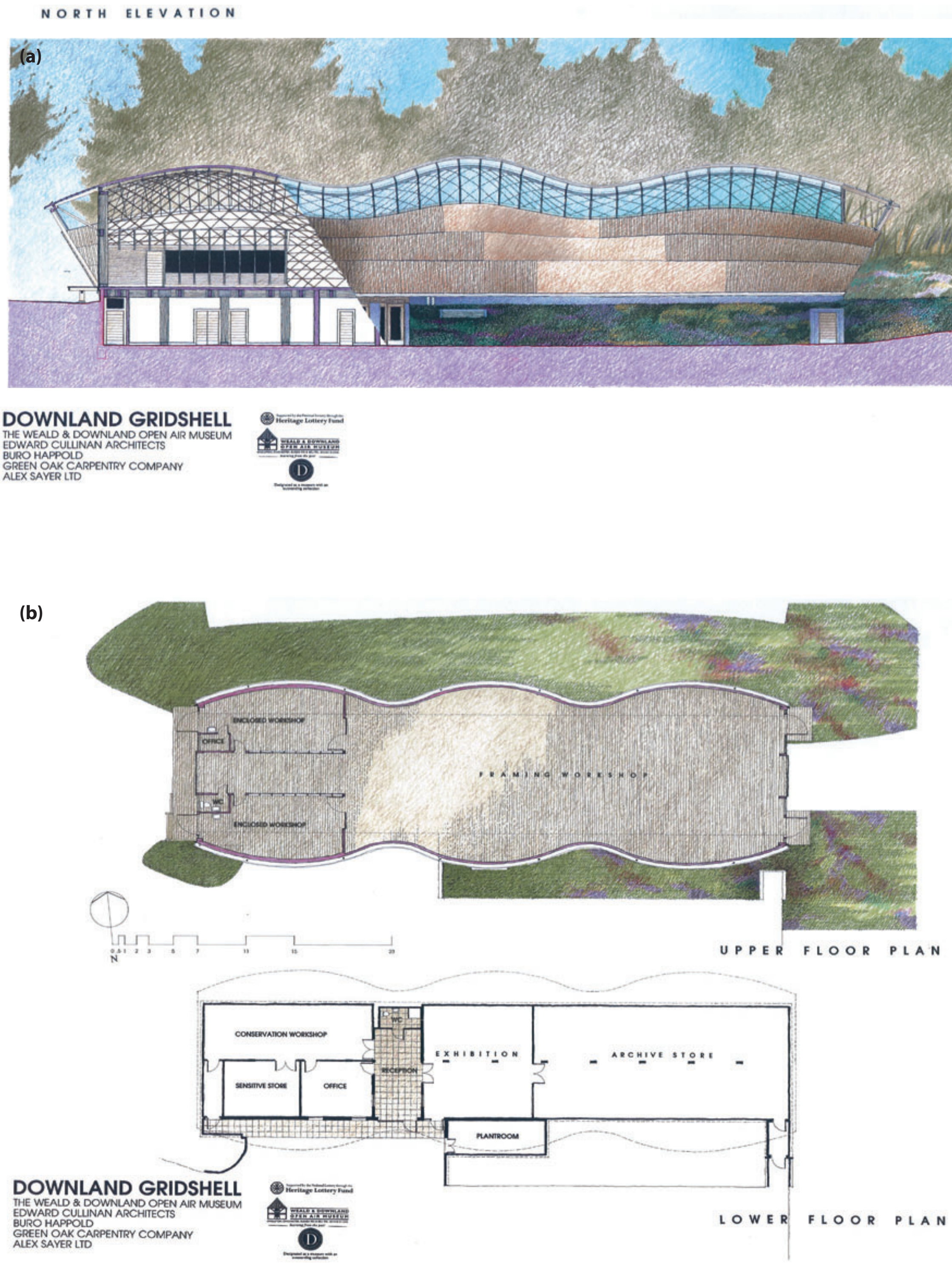

Figure 3.8 (a) North elevation; (b) upper floor plans and lower floor plans
Source: © Cullinan Studio.

Figure 3.9 Section across the gridshell showing the banking of the artefact store at the lower level and the space above where the gridshell is situated
Source: © Cullinan Studio.

store was placed in the earth banking to benefit from ground thermal mass (Figure 3.9).

An important element of the brief was that the building design should express the idea of craft skills (ibid.: 430).

The team

The working relationships between the architect, the engineer and builder are crucial in successful project delivery. Mutual respect and a positive dynamic between various parties are important, especially in timber gridshell projects that deal with innovative non-conventional construction.

Edward Cullinan Architects (as Cullinan Studio was previously known) and engineers Buro Happold had prior experience of working together during their collaboration on Westminster Lodge at Hooke Park for the furniture-maker John Makepeace (Burton *et al.*, 1998; Harris *et al.*, 2003: 429; Hale, 2005: 235). In this experimental collaboration, forest thinnings, which would otherwise have gone to waste, found use in a construction method where roughly lumbered roundings were layered in a cross-gridded manner to form a latticed green roof (Figure 3.10).

Strengthened by the work on the gridshell structures at both the Earth Centre Forest Garden in Doncaster in 1998/99 and the Japan Pavilion in Hanover, Germany, in 2000, Buro Happold's involvement and experience on these projects were instrumental to the furtherance of digital form-finding and digital analysis in the understanding of timber gridshells.

Form-finding through digital and physical modelling

This structure was designed reiteratively by computer modelling and physical models. Seventeen years after the 1975 Mannheim Multihalle, the use of computer aided structural analysis had developed considerably, becoming increasingly sophisticated, refined and more widely used. The development of the digital mathematical model was crucial in gaining an understanding of the geometry of the Downland gridshell. In conjunction with Chris Williams at the University of Bath, computer form-finding programs

Figure 3.10 Interior of Westminster Lodge at Hooke Park shows the use of round wood thinnings as a gridshell roof designed by Edward Cullinan Architects in collaboration with Buro Happold
Source: © Cullinan Studio.

were scripted. Williams had accumulated extensive experience on digital structural analysis, having worked on the Mannheim Multihalle in the 1970s while working for Arup and was responsible for the form-finding of the Japan Pavilion and subsequent projects.

In particular, this project saw the advanced use of *dynamic relaxation* to understand timber gridshell behaviour. However, digital design alone did not result in an effectively communicable format with various parties. It was through the building of physical models that design ideas and problems became comprehensible to both design team and client. To facilitate communication and understanding, physical models were built and developed to foster this understanding (Figure 3.11).

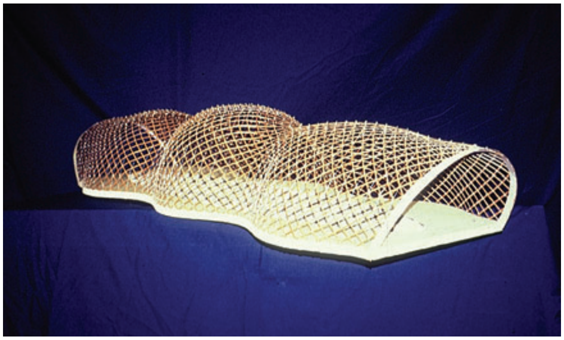

Figure 3.11 One of the physical mesh models built during the design process
Source: © Cullinan Studio.

The benefits and influence of a physical model in the delivery of a project are all-encompassing and it provides an understanding not offered by two-dimensional drawings or virtual digital models. This is summed up by the late John Romer of Edward Cullinan Architects (now Cullinan Studio):

> The physical model came first. Because in a way, with the physical model, you will be able to come up with what you think is right and then put it into a machine (i.e. the computer). The computer can then give you the answers, whereas with the physical model, it gives you the question.

Initial models were made in wire mesh at a scale of 1:100 that served to illustrate the stiffening effect of bracing represented by cotton threads (Figure 3.12). Unlike the Mannheim Multihalle hanging chain model, this model replicated the construction principles of the gridshell and was instrumental in showing the proposed geometry to the client and design team. The physical model also demonstrated the concept of construction and how the flat mat was deployed.

Subsequently, 1:30 scale models were constructed with wood. 'Instructive' in structural behaviour, this assisted in investigating boundary conditions for structural design and communication of the concept to funding bodies. A further 1:43 scale model was also made from wire mesh.

The central dome was in fact set higher than the other side domes to avoid the illusion of the central zone sagging. Reiterative dialogue between model and computer was found to be invaluable in the understanding of the behaviour and performance of actively bent timber gridshells.

One major improvement from Mannheim Multihalle was the way in which the intersections of the sliding grid mats were fixed into position. The Weald and Downland gridshell featured a patented new connection clamp that allowed the timber laths to rotate and slide during the construction process, illustrated in Figure 3.13. The design and feasibility of this nodal connection were tested at a constructional level where a life-sized prototype of the gridshell was constructed for a 5 m x 2.5 m section with a tight radius of 5 m, illustrated in Figure 3.14.

The new clamp connections worked well and this life-sized prototype construction proved that a tight radius of 5 m was achievable. Oak was chosen over larch, Douglas fir and chestnut timbers for its structural characteristics and specifically, for its higher bending strength and plasticity at failure (Harris *et al*., 2003: 436).

Similar to the Mannheim Multihalle, this structure sees a timber gridshell formed from four layers of timber laths. Treated as two double-layer gridshells, one placed on top of another with shear blocks positioned in between, the gridmat was allowed to swivel and rotate at their points of intersections until the desired curvatures were achieved during the drop-down forming process. The geometry was then 'frozen' by fixing these

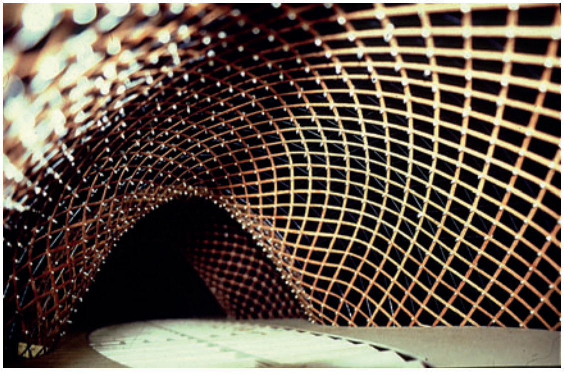

Figure 3.12 Interior spaces as communicated and suggested by the physical model
Source: © Cullinan Studio.

Figure 3.13 Clamping detail as built
Source: © Cullinan Studio.

Figure 3.14 A life-sized mock-up was built to understand the behaviour of timbers during forming
Source: © Cullinan Studio.

intersection nodes and bracing them with timber laths which ran longitudinally along the gridshell.

Physical models were useful in demonstrating the stiffening effect of the bracing elements. Within the model, tension and compression elements were clearly visible.

Structural and material principles

Gridshells derive their structural strength from curvature. The shape of this gridshell, like the Japan Pavilion, was defined by three swellings and two valleys likened to that of an hourglass. Deployable timber gridshells owe their ability to transform into a doubly-curved gridshell from a two-dimensional gridmat to the low torsional stiffness of timber. To investigate its impact on cost, economy and structural efficiency, an initial computer model was made of a gridmat of double lath 50 mm x 30 mm sections spaced at 1 m centre to centre and braced with timber rib-laths. Analysis identified regions

Figure 3.15 Cross-timber bracings triangulate and lend a strong sense of tectonics and constructional expression to the project Source: © Cullinan Studio.

of weaknesses at the side of the domes which led to a structural strategy to apply additional intermediate 0.5 m grids to the identified regions of weaknesses with the 1 m grids remaining in these lightly loaded areas.

Here, unlike the Mannheim Multihalle, which used steel wire cables, timber laths brace and lock the geometry of the final shape of the gridshell, illustrated in Figure 3.15. Being more rigid, timber laths can resist both tension and compression forces while cables can only operate in tension. Another benefit of using timber bracing was the ease with which the timber cladding could be fixed.

Short sections were finger-jointed using a Grecon/Dimter SUPRA E continuous feed finger-jointing machine to produce 6 m lengths. Purbond HB530 adhesive was used as it was capable of curing in spite of the high moisture content of the oak (65 per cent) without the need for infra-red heating which could be costly (Harris *et al*., 2003: 437). During this process, knots, defects and any imperfections in the timber were removed. With a total of 60,000 linear metres of timber lath required, and with an average length of 600 mm, a total of 10,000 finger-joints were made.

Timber offcuts were used in the shear blocks connecting the layers. To reduce material wastage, timber offcuts from the workshop floor were used to make the internal workshop structures.

Fire safety and navigating UK Building Regulations

Fireproofing is an important consideration for any timber structure. For fire regulation purposes, the timber gridshell had been treated as a roof and therefore avoided the fire resistance period stipulated by UK building regulations. To deal with flame spread, the 50 x 35 mm oak timber laths were treated as elements not dissimilar to window frames, thereby avoiding the need to comply with Building Regulations requirement Approved Docs B2 Section 7. The timber grade of D30 with a characteristic bending strength of 30 N/mm^2 and the gridshell structural design comply with Eurocode 5 (Harris *et al*., 2003: 437).

For quality reasons, oak from the French region of Normandy was selected. Compared with oaks that are transported from other parts of the United Kingdom, e.g. from Scotland, oak from the French forests could be considered and treated as a local material in terms of distance.

Construction

The construction sequence is logical: the archives and lower store constructed from masonry were built first. Then, the floor was formed from glue-laminated timber. Above this floor, a PERI scaffolding system was constructed up to 7 m tall using their universal girder, then multi-props with fork-head attachments. These were used to support the timber lattice, as had been done at the Japan Pavilion in Hanover.

As for the gridshell, timbers were finger-jointed off-site, and with defects removed, the 6 m lengths were transported to site and scarf-jointed manually under the protection of a polytunnel to form lengths up to 50 m for the rib laths and up to 37 m for the lattice. Scarf joints with a slope of 1:7 gave a contact surface equal to that of the finger-joints.

It was reported that 145 breakages (ibid.: 438) occurred out of the 10,000 finger-joints in the structure. These were attributed to four main causes: (1) the lattice on the scaffold structure was 'pinched'; (2) curvature was too tight; (3) difficulties with the sliding movement between the two layers; and (4) the joints were too dry.

The deployable gridshell was first of all formed from two layers of oak laths 50 mm x 35 mm running diagonally to the perimeter of the rectangular gridmat before being deformed to create the three-dimensional shell.

Mannheim Multihalle had a detailing challenge in terms of accommodating rotation and slip between grid layers at the node points of the gridmat. Slots were cut into the timber laths and an M8 bolt and spring washers were installed to locate these points as illustrated in Figure 2.26 (p. 32). This allowed all the layers to rotate and the two outer layers to slide freely. However, the labour-intensive slot-cutting had both economic and structural impacts. It was time-consuming, hence costly, and, because it removed material from the laths, wood fibres were cut and the section available to resist the applied load was reduced, thereby weakening the grid.

In this project, an improved patented node connection, first suggested by Andrew Holloway, was used, see Figures 3.13 and 3.16. This consisted of three clamping plates with four bolts external to the node, which, therefore, do not pass through or weaken the timber laths. Buro Happold developed and checked the structural capacity of these. Steve Johnson of Edward Cullinan Architects (now Cullinan Studio) proposed and revised the 4 mm steel plate clamp profiles to make them less visually obtrusive. To fix their position and ensure constant spacing between nodes while retaining their ability to rotate, the central plate has a point that inserts into the two central layers. The two outer layers are free to slide and rotate as necessary to find their equilibrium position. A tapped hole in the underside of the node plate makes the suspension of light fittings possible.

The construction sequence is shown in Figures 3.17 (a)–(f). Following on from the team's experience from the Japan Pavilion and from physical models, three lessons were learnt there and applied here, namely, (1) the appropriate level at which the laying platform should be set; (2) the sequence to achieve the triple bulb hourglass shape; and (3) the use of the PERI scaffolding system.

Principally, the dropping of the gridmat from a high level harnesses gravity to help form the gridshell. Compared to the push-up method used at Mannheim Multihalle, this construction method is considered much safer and more cost-effective.

To create the triple-bulb form first involved the forming of a barrel vault, then the domed and waisted areas were squeezed to define the final shape. Significant out-of-plane forces were required to form the waists. As the considerable forces transfer across these areas, breakages were anticipated. Hence, it was decided that the waists and domes had to be formed simultaneously. Being modular with innovative patented accessories,

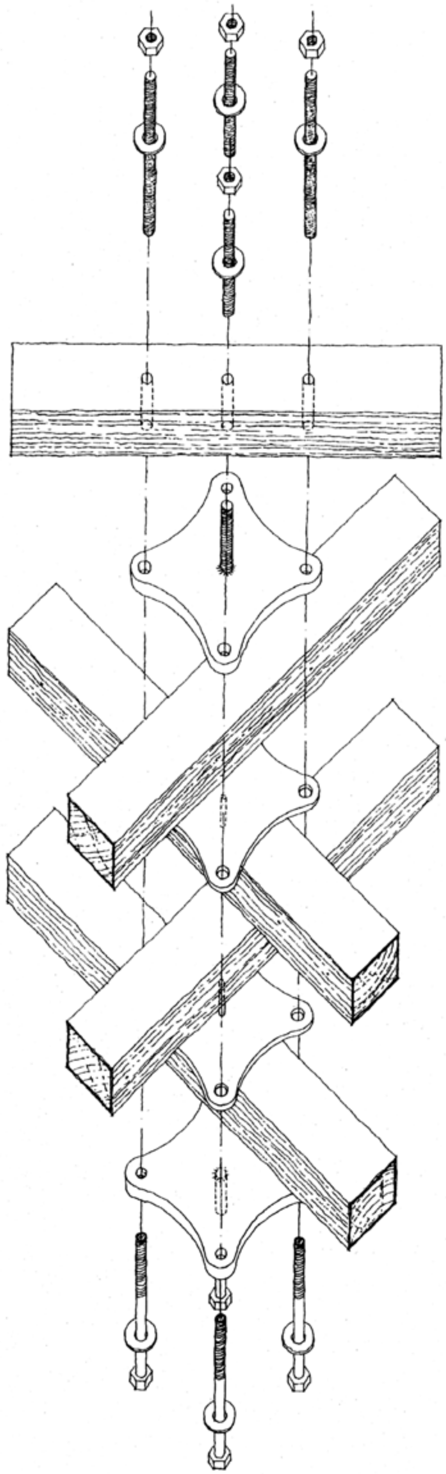

Figure 3.16 Detail connection of the patented system of clamping the layers of timbers together, yet allowing freedom of rotation Source: © Cullinan Studio.

the PERI system was found to be adaptable, useful and suitable to provide accurate vertical adjustment during the formation process.

The flat gridmat was initially laid out on a plan of 47 m x 25 m. It was then stretched out to 50 m long with the central node of each of the three domes on the centre of the gridmat. This became a useful control to ensure the deformation was correct. The eventual gridmat was pulled to measure 49 m x 24.2 m with two 96° and two 84° internal angles.

The clamps allowed only the outer and innermost laths to slide while the gridshell is developing into its final position. Due to the depth of the grid and curved geometry, the outer lath needed to be longer than the inner lath. As the moving nature of this gridmat could make the construction process confusing, it was important to set reference points to track this deformation process. Fortunately, it was apparent that the nodes at the longitudinal centre-points on plan were the only points that did not move. As such, a single bolt was inserted at these nodes that did not require a free clamp and were fixed. Length differences in the outer and inner laths could then be accurately calculated from these stationary points running down the centre along the top of the gridshell.

Co-ordinate-based addresses were assigned to each intersection point within the complicated forest of PERI scaffolding. Additionally, as a greater amount of out-of-plane shear was observed nearer to the perimeter, more shear blocks were eventually placed in these areas.

Harris *et al*. (2003) report that within this sea of grid laths within a forest of PERI scaffolding, it was difficult to locate each lath position in its finished state, the laths were therefore painted to differentiate this. Rib lath intersections were identified too. Plastic ties of two differentiating colours were attached to each node. A red tie represented where a longitudinal lath ran lengthways along the space and a yellow tie denoted a transverse lath running across the gridshell like an arch from one side to another.

To visually monitor vertical movements, plumb lines were installed at specific points. Some interesting unpredicted problems were encountered and had to be addressed during the forming process. These

Figure 3.17 (a)–(f) The sequence of forming the gridshell starting with the flat grid mat being lowered by gravity
Source: © Cullinan Studio.

were described in detail by Harris *et al*. (ibid.) but are summarised below.

At the 25 per cent complete state, the valleys were failing to form, with laths flattening out without a significant display of geodesic curvature to activate the shell action. The design team had to intervene to 'encourage' this to happen. Ratcheting straps attached to specific scaffolding extensions and spreader plates had to be introduced to induce in-plane tension. Shortening the ratchet straps pulled the diagonals closer together to induce the required geodesic curvature.

The behaviour of the gable ends posed a design challenge. The gridshell had a tendency to drop at the ends to form another valley and produce a flatter dome. It was resolved by introducing external supports in the form of arched glulam frames.

It took six months to manipulate the flat mat to the final curved form. It was noted that scaffolding adjustment was immensely time-consuming. When the forming process was nearly complete, vertical elements were no longer appropriate and so raking multi-props had to be installed to pull in the vertical sides of the gridshell horizontally to form curvatures as it met the floor.

The use of straps to encourage scissoring, a lath rotation that brings about a change in the equilateral shapes, was monitored. The strapping was carefully monitored and adjusted. It was learnt that the longer straps were more effective in inducing scissor action than shorter ones. Strapping was used to maximise in-plane forces and minimise out-of-plane forces which 'crinkled' the shell, and could result in local buckling damage.

Through checking against the theoretical model, calculations and predictions, it was found that the shape coincided with the theoretical model. However, some adjustments had to be made. It was found that the areas adjacent to the gabled ends were too flat. In order to correct this, the two side domes needed to be raised. To do this, each of the outer domes had to be propped up at each quarter point. This was effective as it was corrected to just 100 mm below the theoretical height (ibid.: 449).

Cladding challenges and considerations

Roofcrete was applied to the top layer. The second layer forming the clerestory to let in natural light is glazed with polycarbonate. The geometry required some twisting of the material which is comfortably accommodated by the flexible polycarbonate. The three skirting layers of red cedar cladding planks (Figure 3.18) – reminiscent of those used by Hungarian architect, Imre Makovecz (Heathcote, 1997) – were harvested from the forest nearby. Tectonically, these straight feather-like ribbons, being tangential to the gridshell, accommodate the double-curved form and accentuate the effect of light and shadow. This was a practical solution that allowed rainwater to drain away. The attachment of these planks to supporting battens also took into consideration the seasonal movements of timber in use.

Figure 3.18 The timber cladding on the outside of the gridshell sees the gridshell nestling into the surrounding landscape
Source: © Gabriel Tang.

The copper lightning conductor was also positioned to allow for effective water runoff. The reason for it being placed there was so that the weak acidic solution created from the copper would wash away and discourage mosses to grow on these surfaces under the shade of the canopied woods.

Discussed above are careful design considerations and hallmarks of good architectural thinking, achieving practicality with aesthetics. Using scaffolding to reach and work on a gridshell to install insulation and cladding can be very complicated. Conveniently, the gridshell was used as an access platform with cost- and time-saving benefits.

Building costs

The museum is innovative and experimental, but cost is an important consideration. The reported building cost for this project was £1097/m^2 (Harris *et al*., 2003: 453). When compared to other buildings of the visitor/education centre building typology, the project comes within the medium range.

Pure at so many levels, it is not surprising that this project has come to represent the spirit of good design and exemplary material thinking. This project scores highly on all counts of architecture, structure and craft. We also observe many refinements in the construction process, details and application of technology (form-finding, analysis and manufacturing) to propel gridshells forward, building on experience learnt from the Earth Centre gridshell, the Japan Pavilion and the Mannheim Multihalle.

Another way of working with timber, this project reignites the magic, re-inspires the imagination and rekindles architectural interest in actively bent gridshell structures. It is the perfect example of how designers could use timber creatively and efficiently to create architecture that is structurally logical, efficiently beautiful and functionally practical.

THE SAVILL GARDEN GRIDSHELL, BERKSHIRE, UK, 2005

THE 2005 SAVILL Garden gridshell forms an entranceway to the landscaped gardens in Windsor Great Park, Berkshire (Figure 3.19). On approach, from the outside, this gatehouse appears light and intended to meld into the undulating landscape. With a gridshell roof that 'floats' lightly like a silk handkerchief symmetrically fluttering in the wind, the true magnificence of the structure is revealed upon entry into the visitor centre space where the visitor is greeted by the intricate timber gridshell.

Unlike the Weald and Downland gridshell, the Savill Garden gridshell functions only as a roof, as opposed to both wall and roof. It is also much shallower. To achieve this illusion of lightness, the timber gridshell roof is detached from the ground and this is made possible by a steel perimeter beam with inclined steel columns that transfer the load to the ground.

The winning competition entry by Glenn Howells Architects is a lesson in the application of a variety of technologies to achieve their strong architectural vision. The competition brief asked for an environmentally friendly but dramatically distinct building which could enhance the Royal Landscape at Windsor, belonging to the Crown Estates. The winning proposal, an over-sailing curved roof, in the form of a lenticular-plan timber gridshell, was realised with confidence growing from the design and construction of the Weald and Downland gridshell (Figure 3.20).

During the competition process, the architects took the clients to view the Weald and Downland gridshell. The architectural concept was of a lightly floating sheet lifted up from the ground, opening up views through the building to give glimpses of the gardens and beyond (Figure 3.21). The approach to this building was also an important design generator as most visitors arriving from the car park will experience the intriguing roof first as it 'hovers' above before entering the portal in the grassed banking (Figures 3.22 and 3.23(a)).

Flanking this open view on the ground level are ancillary spaces on either side accommodating kitchens,

Figure 3.19 The Savill Garden gridshell roof appears to 'float' over the landscape of Windsor Great Park
Source: © Warwick Sweeney.

Figure 3.20 Original initial sketch by Glenn Howells showing a roof that floats over the landscape
Source: © Glenn Howells Architects.

toilets, plant rooms and teaching rooms, as shown in the plan in Figure 3.23 (b). As can be seen in the section, these spaces are sheltered by the grassed banking, where the building blends into the landscape and the ground – clearly signifying an entrance gateway into the park (Figure 3.24).

Upon entering the glass doors, the visitor experiences the magnificence of this floating timber roof within a single space where the restaurant, a garden shop and ticketing booths are located. Similar to the Weald and Downland gridshell in elevation, the curvature of this gridshell is symmetrically and geometrically defined by the triple-bulb form. Again, the central bulbous section is taller than the side sections; however, with the Savill Garden gridshell having a greater height difference this is more pronounced and noticeable.

The Savill Garden gridshell performs a symbolic role: with a roof that is structural, logical and legible, it is representative and characteristic of the park. Respecting the height of the trees and in order to achieve a seamless connection with the rolling landscape, the gridshell was

Figure 3.21 The underside of the timber gridshell roof expresses a high degree of lightness and undulation
Source: © John Chilton

Figure 3.22 Entrance approach towards the gridshell
Source: © John Chilton.

(a)

(b)

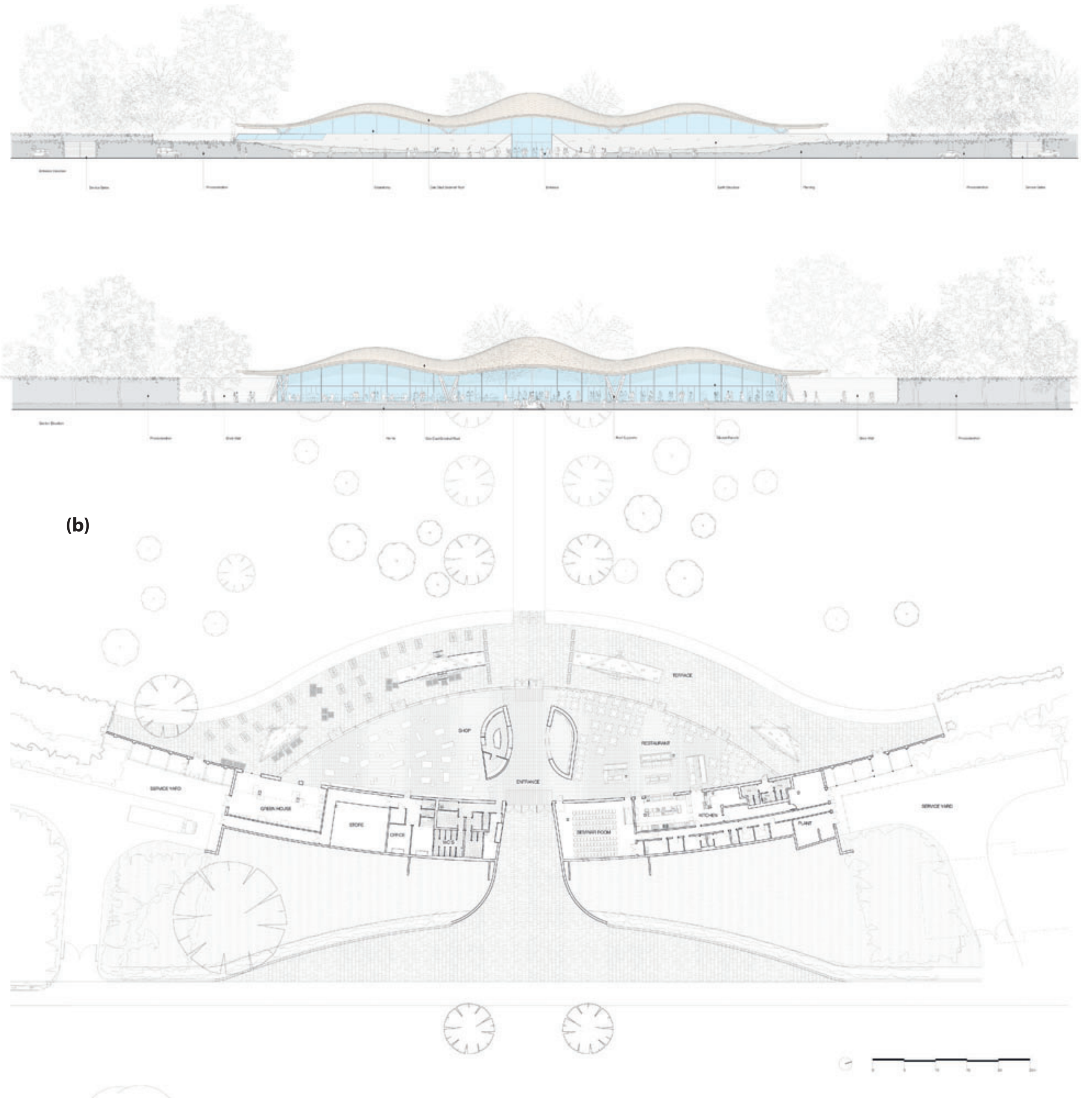

Figure 3.23 (a) Elevations: (upper) entrance approach, (lower) facing the garden; (b) floor plan
Source: © Glenn Howells Architects.

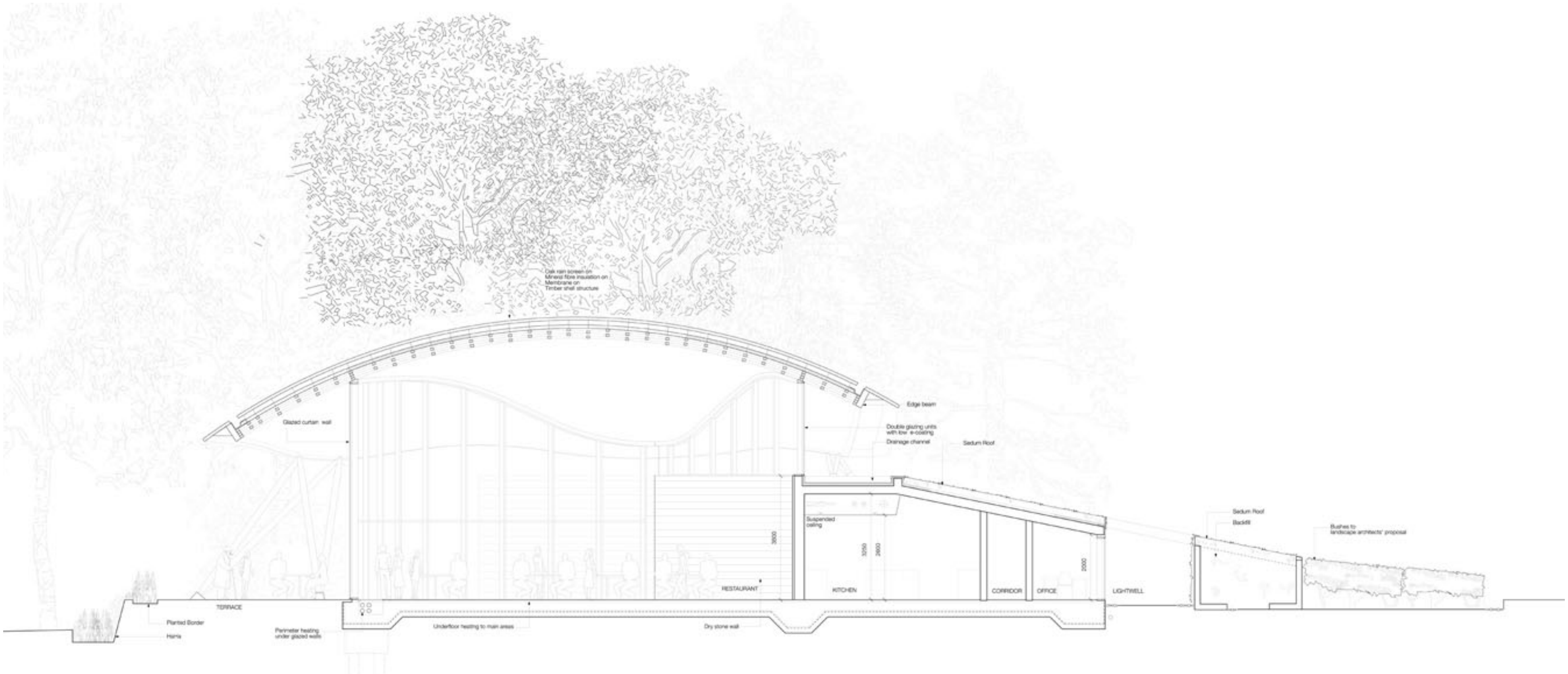

Figure 3.24 Section across the gridshell
Source: © Glenn Howells Architects.

designed to be as low and as flat as possible (Figure 3.23).

On plan, the Savill Garden gridshell is laid out along a largely north–south axis. Measuring 90 m long and 25 m wide (Harris *et al*., 2008: 28), it is longer and wider than the Jerwood Gridshell (at 50 m long and 16 m/12.5 m wide (Harris *et al*, 2003: 442)). The building is open-plan, enclosed by a glass façade drawing internal spaces outside (see Figure 3.25) and was intended to be 'lost' into the earth-form from the car park approach. It is this blending of spaces that exaggerates the experience of the main feature of the building which is that of being under a floating gridshell roof.

Construction

The 80 mm x 50 mm laths that form the gridshell were milled from locally harvested larch trees from within the Royal Landscape. Following a similar procedure to that used for the Weald and Downland gridshell, knots and other defects were first removed by machine, then short lengths were mechanically finger-jointed to form 6 m lengths. Subsequently, they were scarf-jointed with a gradient of 1:7 on site under a polytunnel. A total of 20,000 linear metres of timber laths were used (Harris *et al*., 2008: 30). This process offered numerous benefits – not only did it reduce wastage, it permitted the production of laths of different grades, allowing economic timber use of differing strengths appropriate to the structural requirements at different areas within the gridshell.

The grading of timber was carried out by testing green timber in terms of adhesive performance, strength properties about both axes, and their reactions to different production processes. Categorised into two grades, higher grade Savill 1 (10,000 m) and lower grade Savill 2 (10,000 m), the higher-grade timber went into forming 35 m lengths that formed the gridshell; the lower-grade timber was put into use as packing and shear pieces, translating into an efficient use of the 400 trees that were felled (Harris *et al*., 2008: 30). The process of manufacture was not completely mechanised. An element of craftsmanship was very much evident as each length of larch was visually inspected by a skilled craftsperson to identify any knots, unacceptable slope of grain and other defects (ibid.: 30).

The grids of the shell were laid out on a 1 m x 1 m grid spacing. Similar to previous examples at the Mannheim Multihalle and Weald and Downland, we find four alternating layers of laths used. However, here, the bottom two layers were laid out first, exploiting gravity to ease them into position. Subsequently, the top two layers were added to build up to the full gridshell depth. Shear blocks were then placed to fill in the spaces which results in a greater out-of-plane strength and stiffness, as well as the possibility of greater spacing of the layers.

The Savill Garden gridshell has a less 'cluttered' appearance than its predecessors. This is due to the missing steel tension bracing cables (Mannheim Multihalle) or additional triangulating bracing laths (Weald and Downland). What the Savill Garden gridshell

Figure 3.25 The gridshell roof covers the open shop and café within a single space
Source: © Gabriel Tang.

uses for bracing is in fact a continuous plywood deck formed from two layers of 12 mm plywood laid over the gridshell diagonally to each layer and butt-jointed with steel strips (ibid.: 32). It was noted that higher quality birch-faced ply was to be used as the clients did not like the quality of plywood initially being proposed, as it resembled shuttering ply. Structurally better performing, birch-faced plywood was deemed a better solution. The roof was then finished with a vapour control layer, 200 mm Rockwool insulation, an aluminium standing-seam roof and an oak rainscreen made of 100 x 20 mm boards at 135 mm centres.

Form-finding

Form-finding was carried out digitally with increasingly sophisticated software. Chris Williams from Bath University, who had previous experience of form-finding on the Mannheim Multihalle, the Weald and Downland gridshells and the Japan Pavilion, was again consulted.

Geometrically, the plan of the gridshell is defined by the area of intersection subtended by two intersecting circles as illustrated by Figure 3.26 and in the roof plan in Figure 3.27.

Harris, Haskins and Roynon (2008) state:

> The curved centreline on plan is the midline between the circles. The centreline 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 centreline as a series of parabolic curves of varying shape.

With this sophisticated method of form-finding, the design team collaborated and adjusted dimensions while considering aesthetics and construction practicalities. A gridded pattern was then projected onto this surface to construct a Tchebyshev net.

Upon completion of the form-finding process, structural analysis was carried out with *ROBOT 3D*. The Eurocode for Timber Structures (BS EN 1995, 2004) was used to check structural elements (Harris et al. 2008: 29) The 3D model was useful in the fabrication process to detail various design components. The digital model also enabled gridshell designers, Buro Happold, to communicate with and resolve the structural connections with the foundation designers, Haskins Robinson Waters. Hence, the influence of digital technology is clear. Computer models were crucial in communication (Figure 3.28).

Advances in current technology influenced how the physical models were produced. In the case of the Mannheim Multihalle, the model was crucial in the understanding of the structural behaviour. The Weald and Downland gridshell used the physical model to appreciate the forming and construction process. The more recent availability of physical 3-D printing now means that the digital model can be materialised with precision, resulting in a shift from the role of form-finding to a presentation/geometry/checking tool (Figures 3.29 (a), (b) and (c)).

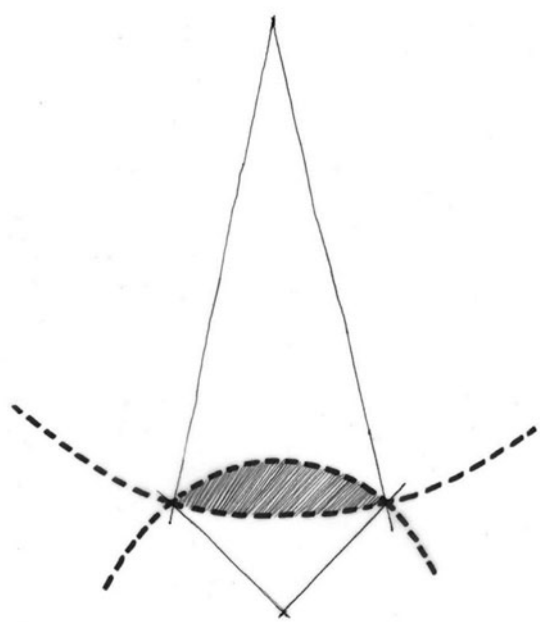

Figure 3.26 The plan area of the gridshell is defined by the area of intersection between two circles
Source: © Gabriel Tang.

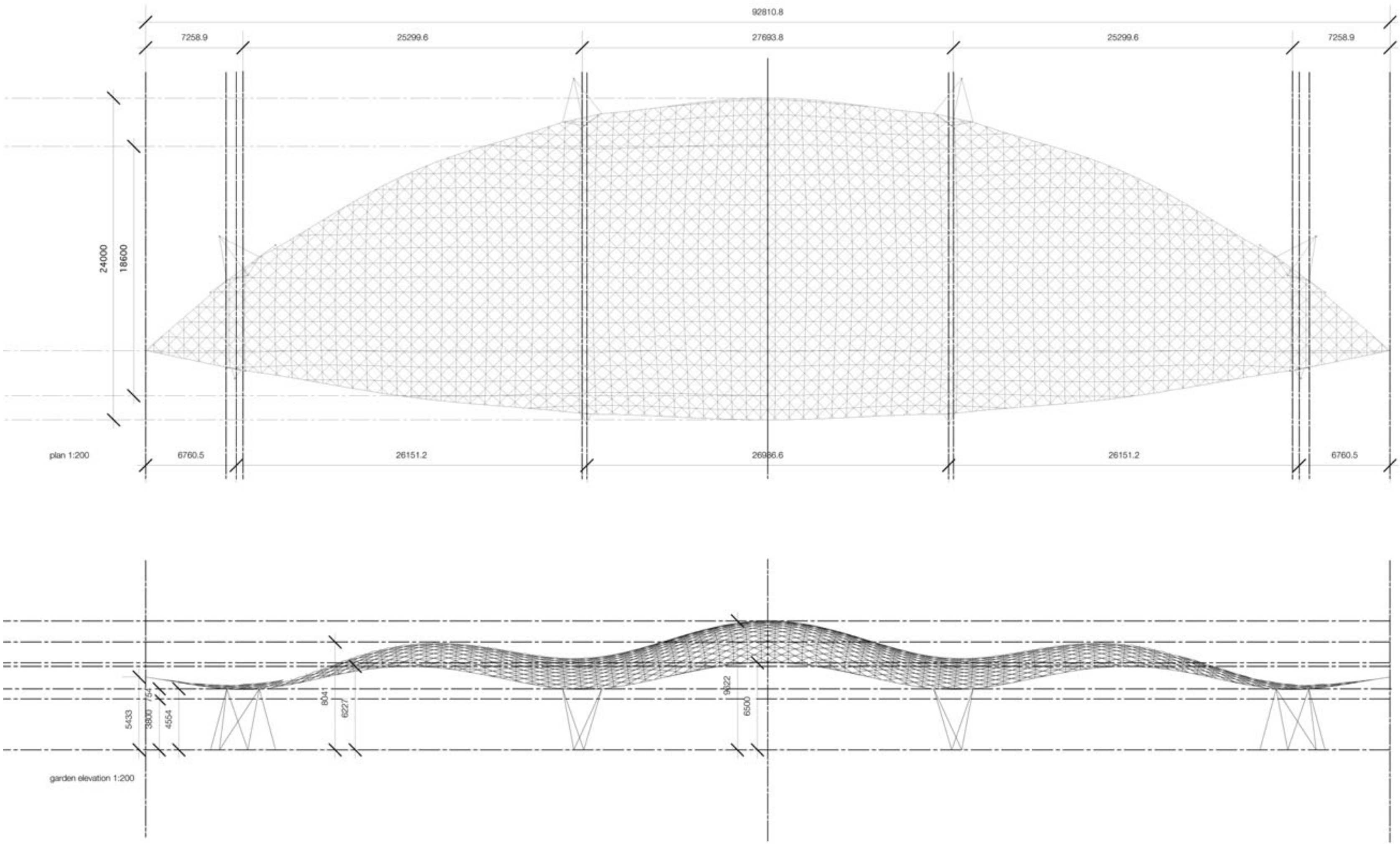

Figure 3.27 Plan and elevation of the gridshell describing the sinusoidal curvature of the shell in section
Source: © Glenn Howells Architects.

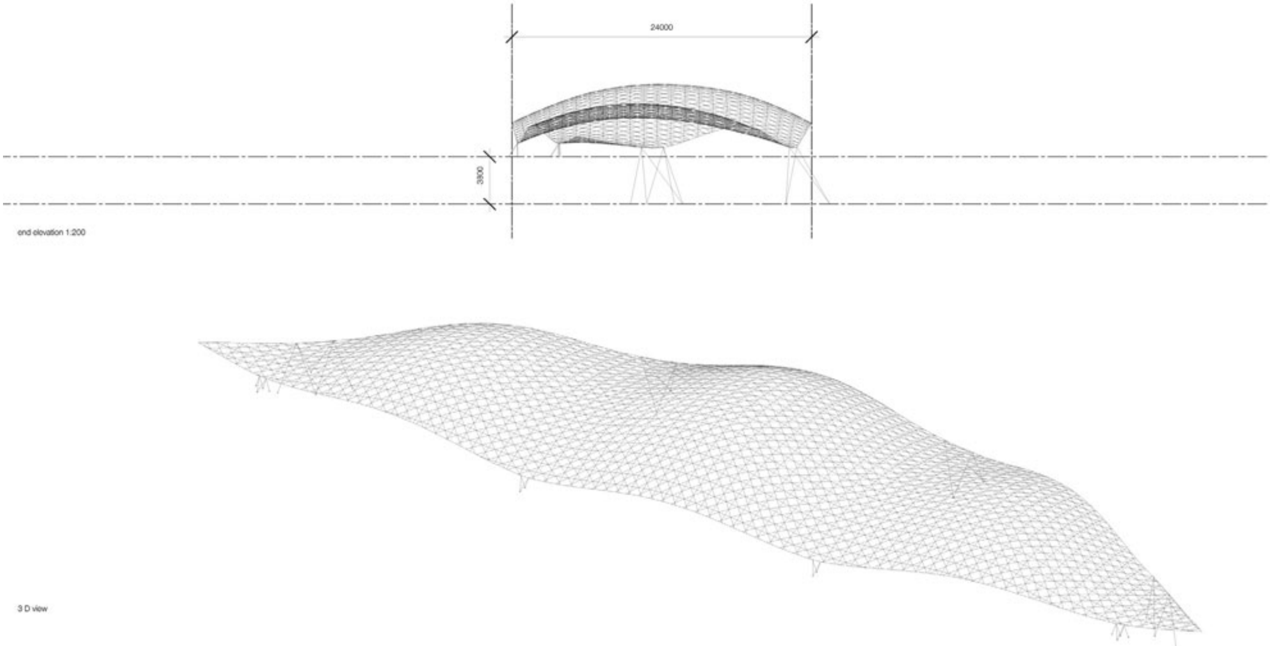

Figure 3.28 Digital three-dimensional model of the gridshell form
Source: © Glenn Howells Architects.

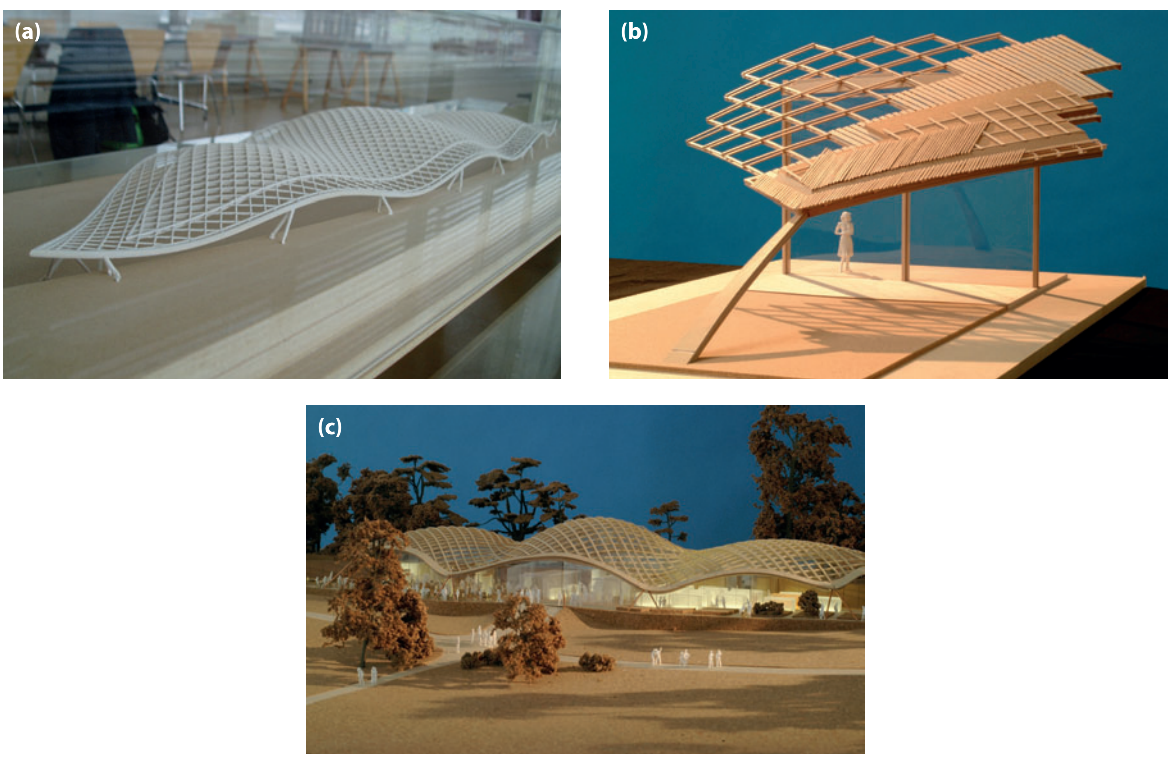

Figure 3.29 (a) A physical 3-D printed model; (b) and (c) timber models presenting the gridshell structure
Sources: (a) © Gabriel Tang; (b) and (c) © Glenn Howells Architects.

That said, sketches remained the staple of communication for innovation and problem-solving by the carpenters, the Green Oak Carpentry Company, especially in the complex detailed connection of the shell to the steel perimeter tube.

To objectively review this design, a full-sized section of the gridshell mock-up was built in a rented medieval barn in West Sussex. From these, the client and architect carefully selected the layout of shear blocks.

The roof

The previous examples of the Weald and Downland gridshell and the Mannheim Multihalle enclosed unheated spaces. The Savill Garden gridshell sees the use of timber gridshell roof for a heated space in a temperate climate.

Principally, the external appearance of the final roof finish was important, especially in the aesthetically sensitive setting of Windsor Great Park. At the competition stage, the proposed scheme prescribed a timber roof made from oak harvested from Windsor Great Park, weathering to a silvery grey and having good decay resistance.

This aesthetic consideration eventually led to a roof to sit over the larch gridshell. This consisted of internal birch-faced plywood, 160 mm insulation, aluminium standing seam roof which then supports a silvered oak rain-screen cladding, which blends into the landscape. The roof over-sails the perimeter ring beam to form a cantilever all around the gridshell.

Quite different from the Downland gridshell, the Savill Garden gridshell is a structure where, without the use of steel, the architectural concept would not have been possible. The lifting of the roof from the ground is made possible by a tubular steel ring beam 400 mm in diameter (*Architecture Today*, 2007: 72), which encloses the timber roof. Edge conditions in shell structures are important factors in gridshell design. In particular, due to the shallowness of the shell, the need for a rigid boundary to pick up loads was imperative. This was achieved through an interface of laminated veneer lumber (LVL) connection and steel flanges welded on to the ring beam (Figure 3.30). The loads were then transferred to the ground by sets of inclined quadruple legs.

The stiffest points along the perimeter are the steel bi-columned legs which attract the load. The ring beam was cut into segments of up to 13 m and connected using internal end plates and tension bolts. Access holes were cut into the tube and later sealed so that the joints then became invisible and the perimeter ring beam achieved the appearance of a complete entity. On the east elevation, the legs were shorter and attracted large moments and had to be thickened. It was then sleeved with non-circular sections with 30 mm wall thickness.

Each supporting leg consisted of two 'V' shapes, one pointing outwards and one pointing inwards. Pin connections to the top and bottom of the central garden legs hold loads up to 980kN (Harris *et al*., 2008: 34). On the west elevation facing the garden, a total of four quadruple legs up to 8 m long hold up the roof (Figure 3.31). On the east, a reinforced concrete support structure allows shorter legs to lift up the gridshell roof.

The main façade glazing is set back from the ring beam. It was calculated that at the glazing bar locations, under snow loading with drifts in the roof valleys, the roof might deflect as much as 150 mm. Conversely, when strong winds blow into the building through the glazed opening, the roof may 'inflate' with an upward deflection

Figure 3.30 Forces within the timber gridshell are transferred to the continuous cylindrical ring beam of 400 mm diameter through an interface of LVL
Source: © Glenn Howells Architects.

Figure 3.31 Each support consists of two 'V'-shaped steel legs. The roof over-sails to provide solar shading to the spaces underneath
Source: © John Chilton.

of up to 70 mm at the same location (ibid. : 31). This total movement of 220 mm was accommodated by a specially designed top bar that consisted of a double-slotted sliding connection which received the glazing (Figure 3.32).

When illuminated internally, the full drama of the gridshell can be appreciated from the garden in the late evening when it is visible through the transparent west façade (Figure 3.33).

In early 2011, a smaller gridshell was constructed by Cowley Timberworks of Lincolnshire to provide a canopy for Savill Garden to complement the original 2005 version. The smaller gridshell, measuring 11 m long

Figure 3.32 The total roof movement of 220 mm was accommodated by a specially designed top bar that consisted of a double-slotted sliding connection which received the glazing
Source: © John Chilton.

Figure 3.33 The gridshell is dramatically visible in the evening when illuminated
Source: © Warwick Sweeney.

and 3 m wide, was fabricated by Cowley Timberworks in Lincolnshire (Figures 3.34 (a)–(d)), then delivered to the site as one complete unit (Figure 3.34 (e)) (Cowley, 2012). This new timber structure forms a pavilion canopy to shelter ticket turnstiles into the Savill Gardens, providing a landmark gateway into the royal landscape.

The Savill Garden gridshell exemplifies the evolution of timber gridshells in an age of rapid technology advances. The collaborative use of steel and other materials helped the timber gridshell to 'leap off' the ground and take flight. The use of a transparent but well-insulated glazing system not only allowed the gridshell to 'hover' and enabled the landscape to flow through and across the visitor centre and in so doing, also allowed the architect to clarify and realise the original architectural intent, with an attempt to sculpt a space that is insulated and thermally sealed.

With regards to its geometrical shallowness, some might argue against the validity of timber gridshell as an appropriate structural system in this instance. Reduced curvature implies reduced stiffness since shell stiffness is primarily determined by form curvature. To the structural purist, the intention to create a gridshell that was as shallow as possible may be viewed as counter-intuitive to the structural function of any gridshell – an important reason for the use of form-active structures. A structural purist might also frown upon the use of a non-timber steel ring beam, an important structural element bearing much weight, both visually and structurally.

In such a situation, it does not, therefore, seem inappropriate to pose the question of structural purity. With steel being so prominently featured in this design, although very commonly referred to as a timber gridshell, this example changes our understanding

Figure 3.34 (a) The oak laths are cross-laid in a 500 x 500 grid over a temporary timber former. (b) The completed gridshell is attached on to the steel ring beam and completely covered by plywood. (c) Cross-battens are laid over a self-healing waterproof membrane. (d) Oak planks are screwed on to cross-battens to complete the rainscreen cladding. (e) With the oak rainscreen trimmed, the finished gridshell is delivered to site on the back of a lorry.
Source: © Gordon Cowley.

of a pure timber structure. In the wider context of technological advances, the designer is now presented with an array of materials, processes and technologies to create new architectural systems. The availability of new technologies, material and design methods, construction and manufacture must be considered to preserve the viability of timber gridshell structure application in the twenty-first century.

On this holistic note, considering all available material and alternative technologies, the following case study illustrates how glass, a material with much less design tolerance and workability, can be used in the construction of a timber gridshell in a different setting.

THE CHIDDINGSTONE CASTLE ORANGERY GRIDSHELL, KENT, 2007

LOCATED IN CHIDDINGSTONE Castle, a remodelled, Grade 1 listed, seventeenth-century house in Kent, England, the gridshell was designed to replace a roof blown down during a storm in 1987 (Olcayto, 2007: 58)

(Figure 3.35). Having an elliptical plan, measuring 12 m x 5 m, the timber gridshell supports a series of frameless glass panels that allow natural daylight to penetrate into the orangery, forming a new roof to provide shelter to the open-air space below (Figure 3.36).

Unlike previous examples in this chapter, instead of being a detached building sited in a rural or semi-rural landscape, this modestly-sized structure is located behind the parapet of an existing stone orangery (Figure 3.37). The structure is simpler, featuring a single synclastic dome.

To support the glazed chestnut gridshell, a ring beam cloaked and sandwiched in plywood sits on a colonnade of galvanised steel columns, which in turn stand on a new raft foundation. The gridshell can be seen as structurally divorced from the existing stone walls. To form the gridshell, laths of local sweet chestnut measuring 40 mm x 35 mm profile were cross-laid in four layers on a 925 mm grid with shear blocks inserted between layers (Figure 3.38). Conceptually, the gridshell acts as a framework upon which 12 mm-thick toughened glass sits. The glass rests on special clamp fixings adapted from the Weald and Downland node clamps, which also support the steel tension cable bracing without the need to drill, which would otherwise weaken the timber.

The laths were finger-jointed to form lengths between 12 m and 16 m. Due to the tight radii involved, the timber had to be split and tapered to safely facilitate bending to tight radii (Carpenter Oak & Woodland, 2015).

To brace the structure, twin 4 mm cables at alternate nodes were employed (Figure 3.39). The ring beam steel plates were laser-cut to design drawings. To connect the timber gridshell, steel brackets were used and these were all manufactured to the exact angle of incidence for the apron (Carpenter Oak & Woodland, 2015).

The erection process was carried out under protection of a scaffolding tent. Once in position, plywood was used to conceal the ring beam. The chestnut lattice was first laid out flat, at height, with nodes loosely attached and resting on the scaffolding floor. Then the chestnut lattice was lifted into position over a number of days with careful monitoring and control of the ambient

Figure 3.35 The Chiddingstone gridshell with glass covering provides a direct vertical visual connection to the skies
Source: © Carpenter Oak & Woodland.

Figure 3.36 A variation of the clamping system used in the Weald and Downland gridshell supports the glass canopy
Source: © Carpenter Oak & Woodland.

Figure 3.37 The gridshell sits within the grounds of the Grade I listed Chiddingstone Castle
Source: © Carpenter Oak & Woodland.

Figure 3.38 Elliptical in plan during construction, the gridshell required careful consideration of the historic structure with dubious structural integrity
Source: © Carpenter Oak & Woodland.

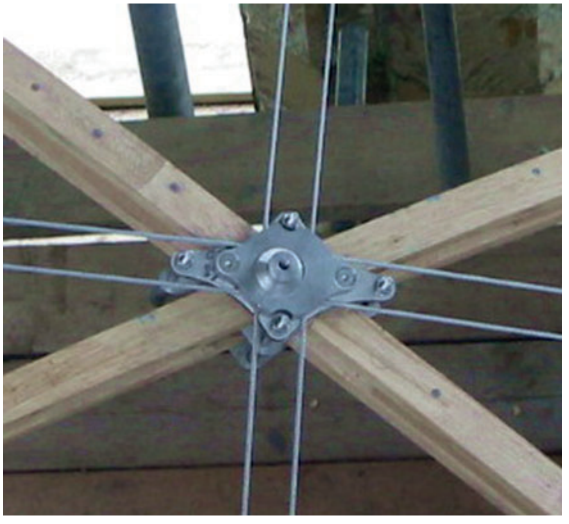

Figure 3.39 The gridshell is braced by cables designed to intersect the node clamps to provide structural stability
Source: © Carpenter Oak & Woodland.

Figure 3.40 The aproning hides the ring beam which is in turn supported by a colonnade transferring load onto the new foundations
Source: © Carpenter Oak & Woodland.

humidity and timber moisture levels (ibid.). It was noted with the temperature being high that the sweet chestnut timber was drying out rapidly, so the timber had to be moistened to maintain flexibility.

Once lifted into the correct position, node positions were verified and the clamps and bracing wires were tightened. The flat frameless glazing panels then rest upon clamp supports to seal the space beneath.

The Chiddingstone gridshell illustrates an advance in gridshell technology. The use of glass proved the possibility of combining materials with different qualities: glass (with low working tolerances) and timber (a material which is much softer and more forgiving). The timber gridshell can now visually connect the sheltered space with the outside. This project demonstrated a method of timber gridshell construction within a historic setting, existing within a historic structure made possible by careful on-site erection skills of the craftsperson (Figure 3.40).

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CHAPTER FOUR

Ribbed gridshells

THE PRINCIPLE OF the ribbed shell is a rational development of the original Frei Otto foldable lattice shell. In their multi-layer form, the separate laths of lattice gridshells have to be linked by some form of shear connection so that the parallel layers work together, in particular, to resist local bending in the surface. This shear connection has traditionally been supplied by inserting short intermittent lengths of lath between the gridshell nodes following deployment.

JULIUS NATTERER'S RIBBED SHELLS

JULIUS NATTERER, FORMER director of IBOIS, the Laboratory for Timber Construction, at the École Polytechnique Fédérale de Lausanne (EPFL) has a reputation for his numerous innovations in timber construction (Haller, 2008), many of which are illustrated in the *Holzbau Atlas*, published in English as the *Timber Construction Manual* (Herzog *et al*., 2004). His innovation in timber spatial structures was recognised, in 2014, by the award of the Torroja Medal, from the International Association for Shell and Spatial Structures (IASS, 2015). His works include shells with glue-laminated and nailed and screwed laminated ribs.

Julius Natterer's ribbed shells include several innovations. First, the shell form is constructed directly onto the final profile on temporary supports rather than being assembled flat and coaxed into the double-curved form. Therefore, unlike Frei Otto's deployable lattices, they do not need to have a regular grid. Second, thinner and wider boards are used for the laths/ribs, meaning that they are more easily bent to a curved profile and are less likely to break during bending. Third, more grid/rib layers can easily be inserted, as necessary. Finally, the space between layers and between nodes is fully filled with a short length of the same thickness plank, glued and/or nailed/screwed to the adjacent layers. The latter effectively creates a single-layer grid of intersecting and interacting, bending, stiff laminated ribs (Figure 4.1). The designer, therefore, has the freedom to explore a greater diversity of non-funicular surfaces, including free-forms, domes, rotational and saddle shapes (Natterer, 2002).

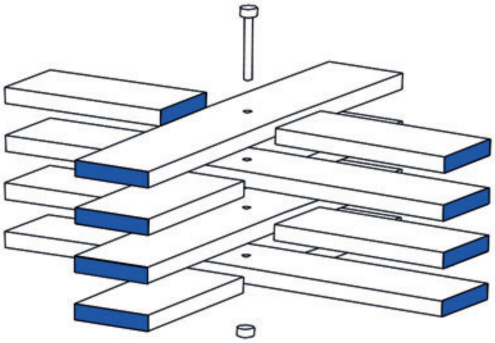

Figure 4.1 The principle of ribbed shells
Source: © Julius Natterer.

SHELL, GERMAN FEDERAL GARDEN EXHIBITION, DORTMUND, GERMANY, 1969

THE PRECURSORS OF the glued, laminated, ribbed shell principle developed by Julius Natterer can be seen in, for example, the suspended saddle-form, timber-ribbed shell pavilion for the German Federal Garden Exhibition, Dortmund, 1969 (Figure 4.2) (structural engineer G. Scholtz, Munich; consultant Natterer Bois Consult). The shell, which may better be described as a timber 'cable' net, primarily hangs between the higher supports. It incorporates 200 x 200 mm ribs at 1.5 m centres in one direction, with a span of up to 65 m between 360 x 1400 mm double-curved and twisted edge beams. It is decked with one 24 mm and two 16 mm-thick layers of boards at oriented at 45 degrees (Natterer, 2002: 120; Herzog *et al*., 2004: 263) (Figure 4.3).

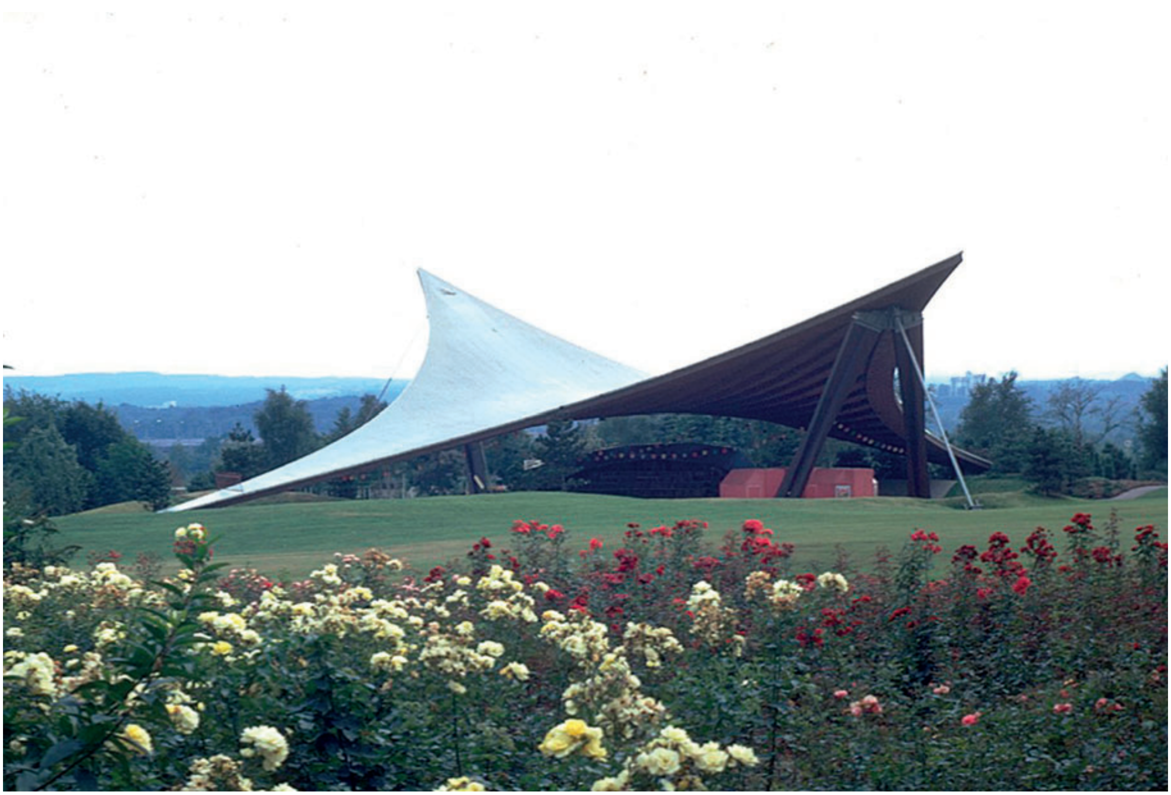

Figure 4.2 Hypar shell, German Federal Garden Exhibition, Dortmund, 1969
Source: © Julius Natterer.

Figure 4.3 Installation of one 24 mm and two 16 mm layers of deck boarding
Source: © Julius Natterer.

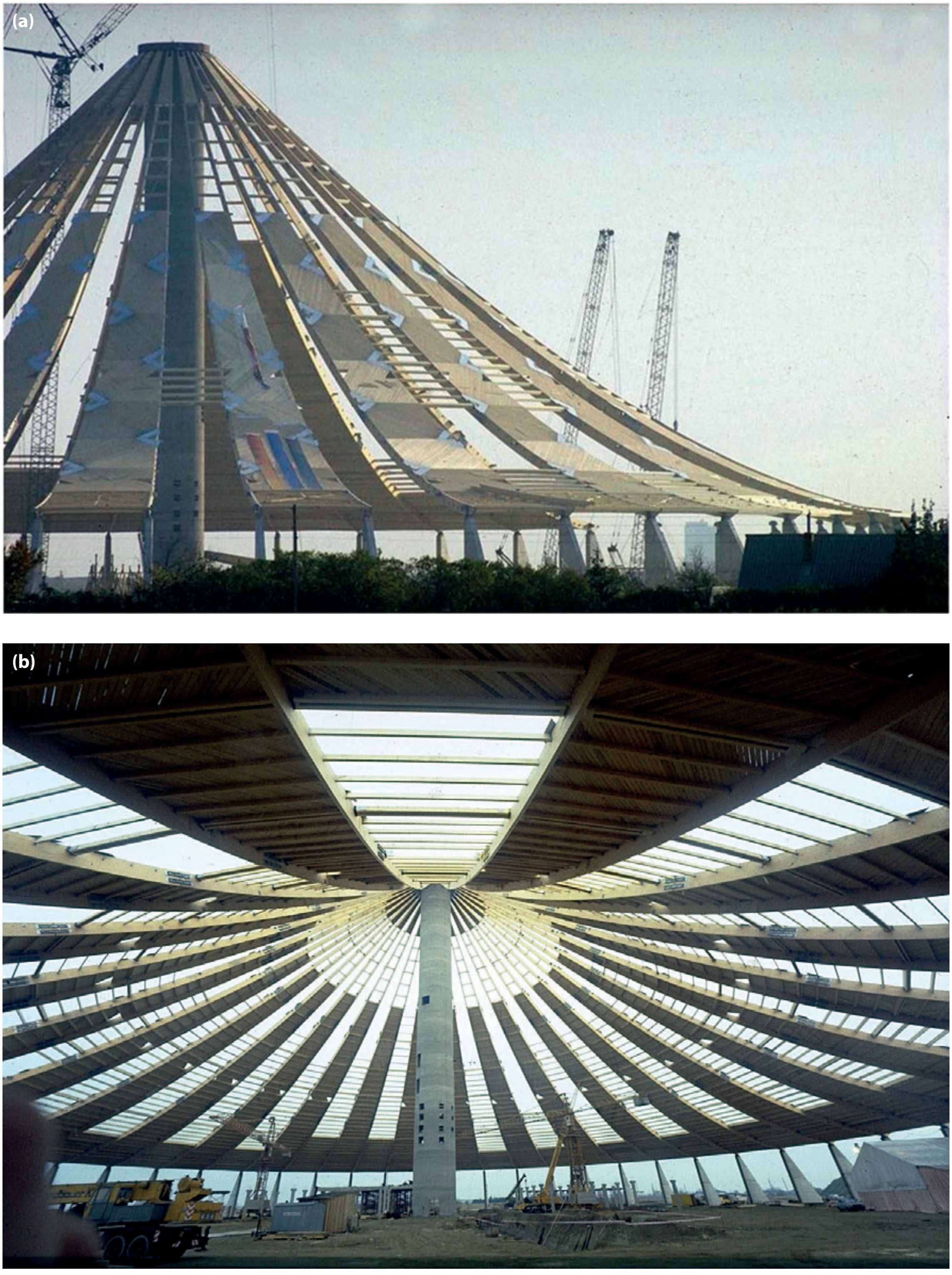

Figure 4.4 (a) Exterior and (b) interior of suspended shell, 170 m in diameter, constructed for a recycling facility in Vienna in 1981
Source: © Julius Natterer.

WASTE RECYCLING FACILITY, VIENNA, AUSTRIA, 1981

AN EXAMPLE OF a hanging ribbed shell is the 170.6 m diameter, circular roof designed for a waste recycling facility in Vienna, in 1981 – architect L.M. Lang, Vienna; structural engineers Natterer und Dittrich Planungsgesellschaft, Munich (Natterer, 2002; Herzog *et al*., 2004). Supported by a central reinforced concrete column 67 m high, the shell has 48 radial ribs varying in section from 200 x 800 mm to 200 x 1100 mm that hang like cables in tension (Figures 4.4 (a) and (b)). Annular purlins 120 x 390 mm and a layer of diagonally fixed boards create the stabilised shell (Natterer, 2002: 120; Herzog *et al*., 2004: 264).

RIBBED PLANK GRIDSHELLS

JULIUS NATTERER'S NAILED laminated ribbed plank principle can be applied at many scales and for both single- and double-curved surfaces. An example of its use as a barrel vault can be seen in a boat house constructed in Morges, Switzerland, in 1995. To maximise the usable internal space, the 60 m long, 20 m span, 12 m high ribbed shell was stabilised laterally with externally placed trusses (Natterer, 2009) (Figure 4.5).

The double-curved Polydôme, on which Julius Natterer worked with architect Badic et Associés, Morges, was constructed at the EPFL Ecublens campus in Lausanne, in 1991, as part of the 700th Anniversary celebrations for the establishment of the Swiss Confederation. Originally intended to be a temporary pavilion to be used for just one year, the dome has a

Figure 4.5 Screwed ribbed plank gridshell boathouse in Morges, Switzerland, 60 m long, 20 m span and 12 m high
Source: © Julius Natterer.

27.5 m radius spherical profile placed on a square 25 x 25 m plan (Figure 4.6).

To construct the roof, intersecting flexible planks were draped over temporary supports and built up into rib members running in a diagonal geodesic pattern (Figure 4.7). In sympathy with the load distribution within the shell, the rib density is greater on the dome diagonals. Bracing of the roof plane was provided by continuous planking screwed across the ribs on the diagonal. In total, 32 m^3 of timber planks were used to fabricate the dome (Natterer and MacIntyre, 1993; Natterer, 2002: 1423).

With the dome supported on four corner columns, the façades are open and fully glazed. The dome's functionality and elegance are evidenced by the fact that, despite the original intentions, it is still in use more than twenty years later (Natterer, 2002: 1423; Bois-consult Natterer, 2015) (Figure 4.8).

A similar 500 m^2 ribbed shell dome for an exhibition hall for handicrafts in Ober-Ramstadt, Germany, constructed in 1997, was based on a rectangular 20 x 25 m plan (Figure 4.9). Ribs were fabricated from 27 x 120 mm boards nailed together to give a total rib depth of 108 mm. As with the earlier Polydôme, the ribs were more closely spaced on the main diagonals (see Figures 4.10 and 4.11) but, in this case, glue-laminated tension beams linked the corners of the ribbed shell. The roof required approximately 50 m^3 of timber planks, representing an average of around 100 mm thickness across the surface (Bauen mit Holz, 1999).

In 1998, ribbed shell construction was also used for a 17 m x 17 m corner-supported timber ribbed dome for a kindergarten at Triesen, in the Principality of Liechtenstein (Figure 4.12). Bois-Consult Natterer SA working with architects Effeff AG were called on to create a child-friendly, low-cost solution, using local raw materials within a very short design and construction period of just 7 months. Here spaces were left between the diagonally fixed bracing planks and a covering of translucent insulation and waterproof membrane allowed natural light to filter through the roof construction (Figure 4.13).

More recently the same ribbed shell method has been used for a spherical dome for an equine therapy centre, in Uzwil, Switzerland, in 2004. Rising to 18 m, the 26 m span dome is fabricated from 60 m^3 of timber, including ribs composed of six layers of 30 x 160 mm planks. These follow geodesic lines to minimise initial internal stresses and were pre-cut using CNC equipment (Bogusch, 2005: 48). The delicate network of ribs, reminiscent of those in Nervi's Palazzetto dello Sport, in Rome, contributes to the 'healing' nature of the building (Figures 4.14 (a) and (b)).

Figure 4.6 Axonometric view of Polydôme, Ecublens, Lausanne, 25 x 25 m ribbed shell, constructed in 1991
Source: © Julius Natterer.

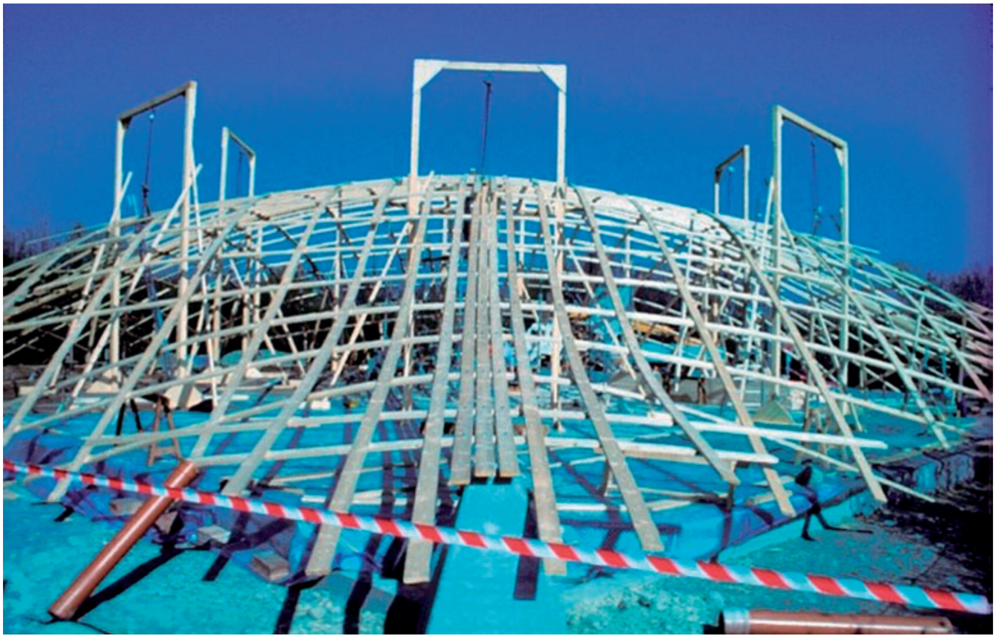

Figure 4.7 Polydôme, Ecublens, Lausanne, under construction. Rib members run in a diagonal geodesic pattern. In sympathy with the load distribution within the shell, the rib density is greater on the dome diagonals.
Source: © Julius Natterer.

Figure 4.8 Interior of Polydôme, Ecublens, Lausanne, 25 x 25 m ribbed shell, constructed in 1991
Source: © Julius Natterer.

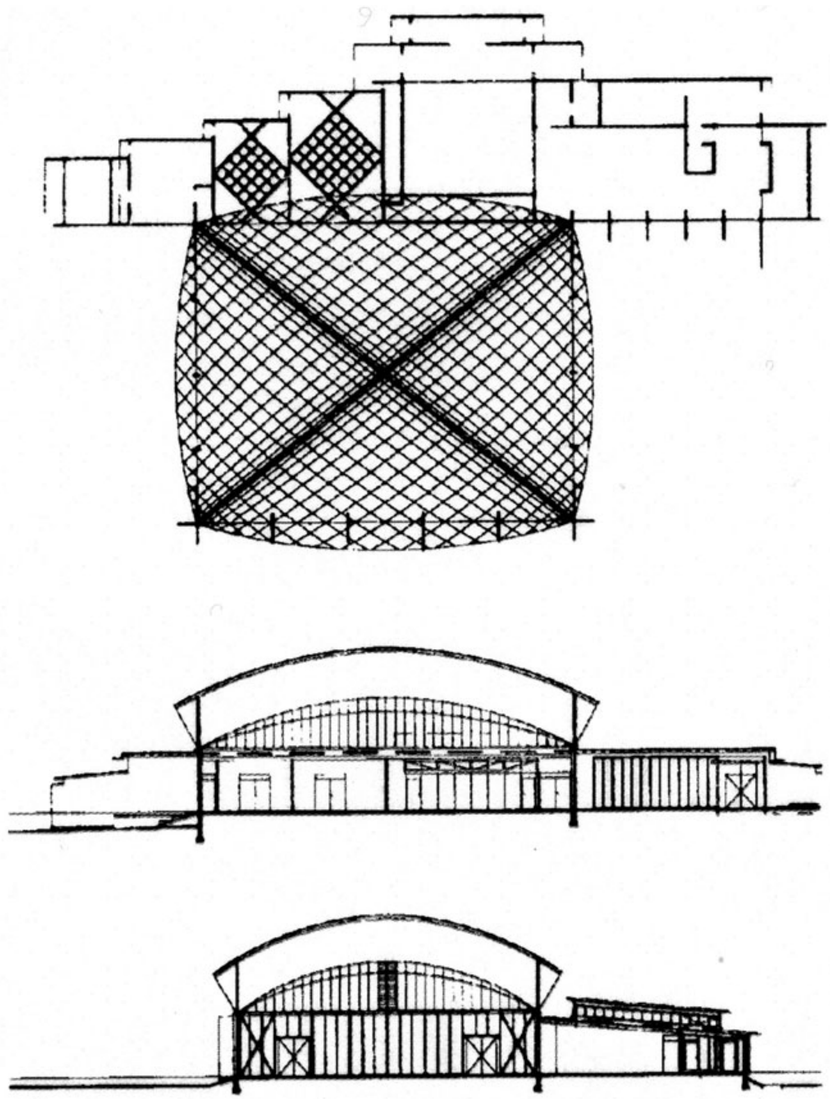

Figure 4.9 20 x 25 m ribbed shell dome for an exhibition hall in Ober-Ramstadt, Germany, 1997
Source: Drawing: © Julius Natterer.

Figure 4.10 Ober-Ramstadt ribbed shell dome under construction
Source: © Julius Natterer.

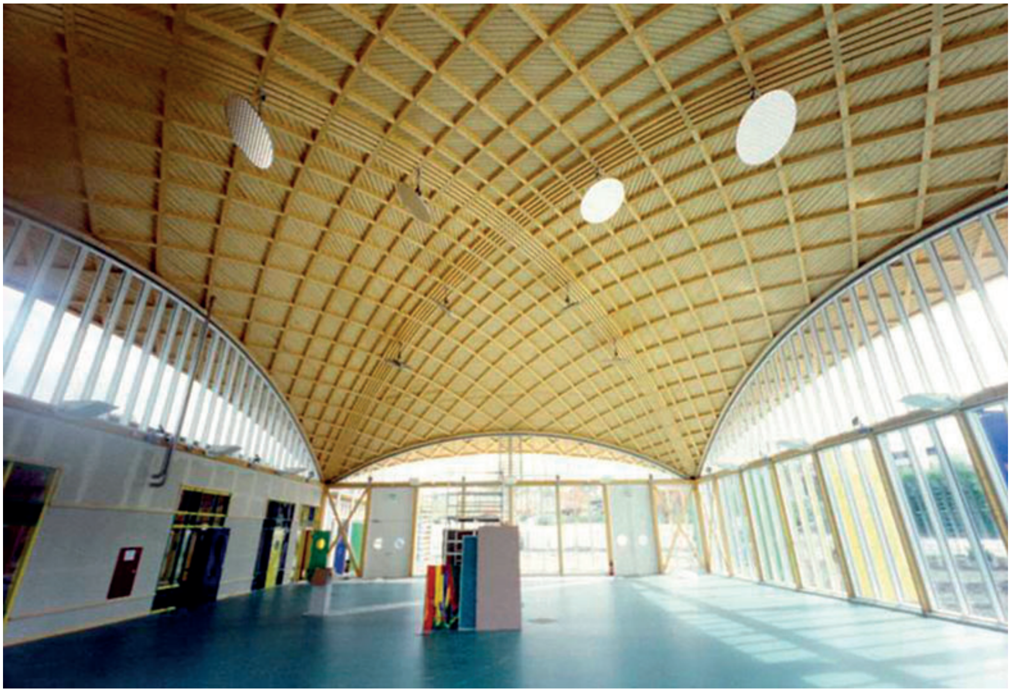

Figure 4.11 Interior of Ober-Ramstadt ribbed shell dome showing variation in rib spacing
Source: © Julius Natterer.

Figure 4.12 Exterior of 17 m x 17 m ribbed shell dome roof for a kindergarten at Triesen, in the Principality of Liechtenstein, 1998
Source: © Julius Natterer.

Figure 4.13 Interior of the 17 m x 17 m ribbed shell dome roof at Triesen, showing the infiltration of natural light through the translucent insulation and waterproof membrane
Source: © Julius Natterer.

Figure 4.14 26 m span ribbed shell dome for an equine therapy centre, Uzwil, Switzerland, 2004: (a) under construction; and (b) interior reminiscent of the reinforced concrete ribs in Pier Luigi Nervi's Palazzetto dello Sport, in Rome
Source: © Julius Natterer.

'EXPODACH', WORLD EXHIBITION, HANOVER, GERMANY, 2000

UNDOUBTEDLY THE MOST spectacular of the stacked plank ribbed shells engineered by Julius Natterer (IEZ Natterer GmbH, Wiesenfelden) are those for the 'Expodach' canopy roof, executed in collaboration with architect Thomas Herzog, Herzog + Partner Architect BDA, and constructed for the World Expo' 2000 in Hanover. As one of the world's largest timber structures, the design and construction of these shells are described in detail.

Constructed in 1999 for Deutsche Messe AG, the 'Expodach' which covered the main event area at the World Exhibition (Expo' 2000) in Hanover dramatically illustrates the alternative method for constructing a timber 'shell with holes' (Figure 4.15). In this case, the ribbed shells were constructed directly in the final curved form, assembled from both continuous and discrete elements.

Figure 4.15 'Expo-Dach' for the World Exposition Expo' 2000, Hanover
Source: © Johannes Natterer, IEZ Natterer GmbH.

Architectural design development

Conceived as an extensive, innovative, sculptural form of weather protection, the 'Expodach' roof created a high-level covering under which open-air events could be presented during and after the Hanover 2000 World Exposition. Architect Thomas Herzog's initial design sketches (Herzog, 2000: 16–17) revealed his interpretation of the main exhibition themes 'humankind: nature: technology' and the design development. The resulting architectural solution, composed of ten square-plan 'umbrella' forms, each extending approximately 40 m x 40 m and rising to 26 m above the event area, reflects nature in its resemblance to the light-filtering forest leaf canopy supported by large specimen trees. It required 'state-of-the-art' timber technology for its implementation.

Ribbed lattice shells

Each of the 40 x 40 m umbrellas is divided by two deep trusses, cantilevering perpendicular to each other and parallel to the umbrella edges. Hence they divide the larger plan into four approximately square grid/ribbed shell elements of 19 x 19 m. Although both grid and ribbed shells ultimately form a double-curved timber spatial grid, the difference between the ribbed shells used here and the gridshells of the projects described in Chapters 2 and 3 is a fine distinction primarily related to their geometry and structural behaviour. Gridshells, such as the Mannheim Multihalle, are composed of, initially flat, orthogonal, regular grids of intersecting continuous timber laths – in the case of the Mannheim gridshell these are 50 x 50 mm – connected at nodes. They accommodate rotation of individual mesh layers in the plane of the shell surface, forming diamond- or lozenge-shaped meshes, which generates curvature out of plane. This is stabilised by the addition of diagonal bracing or rigid cladding elements. In multi-layer gridshells of this type, parallel layers are subsequently connected by intermittent shear blocks to maximise the contribution of the separate layers and forming them into one structural element.

The ribbed shells of the Expodach are formed using a mix of long continuous and short infill timber elements but in this case using wider and thinner, partly wedge-dovetailed, planks of 30 x 160 mm (Herzog, 2000: 45). In highly stressed areas, laminated veneer lumber is used (Natterer *et al*., 2002: 188).

To minimise bending under its self-weight, the shell form should ideally approximate to a minimal surface similar to that taken up by a soap film between the predefined rigid boundaries. In this case, the boundaries consist of four parabolic curves, namely, the lower chords of the supporting cantilever trusses and the edge beams connecting these to the outer unsupported corner. The surface is defined using second-order parabolas suspended between the parallel cantilever and edge beams so that the vertices lie on the diagonal (Herzog, 2000: 48–49). Aligned roughly diagonally to the perimeter beams, the ribs follow geodesic lines on the double-curved surface and are, therefore, not on a regular grid. Arranged so that alternate layers intersect at right angles at each node, they are most densely spaced, at 380 mm centres, on the principal diagonal that runs from the column to the cantilevered corner, relaxing to 1600 mm centres in the more lightly stressed areas adjacent to the ends of the main truss supports (Figure 4.16).

It should be noted that the corner diagonally located with respect to the column (the unsupported corner) is not the highest point on the ribbed shell surface. That is found at the ends of the main supporting truss cantilevers. However, to avoid the impression that these corners were sagging and to reduce the possibility of water ponding on the roof surface, they were given an upward pre-camber of 150 mm (Herzog, 2000: 49). In this respect the structures resemble large leaf forms where there may be a central strong rib with double-curved membrane surfaces rising on either side to provide additional stiffness.

There are more layers here than in a 'traditional' deployable lattice gridshell – between eight and ten rather than between two and four – and, unlike the intermittent shear block of the gridshells, the full space between parallel plank layers is filled with a separate short plank which is connected by screws, bolts, dowels or gluing to the adjacent planks. However, as with more 'traditional' gridshells, a through bolt also connects the continuous planks at each node. The result is effectively a double-curved laminated timber grid of ribs 160 mm wide and 240 or 300 mm deep. Structural requirements dictate that the ribs in the direction of the principal diagonal are deeper than those in the orthogonal direction. Unlike the 'traditional' lattice gridshells, it is not possible to flatten this surface. It is not developable yet it may still be accurately described as a 'shell with holes'.

On top of the primary ribbed shell, there are two further layers of boards 24 mm deep x 100 mm wide, set orthogonally and diagonally to the ribs at a spacing of 100 mm centres (Figure 4.17). These are required to fully stabilise the shell. In the shell throat areas adjacent to the column, additional stiffening is necessary due to the high stresses and curvature. This is provided by a shell consisting of six glued layers of laminated veneer lumber (Natterer *et al.*, 2002: 188).

Each roughly 19 x 19 m ribbed shell quadrant is 6 m deep and weighs 37 tonnes (Herzog, 2000: 45). The quadrants were pre-assembled by MERK Timber GmbH

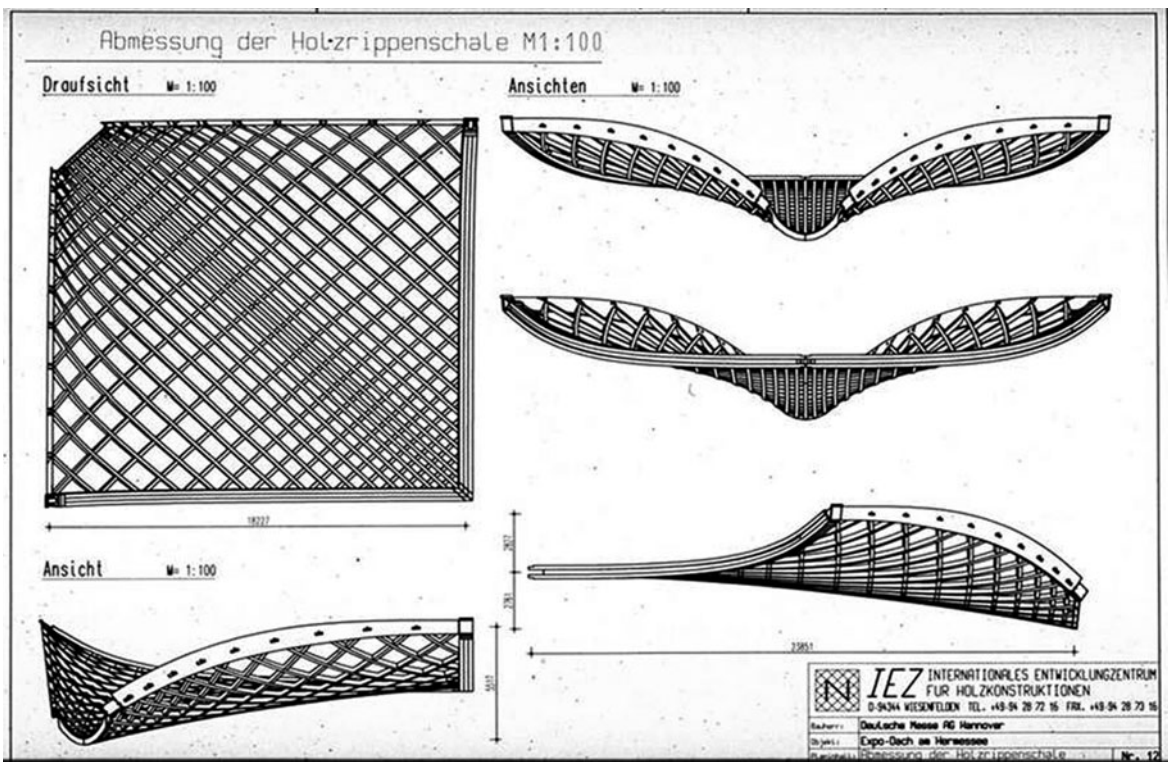

Figure 4.16 Grid geometry of one quadrant ribbed shell
Source: © IEZ Natterer GmbH.

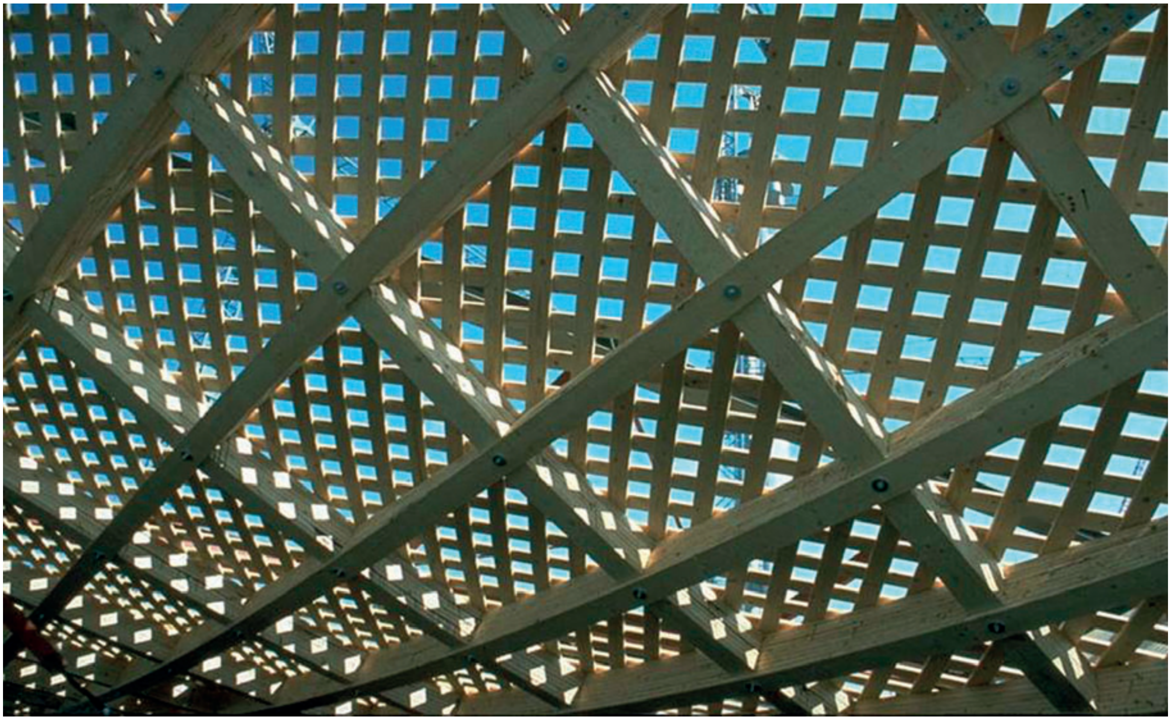

Figure 4.17 Two further layers of boards 24 mm deep x 100 mm wide, set orthogonally and diagonally to the main ribs at a spacing of 100 mm centres, stabilise the grid and support the roof membrane
Source: © Julius Natterer.

in one of the vacant exhibition halls on falsework, having a tolerance of ±2 mm from the digitally calculated geometry (Figures 4.18 (a) and (b)). Once completed, the canopy quadrants were transported to the site in one piece, craned into position and connected to the trussed cantilever arms of the supporting column (Figures 4.19 (a) and (b)). This repetition – manufacture of 40 quadrants of the same curved form and configuration – and method of assembly overcome some of the difficulties encountered in the fabrication of gridshells of similar scale.

To protect the lattice structure, the 0.9 mm-thick, PTFE-coated, glass-fibre fabric roof membrane, with a translucency of around 10 per cent (Herzog, 2000: 67) is suspended above the timber grid. The lightly pre-stressed membrane is connected to the gridshell by steel cables, which are threaded though pockets welded to its underside and also pass through 12 mm diameter eyebolts screwed into the top of the principal timber ribs. This reduces the likelihood of any condensation coming in contact with the timber and, if it were to do so, allows air to circulate freely to quickly dry any moisture (ibid.: 55).

In total, the ten canopies cover 16000 m^2 (Figure 4.20), and, according to timber construction company Merk Holzbau GmbH, around 5190 m^3 of solid and laminated timber was used, of which 1950 m^3 was boarding installed in the lattice ribbed shells (ibid.: 67). Although each canopy was designed to be independently stable, it was predicted that depending on the distribution of snow and wind loading, the differential deflection at the ribbed shell tips could be as much as 500 mm. Therefore, the individual canopies were connected, in order to better distribute the applied loads and limit maximum column loads (ibid.: 60) (Figure 4.21).

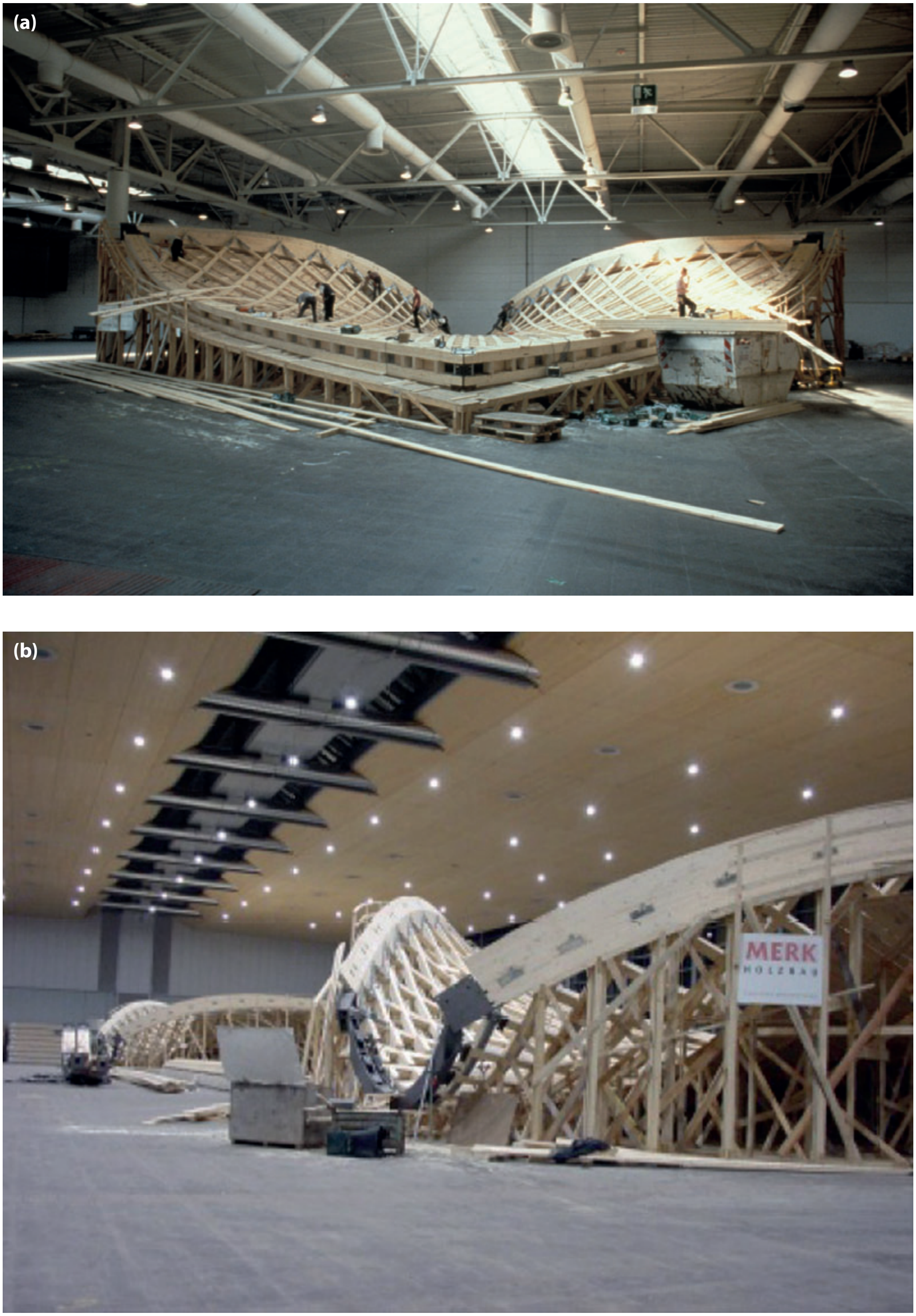

Figure 4.18 (a) and (b) Pre-assembly of grid quadrants by MERK Holzbau GmbH in a vacant exhibition hall on falsework having a tolerance of ±2 mm
Sources: (a) © Julius Natterer; (b) © MERK Timber GmbH.

Figure 4.19 (a) Transport and (b) installation of 19 x 19 m ribbed shell quadrant, 6 m deep and weighing 37 tonnes
Sources: (a) © Julius Natterer; (b) © MERK Timber GmbH.

The Expodach was a triumph for timber architecture and engineering, demonstrating to a wide international audience the flexibility and sustainability of the material used in elegant, durable and lightweight forms. Through the variable spacing of the ribs the flow of forces within the gridshells is clearly visible day and night (Figure 4.22). However, as observed by Manfred Sack in his critique of the Expodach (Herzog, 2000: 14), the roof does not appear to float but 'declares itself to be a sturdy, visibly daring, muscular structure with strangely filigree features'. But with a full understanding of its materialisation, the elegance of the solution is eventually revealed.

LAW COURT BUILDING, ANTWERP, BELGIUM, 1998–2005

Four years after completing the Expodach in Hanover, the same timber fabricator, MERK Timber GmbH, was able to use the experience gained in producing the earlier extensive ribbed gridshell canopies to construct the dramatically peaked 'sail-like' hyperbolic roof forms of the Law Court Building in Antwerp, Belgium. Designed by Richard Rogers Partnership (now Rogers Stirk Harbour + Partners) in collaboration with engineers Arup, each of the stainless steel-clad 'sails' was formed from two mirrored pairs of hyperbolic paraboloid ribbed shells

Figure 4.20 The ten canopies cover 16000 m^2 and incorporate 1950 m^3 of boarding in the lattice ribbed shells
Source: © MERK Timber GmbH.

Figure 4.21 Connection of individual roof canopies to distribute applied loads and reduce maximum column loads
Source: © MERK Timber GmbH.

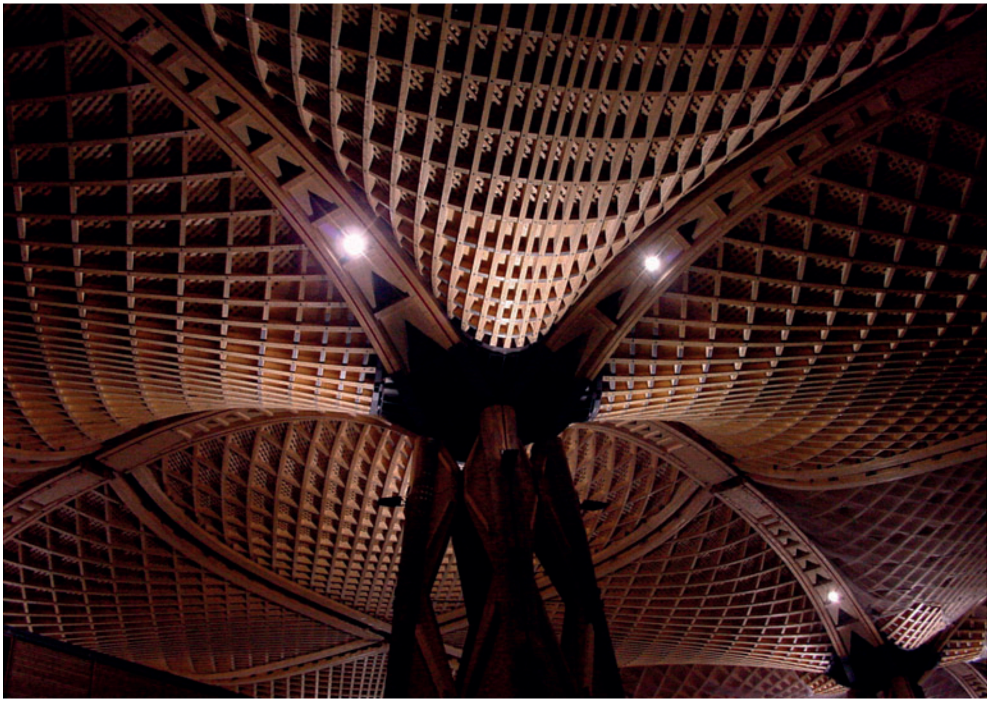

Figure 4.22 Night view of the underside of the Expo-Dach showing how the variable spacing of the ribs reveals the flow of forces within the gridshells
Source: © MERK Timber GmbH.

(Figure 4.23). Separated by a strip of glazing, the two larger shells rise to a high peak that cantilevers over two smaller low-level shells. The linking glazed surface is oriented towards the north-west to limit solar glare in the hearing rooms located below the roof (Arup, 2015; Rogers Stirk Harbour + Partners, 2015a).

Following the glued and screwed lamella construction technique used previously for the Expodach canopies in Hanover, the timber fabricator MERK Timber GmbH prefabricated the hyperbolic paraboloids ribbed shells on formwork set to the roof profile (Figure 4.24). The timber ribs were attached to a perimeter tubular steel frame. Assembly was carried out at a shipyard located several kilometres from the site. Completed shells were transported to the site using barges on the River Schelde, then on wide-load vehicles across land before being craned into position (Rogers Stirk Harbour + Partners, 2015b).

Oriented with glazed façade to the north-west the courtroom roofs are formed from four hyperbolic paraboloids. The light from the glazing strips casts shadows of the pale spruce ribs across the shell surface, emphasising its double curvature and revealing the drama of the form on the interior (Figure 4.25).

This chapter has described the fabrication of gridshells using the ribbed shell technique. Chapter 5 introduces further methods of design, manufacture and construction of gridshells and bamboo as an alternative material.

Figure 4.23 Stainless steel-clad 'sail-like' hyperbolic roof forms of the Law Court Building in Antwerp, Belgium
Source: © MERK Timber GmbH.

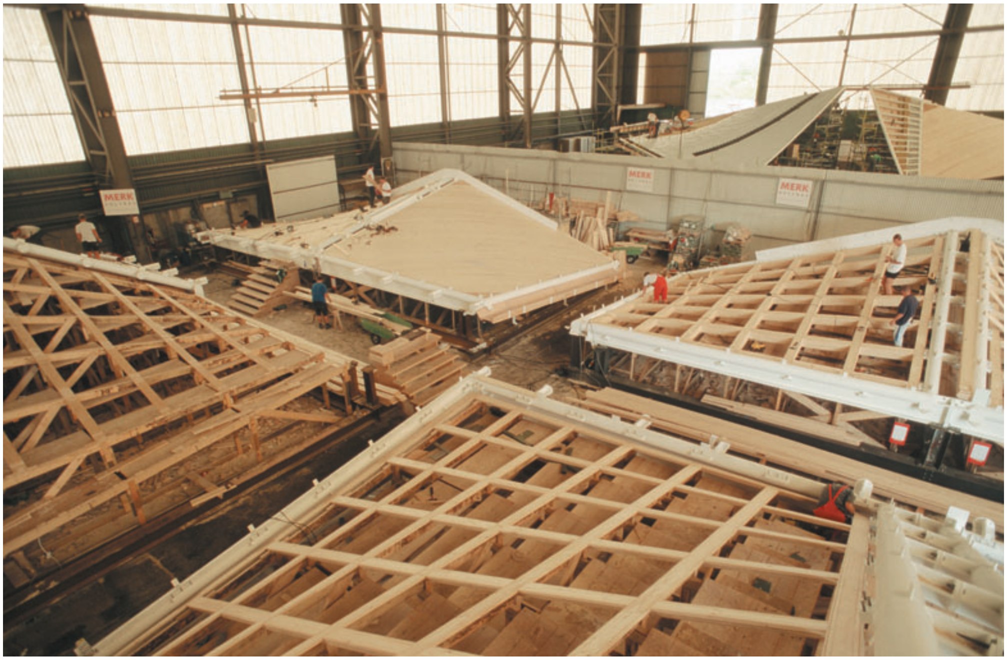

Figure 4.24 Assembling the ribbed shell hyperbolic paraboloids on temporary jigs
Source: © MERK Timber GmbH.

Figure 4.25 Interior view of the hyperbolic paraboloid ribbed shells for the Antwerp Law Courts
Source: © MERK Timber GmbH.

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CHAPTER FIVE

Alternative materials and systems

A MAJOR DISADVANTAGE of the deployable gridshells is that the grid generally has to be fully assembled before the uniform lattice is deformed into the double-curved shape. To overcome this, some gridshells have exploited the advantages of prefabrication. Small sections of the lattice are fabricated from components already manufactured to the correct shell curvature. These are then assembled to form the double-curved structure.

The first major gridshells to be constructed using this technique were three, sadly now almost forgotten, pavilions for the Silk Road Exposition held in Nara, Japan, in 1988.

SILK ROAD EXPOSITION, NARA, JAPAN, 1988

NARA IS ONE of the historic cities of Japan with many outstanding examples of ancient timber architecture including the Golden Hall of the Todai-ji Temple, the world's largest non-engineered timber building (built in the eighth century and rebuilt in the eighteenth century) and the seventh-century five-storied pagoda of the Horyu-ji Temple (Sakamoto, 1992: 109). It was, therefore, fitting when, following the success of the timber lattice gridshell for the Multihalle, Mannheim, a similar structural typology was adopted for three pavilions at the Nara Silk Road Exposition.

To protect archaeological remains at the Expo' site, strict regulations constrained foundations to a maximum of 500 mm below the ground surface (Taiyo Kogyo Corporation, 1991: 98). Hence, the architect, Takao Doi, had to resolve two conflicting demands: the need to provide wide column-free spaces while using only the minimum of foundations. Consequently, timber was chosen as the principal structural material for the Nara Pavilion, Theme Pavilion and Information Office, primarily because of its lightness and flexibility but also to reflect the timber architectural heritage of Nara in a contemporary way. The Expo's focus was captured in the gridshell form, which was reminiscent of a silk moth cocoon. While the white tensile fabric covering of the gridshells reflected the transience of the nomadic tents used along the Silk Road, it also mimicked the lightness and strength of the silk material that was being transported (ibid.: 99).

Each of the three gridshells was different in form and size (Figure 5.1). For the 1531 m^2 Nara Pavilion, 62.5 m in length and up to 32 m wide, two domed spaces were linked by a wide corridor. The 2123 m^2 Theme Pavilion was a graceful S-curve, 104.5 m long and up to 30 m wide – domed at the centre and tapering to each end. A smaller sickle-curved shell, 39.5 m long, was the Information Office.

The timber chosen for the shells was *sugi* (*cryptomeria japonica*), Japanese cedar, symbolically the national tree, which is frequently associated with sites of religious significance in Japan. Constructed as a double, in total four-layer, grid with a lath cross-section of 70 mm wide and 40 mm deep, on a 500 mm grid and with single bolted node connections, the gridshells were engineered by Takenaka Corporation (designers T. Maeno, M. Wada, T. Nagase and T. Hisatoku) with structural advice from the renowned Japanese engineer Gengo Matsui (Melaragno, 1991: 110; Sakamoto, 1992: 115). Although superficially very similar, the major difference between the Nara and Mannheim gridshells was the size and shape of the laths. At Mannheim, these were 50 mm x 50 mm with a cross-sectional area of 250 mm^2, whereas in Nara they were 70 mm x 40 mm with a cross-sectional area of 280 mm^2 (Figure 5.2). The wider and thinner laths used in Nara facilitated their bending and the larger cross-section increased their resistance to compression. The assembly and erection techniques were also different. The Mannheim gridshells were assembled as a flat grid over an extensive area and then pushed up from below. In contrast, the Nara gridshells used pre-bent laths with a minimum radius of curvature of 10 m (Melaragno, 1991: 110). These were assembled into 4 m-wide prefabricated sections that were then craned into position and connected, in the air, using steel sleeves and pins/dowels/bolts (Herzog *et al.,* 2004: 257).

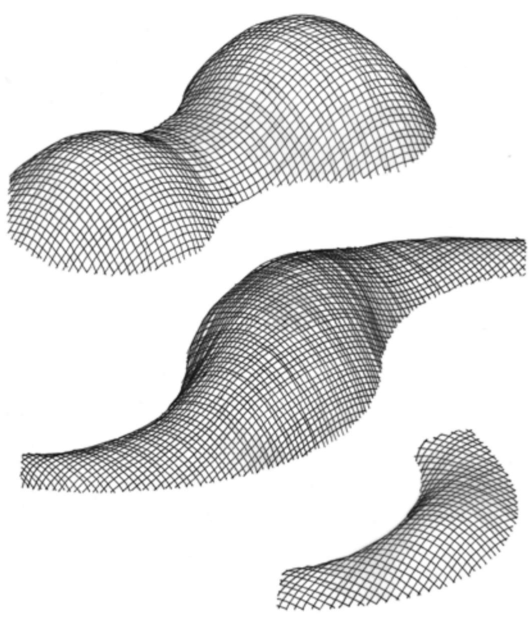


Figure 5.1 Forms of the gridshell for the Nara Pavilion (top), Theme Pavilion (middle) and Information Office (bottom) at the Silk Road Exposition, Nara, Japan, 1988
Source: © Gabriel Tang, after ja+u (Japan architecture + urbanism) (1992).

As Sakamoto (1992: 115) comments, the architect Takao Doi and structural designers should be given credit 'for introducing attractive large wooden lattice shell structures to Japan, where natural conditions such as earthquakes and typhoons are very severe and design regulations are very strict'. It is, therefore, sad that these were only temporary pavilions and had already been demolished by the time Sakamoto was writing, only four years after their construction.

In his essay 'Sustainable architecture' (Shoei Yoh + Architects, n.d.), the Japanese architect Shoei Yoh (1940–) champions the advantages of optimum three-dimensional forms, and their use in combination with natural materials such as timber and bamboo for the construction of self-build community facilities. He emphasises the benefits of these materials in reducing embodied energy in construction, for the efficient use of locally grown natural resources and for the social benefits of employing local craftspeople. A number of projects employing timber or bamboo are described, three of which incorporate single layer gridshells.

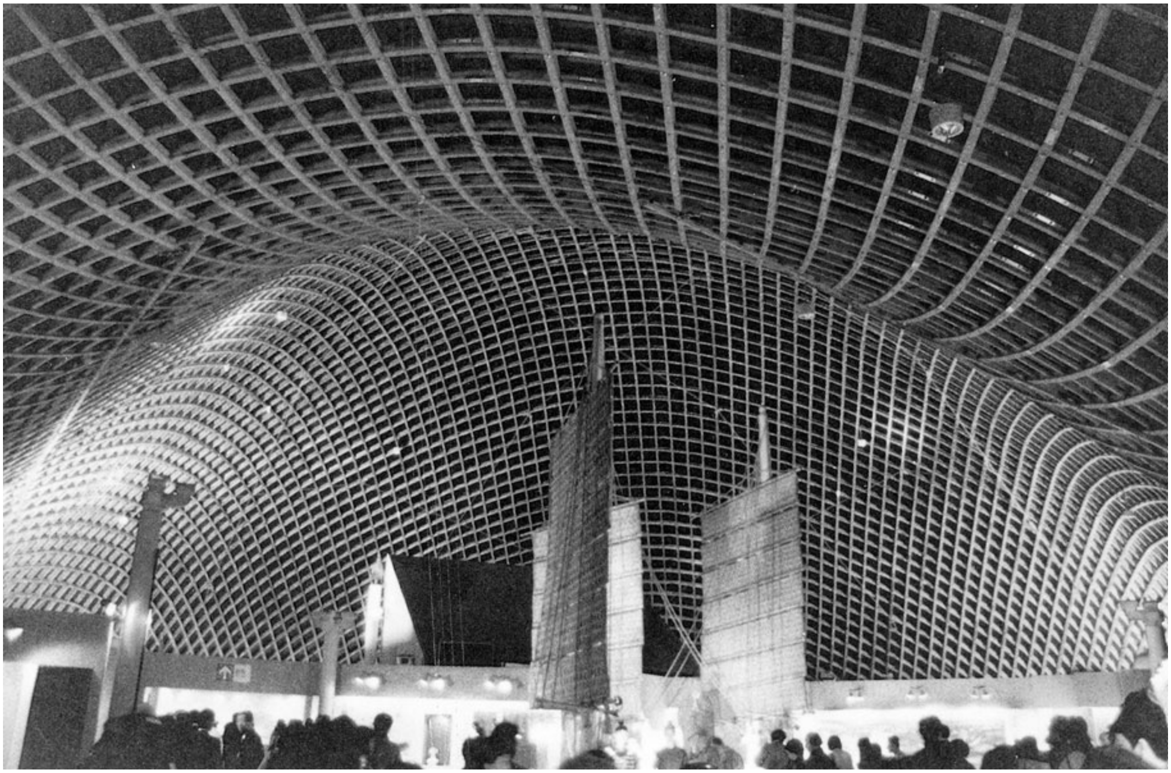


Figure 5.2 Interior of the Nara Pavilion at the Silk Road Exposition, Nara, Japan, 1988
Source: from Sakamoto (1992: 116), courtesy of the International Association for Shell and Spatial Structures.

MERMAID BOWL, EXPOSITION OF SEA AND ISLAND, HIROSHIMA, JAPAN, 1989

A YEAR AFTER the Nara Silk Road Expo, an Exposition of Sea and Island was held in Hiroshima, Japan. Here, informed by their experience with the double-layer timber space grid of the Oguni Dome, Kumamoto Prefecture, Kyushu, Japan (Chilton, 2000: 75–78) completed in 1988, Shoei Yoh, working with engineers Gengo Matsui and Masao Saito, selected a suspended timber gridshell for the roof of the Mermaid Bowl. Employed as the main performance stage, with a covered area of approximately 40 m diameter, the grid was suspended from a central steel lattice truss arch and supported on a tubular steel perimeter beam (Figure 5.3). The membrane-covered shell was composed of twin 100 mm x 100 mm timbers separated by 100 mm, on a 1.8 m mesh grid (ja+u (Japan architecture + urbanism), 1992; Sakamoto, 1992: 116–117). In this case, the two grids, one each side of a tubular steel truss arch, have anticlastic curvature so that the ribs in one direction are hanging (in tension) under self-weight loads while in the direction they are arching (in compression).

An interesting difference in this shell, compared to those built previously, is that the grid-line timbers are not continuous (or at least are not long compared to the mesh spacing). Unusually, like links in a chain, they are in straight lengths of approximately 3.6 m coupled with bolted steel plates at the mid-points between alternate mesh nodes, see Figure 5.4. The two orthogonal layers are also linked by 6 mm-thick profiled steel plate connectors fastened with a single 20 mm bolt at intersection points. This means that, effectively, the shells are made from prefabricated '#'-shaped units. This might be seen as a logical progression from the prefabricated assembly method used for the Nara Silk Road Expo gridshells, perhaps inspired by the timber engineer Gengo Matsui, who was involved in both projects (Shoei Yoh, n.d.).

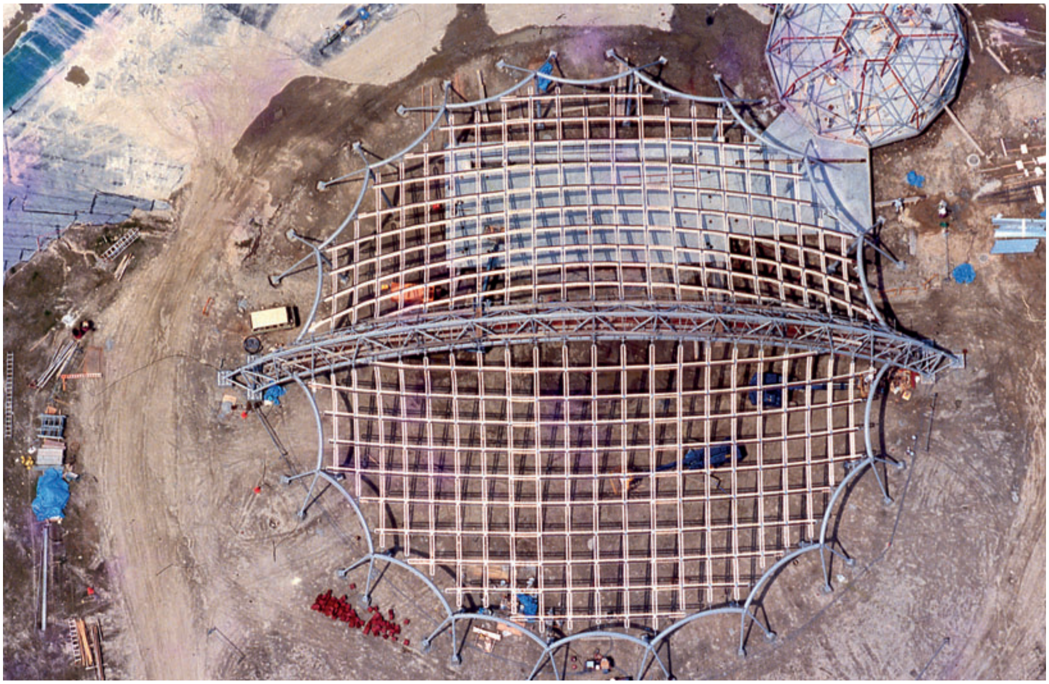


Figure 5.3 Plan view of timber hanging grid of the Mermaid Bowl, Exposition of Sea and Island, Hiroshima, 1989, during construction
Source: © Shoei Yoh + Architects, Fukuoka, Japan.

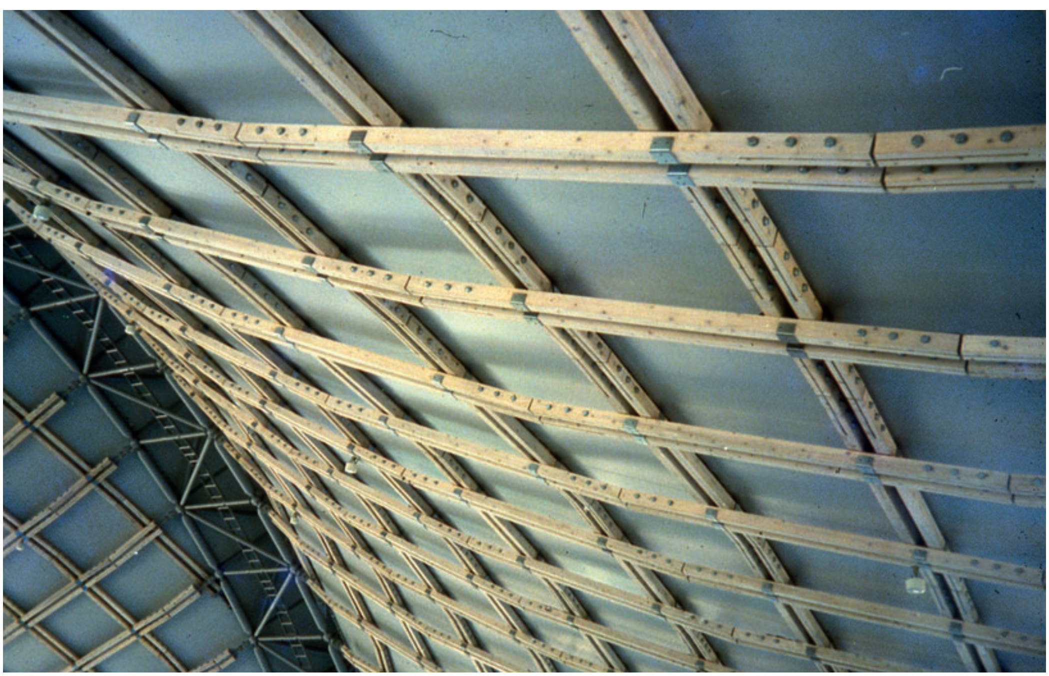


Figure 5.4 Interior of the Mermaid Bowl roof showing the chain-like mesh of straight timber elements connected longitudinally at alternate midpoints between nodes and transversely at each intersection
Source: © Shoei Yoh + Architects, Fukuoka, Japan.

NAIJU COMMUNITY CENTER AND NURSERY SCHOOL, FUKUOKA, JAPAN, 1994

ALTHOUGH THIS BOOK is primarily devoted to the use of timber in gridshell architecture, it is also considered appropriate to include examples employing other bio-based materials such as bamboo. One such example is Shoei Yoh's Naiju Community Center and Nursery School, Chikuho, Fukuoka, Japan, completed in 1994 (Shoei Yoh + Architects, n.d.; Stungo, 1998).

This project is innovative on a number of levels: the use of bamboo rather than timber (a locally available material), the basket-like weaving of the grid, the manner of forming, the cladding material and the final structure. Assembled on the ground by weaving split bamboo laths, the deployable grid was lifted by crane (Figures 5.5 (a)–(c)). It was then propped up at the centre and

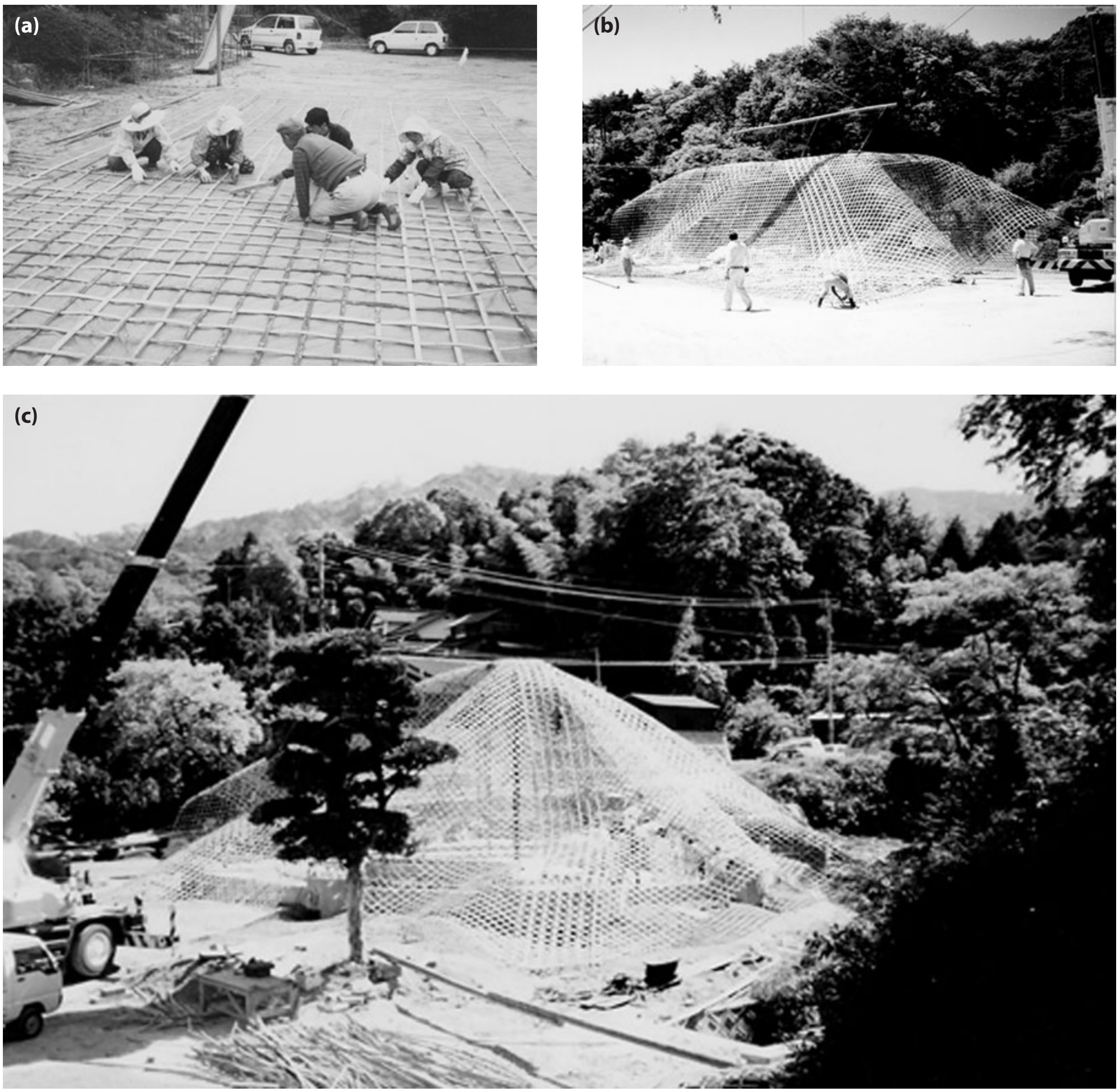


Figure 5.5 (a) Assembling the bamboo for the grid of the Naiju Community Center; (b) and (c) lifting the grid by crane
Source: © Shoei Yoh + Architects, Fukuoka, Japan.

adjusted to form an intricate folded surface, much like a tent draped over a central pole (Figure 5.6 (a)). Once raised to its full height, the grid was covered with fabric membrane and coated with reinforced concrete (Figures 5.6 (b) and (c)).

After the hardening of the concrete, the central support was removed, thereby transferring the load to the exterior reinforced concrete shell and leaving the gridshell as a permanent formwork displayed on the interior to reveal the forming process (Figure 5.7).

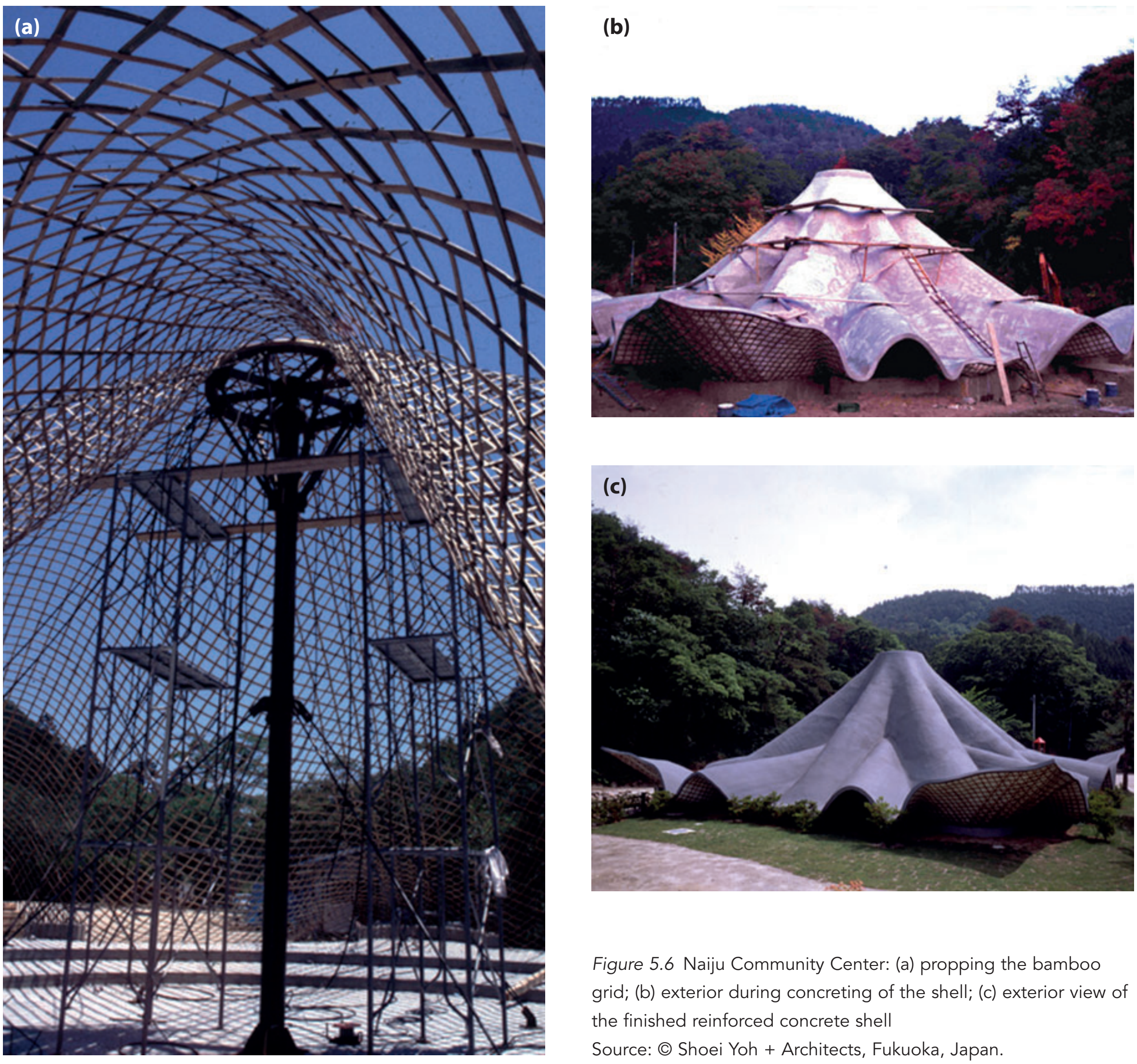


Figure 5.6 Naiju Community Center: (a) propping the bamboo grid; (b) exterior during concreting of the shell; (c) exterior view of the finished reinforced concrete shell
Source: © Shoei Yoh + Architects, Fukuoka, Japan.

Figure 5.7 Interior of the Naiju Community Center, showing the bamboo gridshell used to form the exterior reinforced concrete shell
Source: © Shoei Yoh + Architects, Fukuoka, Japan.

UCHINO COMMUNITY CENTER, FUKUOKA, JAPAN, 1995

THE FOLLOWING YEAR, Shoei Yoh used a bamboo gridshell as formwork again in a community centre for elderly people and young children at Uchino. Here he applied his theory of topological optimisation that he had developed during his design of a roof in Toyama, in 1991, which was automatically generated by the distribution of the snow load (Shoei Yoh + Architects, n.d.). Designed as a partition-free space apart from some private rooms, the apparently random ceiling height is derived logically, varying in proportion to the distance between opposing perimeter columns (Figure 5.8). An initially square bamboo grid was distorted to form the three-dimensionally curved surface, which was used as formwork to cast the reinforced concrete roof shell (Figure 5.9).

FLIMWELL WOODLAND ENTERPRISE CENTRE, KENT AND SUSSEX BORDERS, UK, 1999

THE MAIN FEATURE of Flimwell Woodland Enterprise Centre is the five arched timber gridshells, each measuring 6 m wide, that house the centre (Figure 5.10). Located in the Weald Woodland south of Tunbridge Wells in England, this is a built winning entry for a design competition in 1997, which stipulated the use of chestnut hardwood that is plentiful in the locality (Saunders, 2015a). The new visitor centre combines an exhibition/conference area with offices on two floors for organisations involved in forestry. It is intended to promote the interaction between forestry-based organisations and commercial timber-based industries as well as to showcase the application of timber products.

The brief for the Wood Enterprise Centre was, first, to demonstrate the use of species/sizes of trees typical of the surrounding woodland and, second, to build it to a budget of approximately £1,000/m^2.

Feilden Clegg Bradley's design (Figures 5.11 (a) and (b)), engineered by Atelier One, was chosen because their entry clearly demonstrated the use of local coppice and small-diameter softwood thinnings, much in the spirit of the inspiring pioneering work carried out by John Makepeace and the architects at Hooke Park on a realistic budget.

At the initial stages of design, the proposed building was a series of six adjoining single-curved parabolic barrel vaults with individual structurally independent bays. This was eventually revised to five gridshell bays, each measuring 6 m wide and spanning 12 m across. Each module was formed on site and was bounded on both long edges by a parabolic glulam arch. They were raised onto propped eaves beams with machined, rounded, external diagonal struts, sawn from local Scots pine (Braden, 2001).

The chestnut hardwood (*castanea sativa*) was coppiced from the site. The suitability of this timber depended on factors such as grain direction and knot ratio and, as such, required an experienced assessor. After suitable timber was selected, it was cut and sent to Newcastle (to the only UK facility available at the time) to remove defective knots where subsequently the timber was finger-jointed to form 10 m-long laths. To form the gridshell, these were bolted at 600 mm centres (Saunders, 2015b).

The construction effectively demonstrated the versatility of coppiced chestnut timber. The gridshell lattice chestnut laths were made from fencing-quality timber sawn into 100 mm x 25 mm random-length planks (Figures 5.12 (a) and (b)). The chestnut coppices produced a high yield of straight-grained timber with minimal knots, compared to the older growth of oak and chestnut wood. In all, 2 km of timber staves were created with 2,500 finger joints. Impressively, there were only two failures observed during installation (Braden, 2001). Glue-laminated chestnut was also used for external joinery.

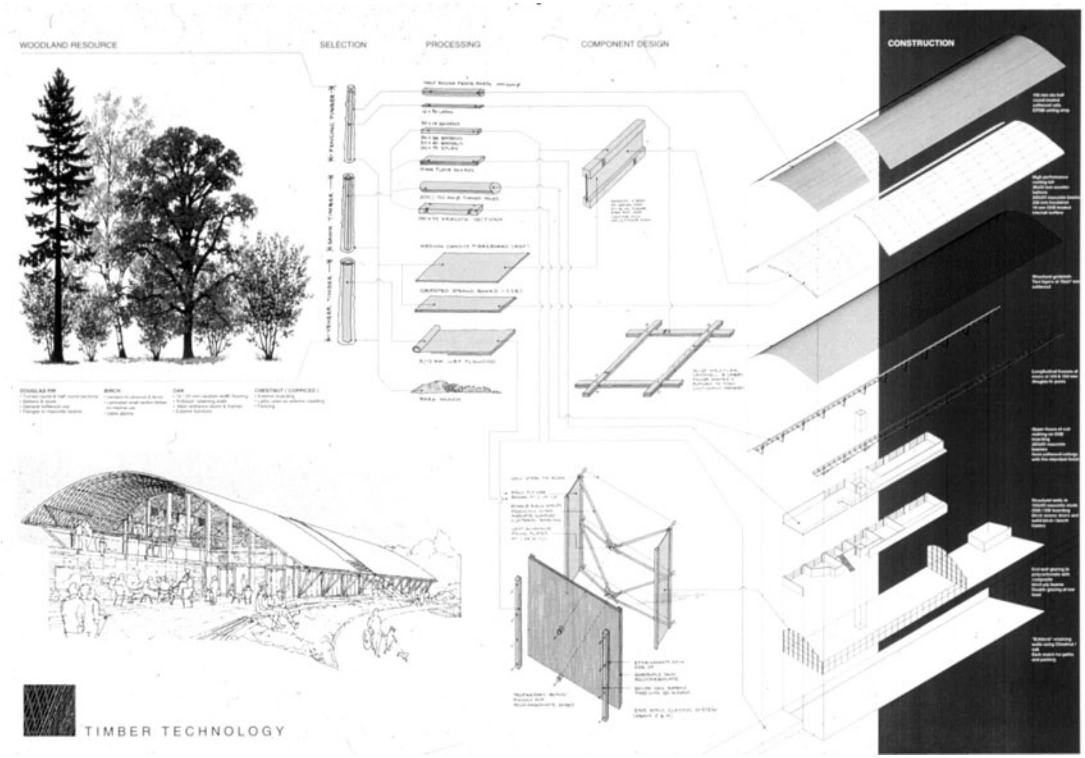
Because the form of the gridshell was less complex, the re-formed 10 m-long chestnut laths were pre-drilled to tight tolerances and site-assembled at ground level before being lifted into position. The lattice work was formed on site by Cowley Timberworks Ltd (now Cowley

Figure 5.8 Exterior view of the reinforced concrete shell roof of the Uchino Community Center, Fukuoka, 1995, formed using a bamboo gridshell
Source: © Shoei Yoh + Architects, Fukuoka, Japan.

Figure 5.9 Interior view of the Uchino Community Center, showing the permanent bamboo gridshell formwork
Source: © Shoei Yoh + Architects, Fukuoka, Japan.

Figure 5.10 Gridshell roof of the Flimwell Woodland Enterprise Centre, Kent and Sussex borders, UK
Source: © Woodnet.

(a)



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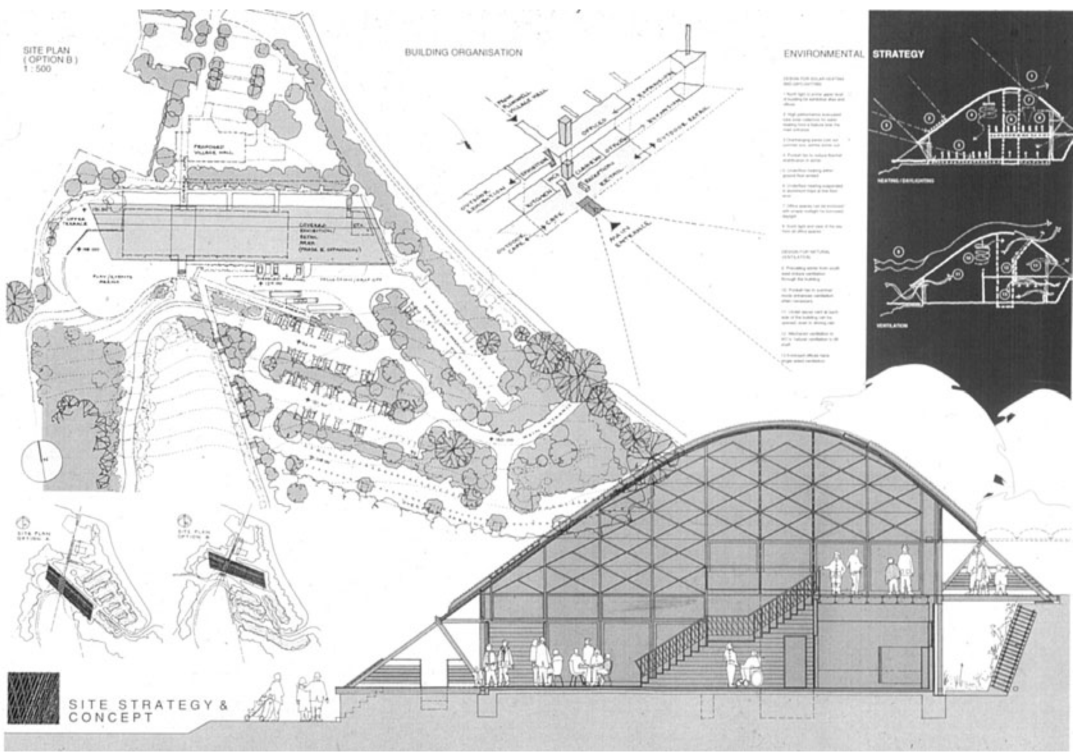


Figure 5.11 (a) and (b) Feilden Clegg Bradley's design for the Flimwell Woodland Enterprise Centre
Source: © Feilden Clegg Bradley Architects.

Figure 5.12 (a) Assembly of chestnut gridshell; (b) installation of plywood decking
Source: © Woodnet.

Timber + Partners) from Lincolnshire. By crossing the two layers of chestnut lathes spaced 600 mm apart, a gridded lattice surface was formed between the two edge glulam arches that were temporarily held apart with timber beams as seen in Figure 5.12. The chestnut lattice was locked into position by bolts. The pertinent problem of introducing natural daylight in a gridshell is solved by the articulation of the different modules which incorporate glazed strip skylights between each structural bay. A design iteration of the gridshell concept was to suspend these between curved glulam arches. This reduced the structural 'purity' of the gridshell concept, as the roof loads were partially carried by the arches, but this move simplified the construction with Cowley Timberwork assembling the frame and roof modules in just a few weeks (Figures 5.12 (a) and (b)).

Woodnet funded the testing of the coppiced timber at the Building Research Establishment, and also accelerated weathering trials to prove the durability of the Collano polyurethane glues with this type of

Figure 5.13 (a) Interior and (b) exterior views of completed Flimwell Woodland Enterprise Centre
Source: © Woodnet.

timber that has a relatively high moisture content, but it has performed well up to the time of writing. Another development related to the structural use of sweet chestnut – a species of timber local to the area, generally grown as coppice on a 15–25 year cycle, but rarely used in the UK for construction (Braden, 2001).

The building has a reported cost of £650/m^2 at 2001 prices, comparing well with conventional building costs.

BEATFUSE!, NEW YORK, USA, 2006

CONCEIVED BY OBRA Architects, a practice founded in New York City in 2000 by Pablo Castro and Jennifer Lee, Beatfuse!, in 2006, was the winner of an international competition for a temporary installation, organised jointly by the PS1 Contemporary Art Center Long Island City and the Museum of Modern Art, New York (OBRA Architects, 2006a). Comprising 10 gridshells in total, seven of which partially covered a large triangular courtyard gallery, the structures were named 'concertina' by the architects, due to their ability to fold (Figures 5.14 (a) and (b)).

Initially, the dynamic curved shell forms were modelled digitally. An approximately 600 mm x 600 mm (2′ x 2′) diagonal grid was then superimposed. The resultant mesh was flattened and produced, fashioned from 6.4 mm (¼′) thick luan plywood CNC cut into strips 114.3 mm (4½′) wide (OBRA Architects, 2006b) (Figures 5.15 (a) and (b)).

The slenderness of the 6.4 mm-thick plywood strips is evident in Figure 5.16 (a) but once all the strips are installed and they are bolted at the intersections, on the irregular grid, structural stability is restored (Figure 5.16 (b)). This is an example of the structural efficiency of timber gridshells where, in this case, the maximum span of the plywood strips is over 1000 times their thickness.

Rather than a continuous cladding, the gridshells are covered with hexagonal scales of polypropylene mesh, each attached to the structure at just one point. This provides the necessary shade, and also reduces uplift and lateral wind forces on the temporary structure (OBRA Architects, 2006b) (Figures 5.17 (a) and (b)).

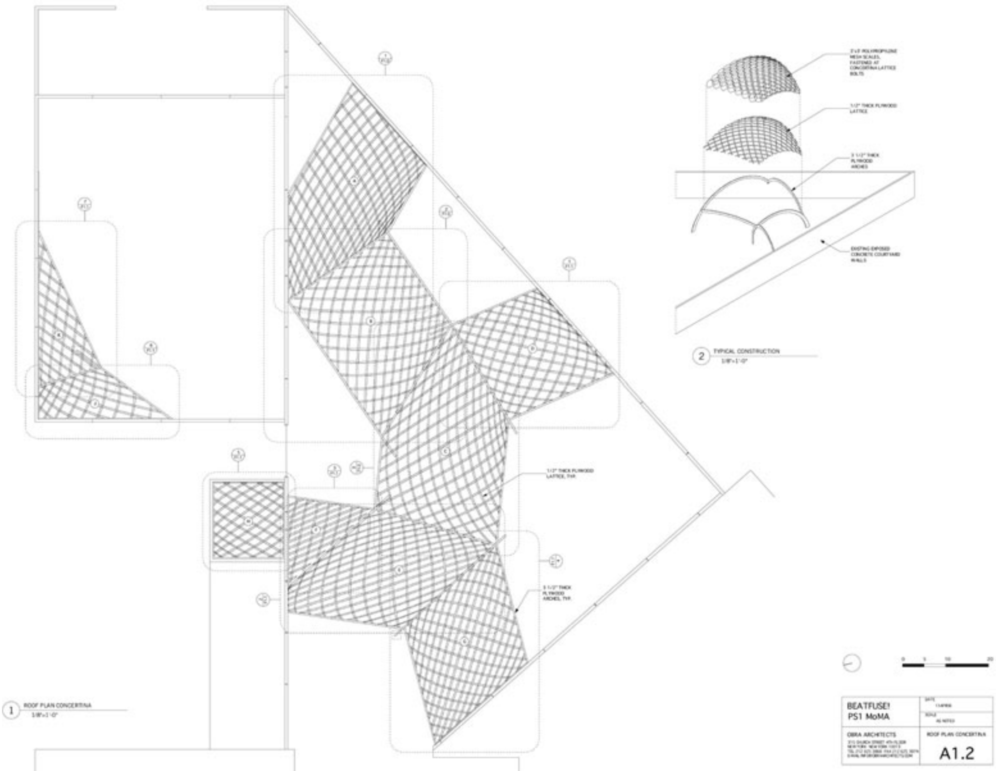
WAITOMO GLOWWORM CAVES VISITOR CENTRE, OTOROHANGA, WAIKATO, NEW ZEALAND, 2010

THE CANOPY ROOF of the award-winning Waitomo Glowworm Caves Visitor Centre, Otorohanga, Waikato, New Zealand, completed in 2010, integrates one of the lightest and most translucent architectural cladding materials, ethylene-tetra-fluoro-ethylene (ETFE) foil, with one of the lightest and most sustainable structures, a timber gridshell (Figure 5.18). It is claimed that this gridshell is the first in the southern hemisphere (ACENZ, 2011).

Taking inspiration from the Hinaki or Maori woven eel trap, Wellington architect Architecture Workshop's concept for the gridshell form reflects the underground cave space (Figure 5.19). Having an arched cross-section and a plan that follows the curve of the adjacent Waitomo stream to connect the structure to the water that flows through the caves, the resulting roof form is toroidal (Figures 5.20 and 5.21) (Architecture Workshop, 2012).

The grid is based on one of the geodesic patterns which can be drawn on the surface of a toroid or doughnut (Figure 5.22). In this case, Architecture Workshop and structural engineer, Dunning Thornton Consultants, selected a grid of orthogonally intersecting diagonal spirals aligned at 45˚ to the principal generatrix of the torus. This allowed a regular grid geometry and repetition of individual ribs, which each follow the same curve. As the ribs span diagonally along geodesics, rather than parallel to the principal curvatures of the toroid, they twist along their length to remain perpendicular to its surface (Figure 5.23). This avoided the need to bend ribs about two axes as well as twist them, as they were permitted to 'relax' into a slight S-shape (Figure 5.24). This aided positioning before the bolting of nodes

(a)



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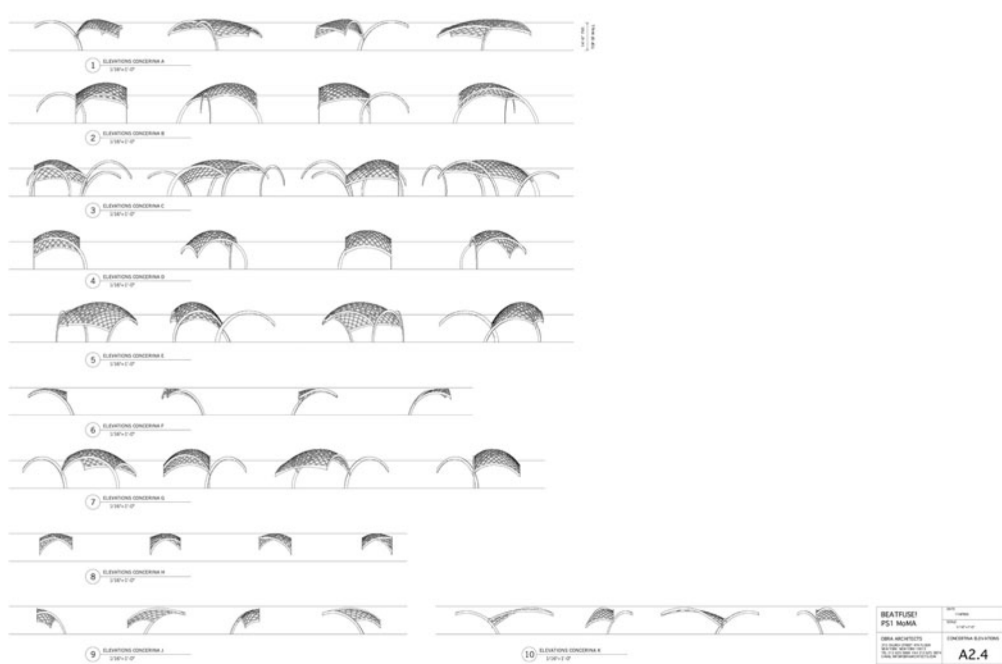


Figure 5.14 (a) Plan and (b) multiple sections of the Beatfuse! temporary installation at PS1 Contemporary Art Center, Long Island City, New York
Source: © OBRA Architects.

Figure 5.15 (a) CNC-cut 6.4 mm plywood strips 114.3 mm (4½′) wide; (b) supporting arch frames
Source: © OBRA Architects.

Figure 5.16 (a) and (b) Assembly of the 6.4 mm-thick plywood strip gridshell
Source: © OBRA Architects.

Figure 5.17 (a) and (b) Completed Beatfuse! gridshells showing the lightweight canopy and the pleasant shade produced
Source: © OBRA Architects.

Figure 5.18 ETFE-clad, laminated, timber gridshell canopy for the Waitomo Glowworm Caves Visitor Centre, Otorohanga, Waikato, New Zealand
Source: © Architecture Workshop.

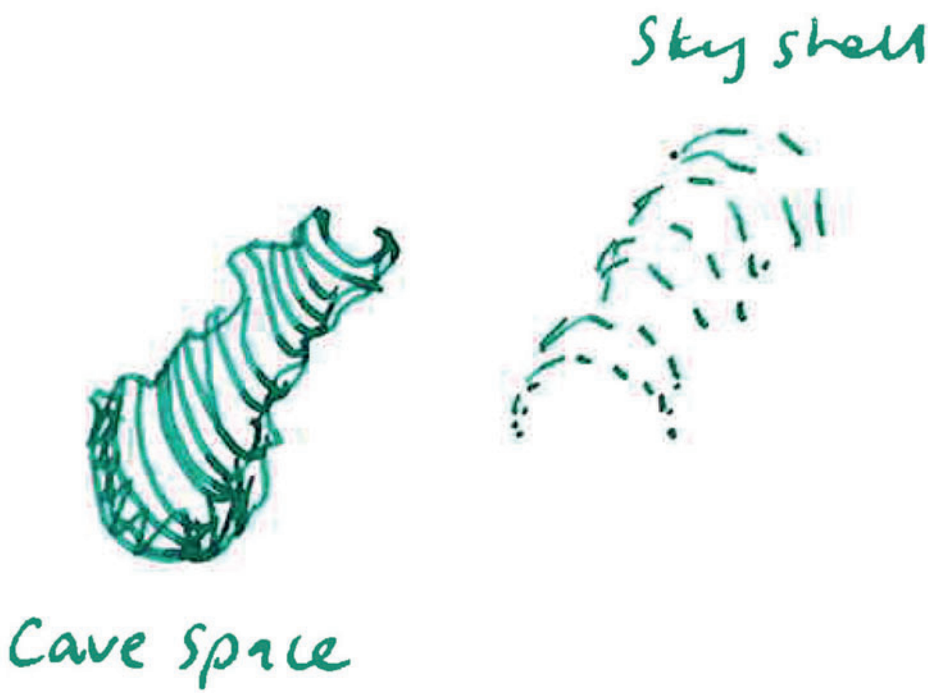


Figure 5.19 Concept sketch for gridshell (skyshell) reflecting the eroded cave space below ground
Source: © Architecture Workshop.

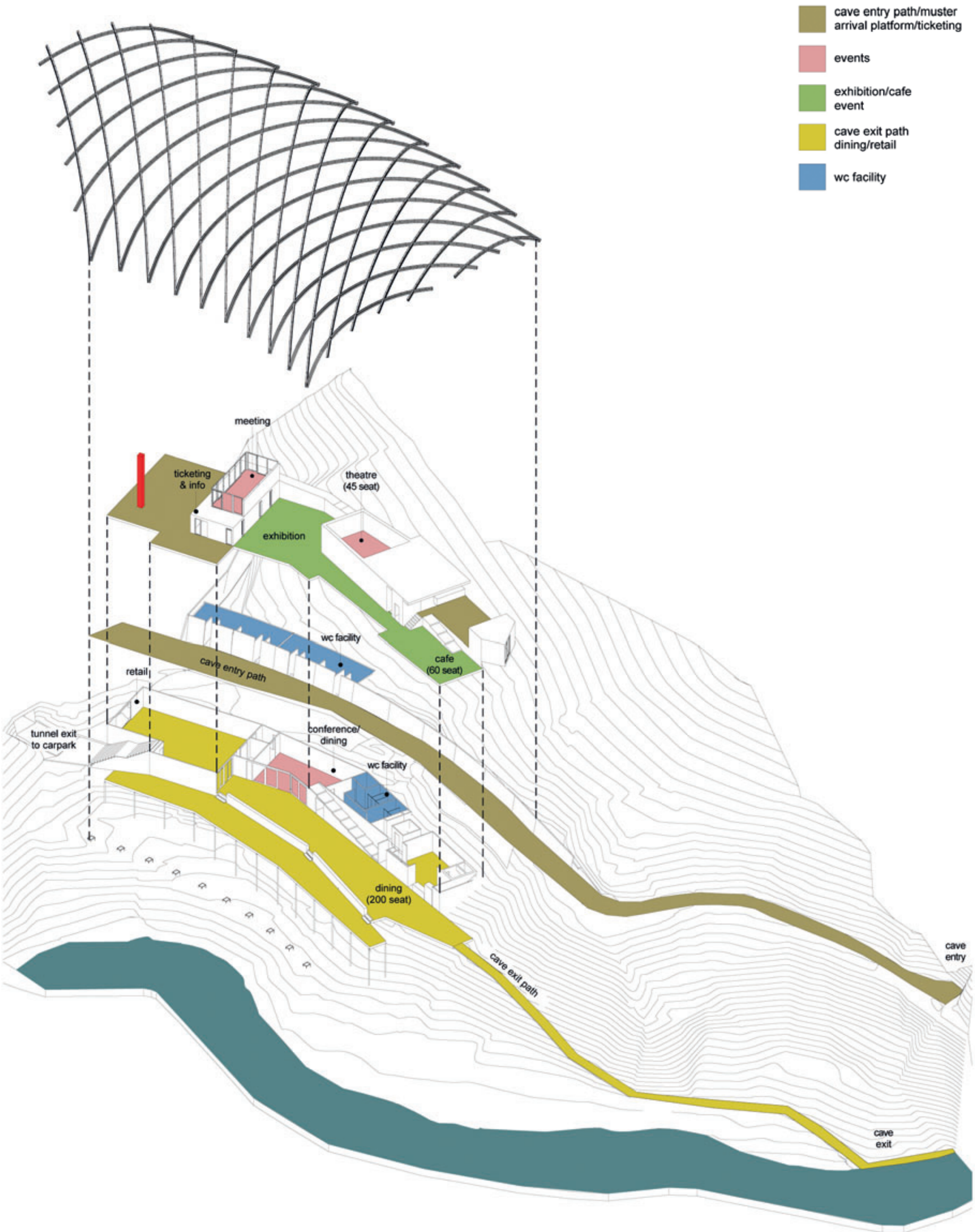


Figure 5.20 Axonometric showing relationship of the gridshell to site contours and the adjacent stream
Source: © Architecture Workshop.

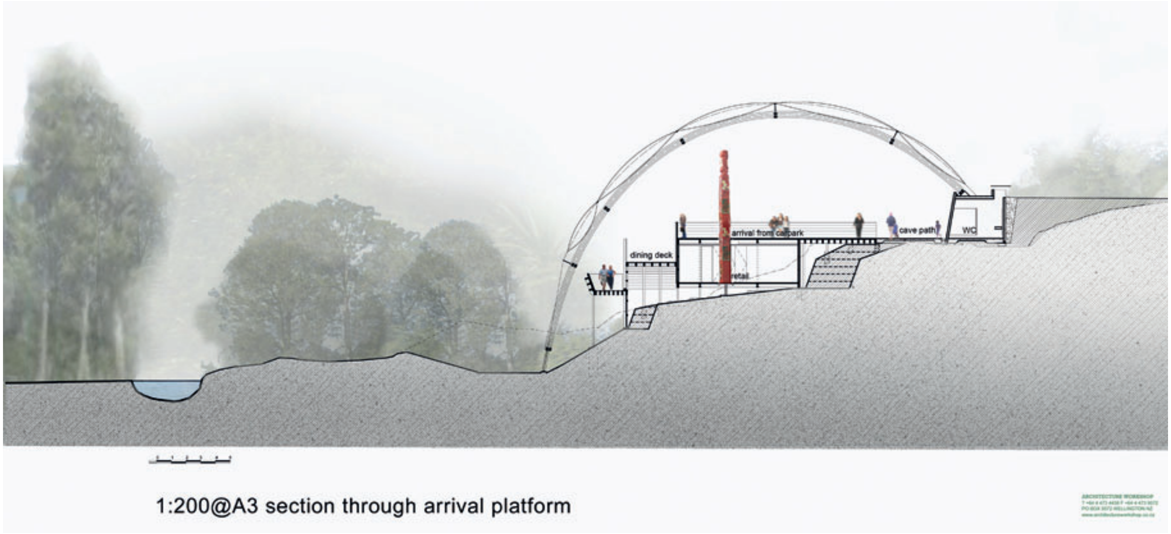


Figure 5.21 Site section showing relationship of the gridshell to the adjacent stream
Source: © Architecture Workshop.

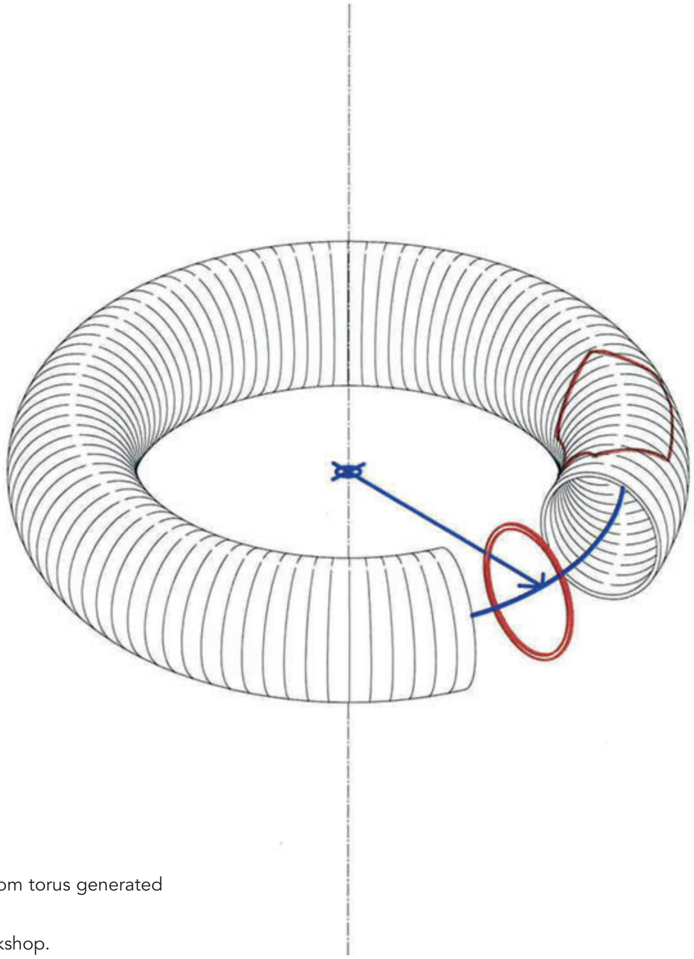


Figure 5.22 Roof grid cut from torus generated
by rotation of an ellipse
Source: © Architecture Workshop.

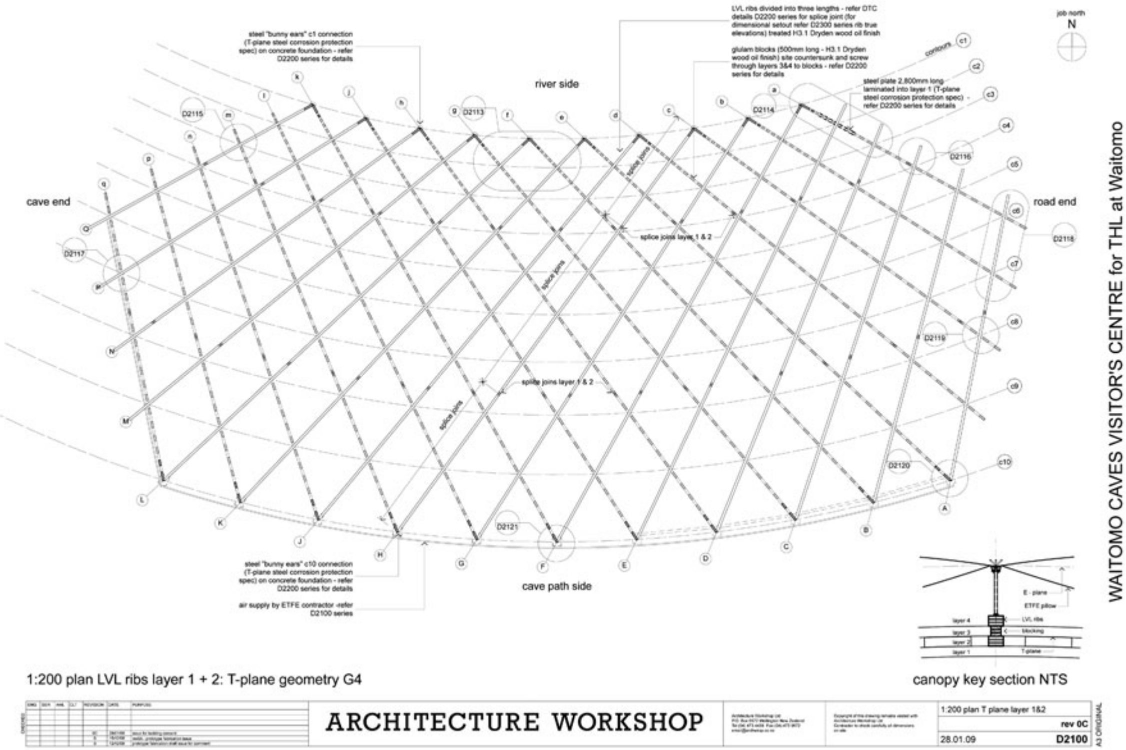


Figure 5.23 Plan on roof grid
Source: © Architecture Workshop.

Figure 5.24 Twisted beam 'relaxed' into an S-shape
Source: © Architecture Workshop.

(Dunnington Thornton and Architecture Workshop, 2009; NZ Wood, 2011).

Prefabricated from laminated veneer lumber (LVL) manufactured from Radiata pine, the 324 mm-deep double ribs with intermediate glue-laminated block spacers are connected at the nodes using a single 20 mm diameter bolt. Each layer of the 28 m-long ribs was fabricated in up to three sections, by Hunter Laminates Nelson Ltd, from three layers of 160 x 36 mm (ex 170 x 39 mm LVL) glue-laminated to predetermined curve and twist (Figures 5.25 (a) and (b)).

It is interesting to note the contrast of this technique – assembly of pre-formed curved elements – with that of the more traditional gridshells – deformation of an initially flat grid. The sections were joined, interlaced and screwed together during assembly on site by Hawkins Construction. Clamping the discontinuous blocks between upper and lower ribs induces Vierendeel action to transmit local loads to the grid nodes. Structural analysis and design of the grid were carried out by Dunning Thornton Consultants, in Wellington, and reviewed by Buro Happold in London (Architecture Workshop, 2012).

The ETFE cladding is in the form of inflated cushions or pillows. However, although the timber gridshell forms a regular and similar trapezoidal pattern between the curved ribs, the cushions do not fill individual grids but are raised above the shell. This allows the use of larger cushions, which span continuously and diagonally between the gridshell perimeters. At each grid intersection and intermediate points along the top lamella, in one of the grid directions, 33.7 mm diameter steel struts support curved aluminium extrusions approximately 500 mm above the timber ribs (Figure 5.26). The profile, which as with the timber ribs has to twist along its length, then clamps the long ETFE cushion boundary. In total, there are 14 cushions. The eight central cushions are made to the same geometry and there are three different forms at each end of the gridshell.

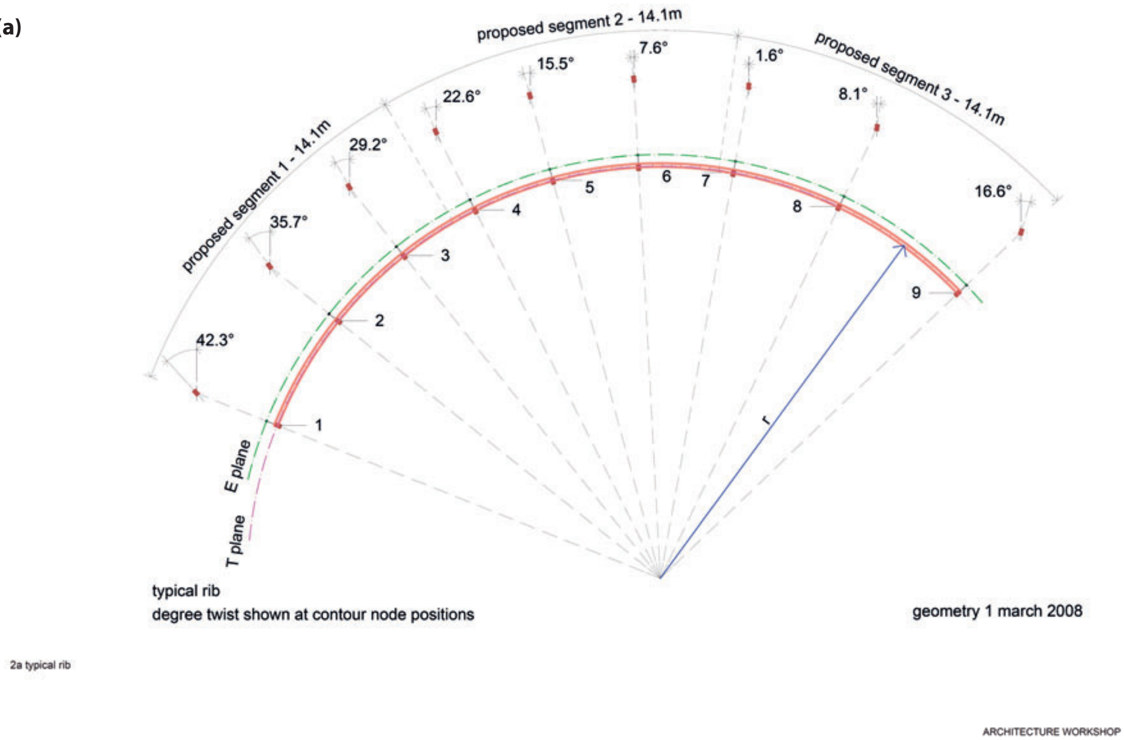
The 4.25 m grid is stabilised with double stainless steel diagonal ties between selected nodes (Figure 5.27). Exposed to view and in close proximity to the hundreds of thousands annually who visit the caves (one of New Zealand's top tourist attractions), the canopy structure is elegantly detailed, articulating the flow of forces within the grid. Edge cables stressed between adjacent timber rib nodes tension the short cushion edges (Figure 5.28 (a)). By using single long cushions following the diagonal flow of one grid direction, the inflation tubes can be located at one end, thereby minimising the air distribution system. The only visible components are flexible tubes emerging from behind a retaining wall to the side of the cave path (see section in Figure 5.21) and located either side of the upper gridshell support shoes (Figures 5.28 (b) and 5.29). This maintains the clarity of the timber grid by eliminating the possible visual intrusion that a more extensive system passing along the grid members might have introduced.

As noted in Chapter 1, timber gridshells are strongly related to traditional woven structures and in this case the roof canopy has been likened to the woven form of the Maori eel trap (NZ Wood, 2011). However, the segmented curved form of the canopy and its ETFE cushion cladding may perhaps be seen as a biomorphic reference to the glow-worms that inhabit the caves, which are the larval stage of a gnat, *Arachnocampa luminosa* which has a segmented wormlike form.

Highly regarded, the project has received a series of design awards: Association of Consulting Engineers New Zealand Gold Award of Excellence 2011; New Zealand Institute of Architects, Architecture Medal 2011; Local Architecture Awards 2010; Australia New Zealand, Timber Design Awards 2010; NZ Wood, Timber Design Award 2010 (Figure 5.30).

With the increasing application of digital design and fabrication, architects and engineers are no longer dependent on the regular grids of the early gridshells. This design constraint has been removed and complex double-curved surfaces can be manufactured and built directly. Recently there have been some inspiring applications of these new technologies in small-scale and interior gridshells, an outstanding example being for Hermès, in Paris.

(a)



(b)

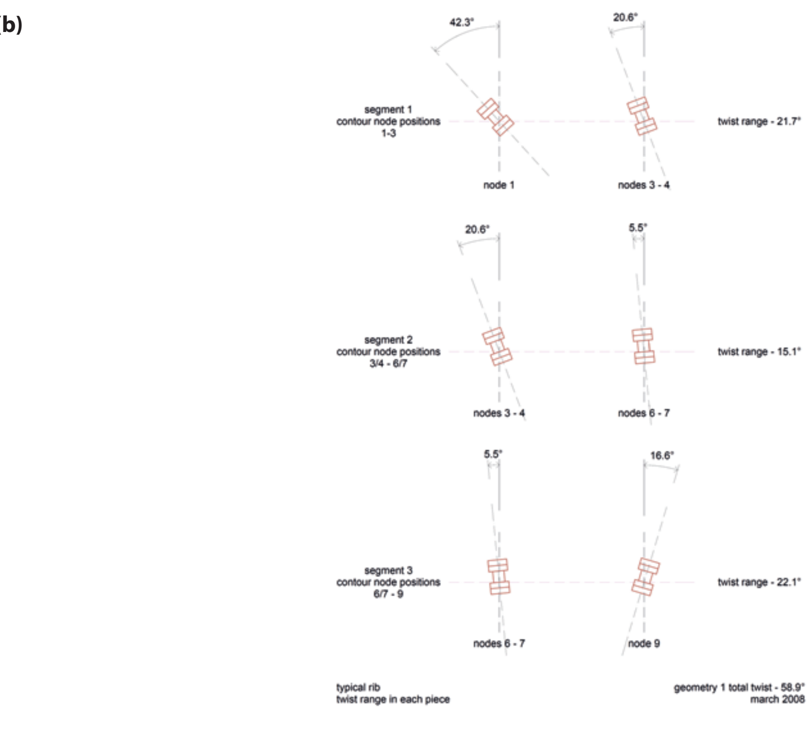


Figure 5.25 (a) Typical rib divided into three segments; (b) angle of twist at positions along the rib
Source: © Architecture Workshop.

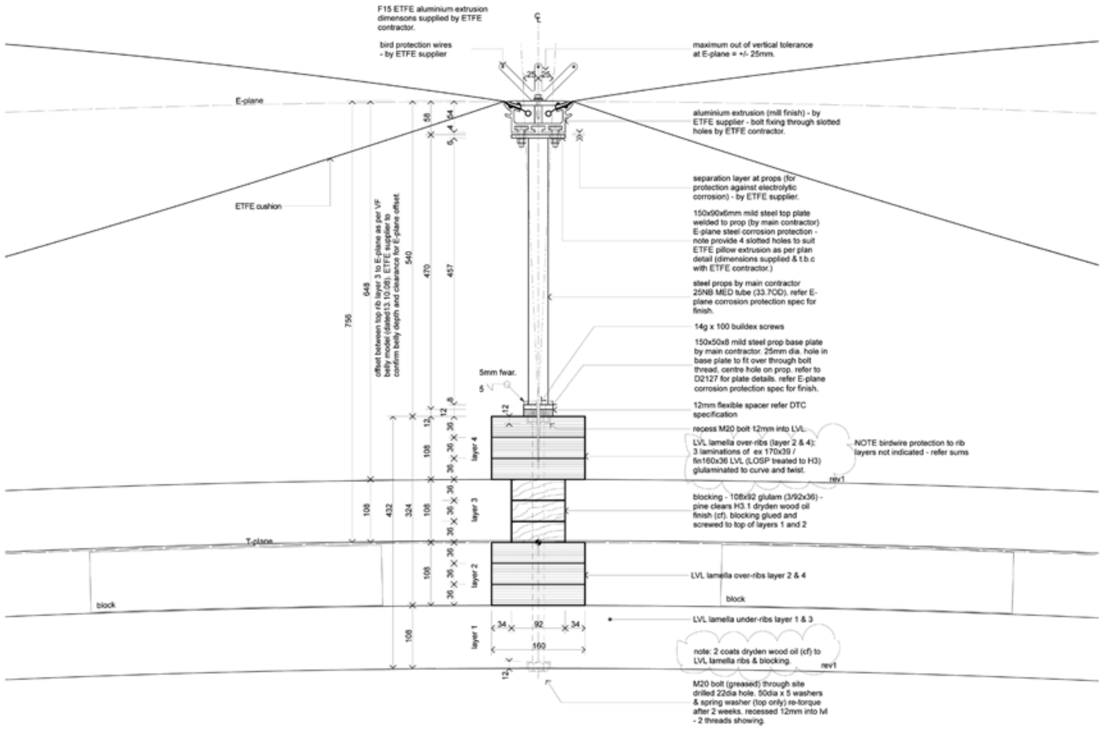


Figure 5.26 Section through the prefabricated upper rib showing intersection with lower rib and details of ETFE cushion support
Source: © Architecture Workshop.

Figure 5.27 Node detail showing connection of stainless steel diagonal ties
Source: © Kirsten Gibbs/Jason Hall.

Figure 5.28 (a) Edge cables stressed between adjacent timber rib nodes are used to tension the short edges of the ETFE cushions; (b) flexible tubes of the cushion inflation system
Sources: (a) © Kirsten Gibbs/Jason Hall; (b) © Architecture Workshop.

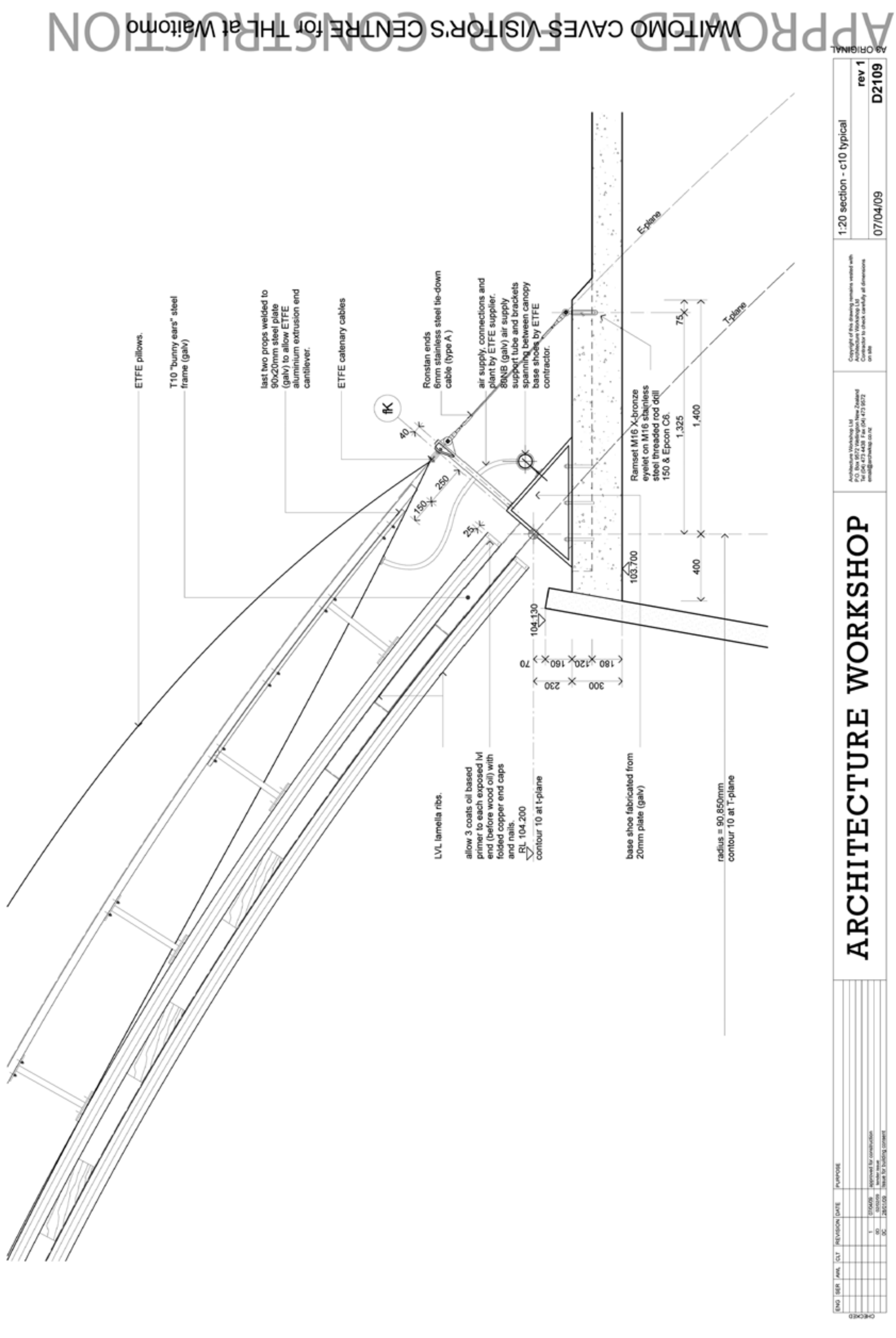


Figure 5.29 Gridshell canopy upper support shoe details showing air distribution system
Source: © Architecture Workshop.

Figure 5.30 Internal view under the open, visually light and transparent ETFE-foil-covered gridshell roof
Source: © Kirsten Gibbs/Jason Hall.

HERMÈS STORE, RIVE GAUCHE, PARIS, FRANCE, 2010

THE FLAGSHIP RIVE Gauche store of the fashion label Hermès, completed in 2010, is located in a Grade 2 listed former swimming pool, 'Piscine Lutetia', designed by Lucien Béguet in 1935 (Theophile and Yee, 2011) in the Rue de Sèvres, in Paris. Rena Dumas Architecture Intèrieure (RDAI), who plan Hermès stores worldwide, designed the pool conversion, which includes three free-form timber gridshell pavilions or 'bulles' (Figure 5.31). At up to 12 m in width and varying in height from 8 to 9 m, the intricate organic shell forms, engineered by Ingenieurbüro Bollinger + Grohmann, Frankfurt, dominate the sales space. Reminiscent of onions or flower bulbs, the globular forms are reinterpreted as giant wicker baskets constructed from thin timber laths. Timber was the chosen construction material to demonstrate Hermès' philosophy of sustainable fashion and reflect their brand image of high-quality design, attention to detail and pursuit of perfection (De Rycke and Bohnenberger, 2011).

Translation of the architect's original three-dimensional, volume-based model to finished objects fabricated from discrete linear elements defining the free-form surface required close collaboration between architect and engineer, as is common in the realisation of complex surface structures. The engineer's initial evaluation of the three forms to define the 3D shape of the laths found no defining rules, continuous curvature or relationship between them. A re-parametered geometry, developed with McNeel's Rhinoceros 3D-modeller (McNeel, 2012) used curvature tolerance, intersection angle, intersection area, section and dimensions of the laths with mesh density, connection point alignment and torsion tolerance to evaluate and optimise alternative models according to structural, aesthetic and fabrication criteria (De Rycke and Bohnenberger, 2011).

Two initial models were considered. The first with bars projected onto the surface had a uniform mesh size but suffered from large curvature of the laths about all three axes (Figure 5.32). This would have been difficult to manufacture. A modified projection cutting the surface avoided the complex curvature but resulted in excessive distances between nodes. This alternative was rejected for both aesthetic and structural reasons.

In the second model, for each 'bulle', contours at the base, one-third height and top were divided into the same number of uniform segments. Sections were then created by connecting selected offset nodes (Figures 5.33 (a) and (b)).

Two variants of this model were considered, one with the laths aligned perpendicular to the cut surface and the other with the laths aligned parallel to the free-form surface. In the former case, intersecting laths were twisted by up to 30° at the nodes (Figure 5.34), while in the latter case, intersecting planks were not twisted relative to each other (Figure 5.35). Preferred by the fabricator and installer, Holzbau Amann GmbH, the final geometry was developed on this basis.

Each of the three 'bulles' comprises a different non-developable surface. To accommodate the heavily tapering forms of the gridshells, the mesh density decreases from base to top (Figure 5.36). After consideration of several alternative methods, the final construction is of site-assembled, 60 x 40 mm, pre-bent laminated battens which were fabricated using CNC cutting, bending and gluing (Figures 5.37 (a) and (b)) and a batten-cutting pattern (Figure 5.38).

Stability of the 'bulles' was considered in parallel with the geometry. Incorporating stabilising rings near the top and steel arches over openings near the base, the grids also required development of the node details to restrain rotation. Hence bars are connected at each intersection by one 8 mm diameter invisible bolt with two hidden 5 mm diameter dowels to restrict rotation of the node.

Detailed planning of fabrication comprising more than 7,000 components and 4,000 points of connection was carried out by designtoproduction GmbH, Zürich and Stuttgart (designtoproduction GmbH, 2016). Familiarity with the digital and physical models allowed the engineers to develop an erection system which included templates to control the curvature of the laminated laths during assembly, see Figure

Figure 5.31 Hermès, Rive Gauche, Paris – free-form timber gridshell pavilions or 'bulles'
Source: © Bollinger + Grohmann.

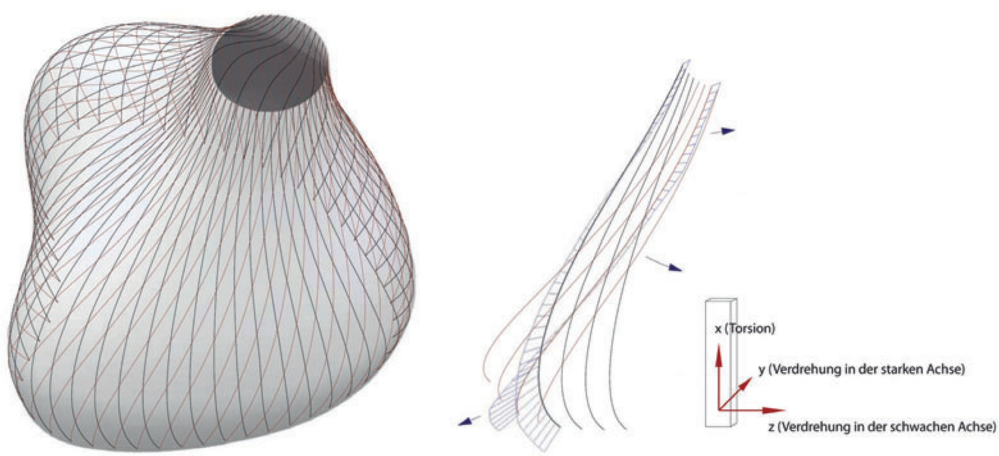


Figure 5.32 Initial projection of axes on free-form surface: model variant 1
Source: © Bollinger + Grohmann.

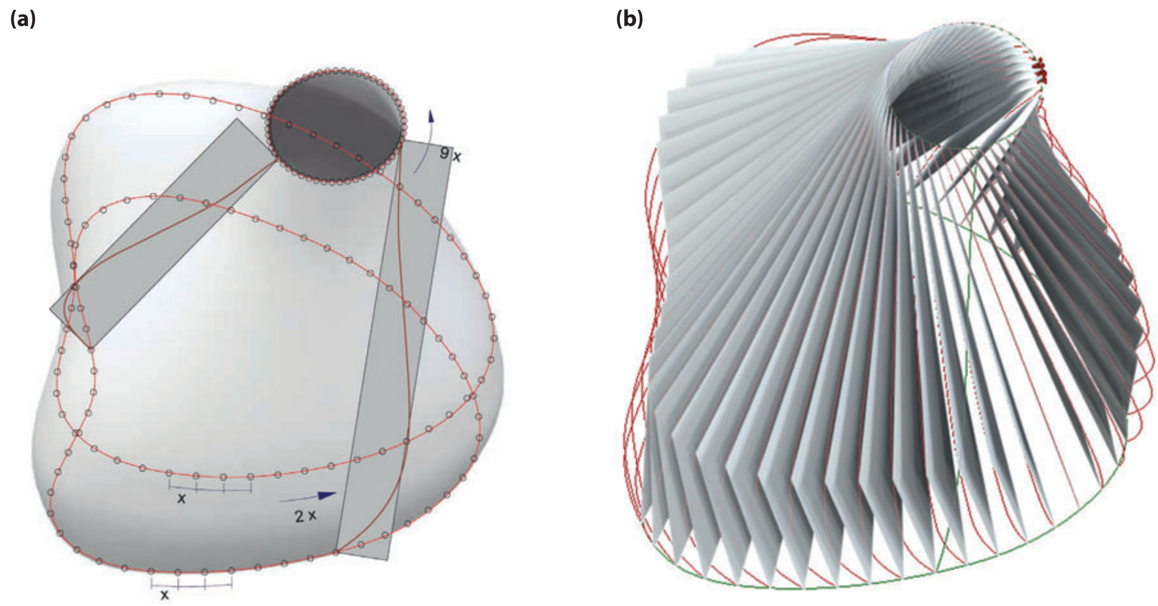


Figure 5.33 (a) Division of three contour curves into uniform segments; (b) sections created by connection of selected offset nodes; model 2
Source: © Bollinger + Grohmann.

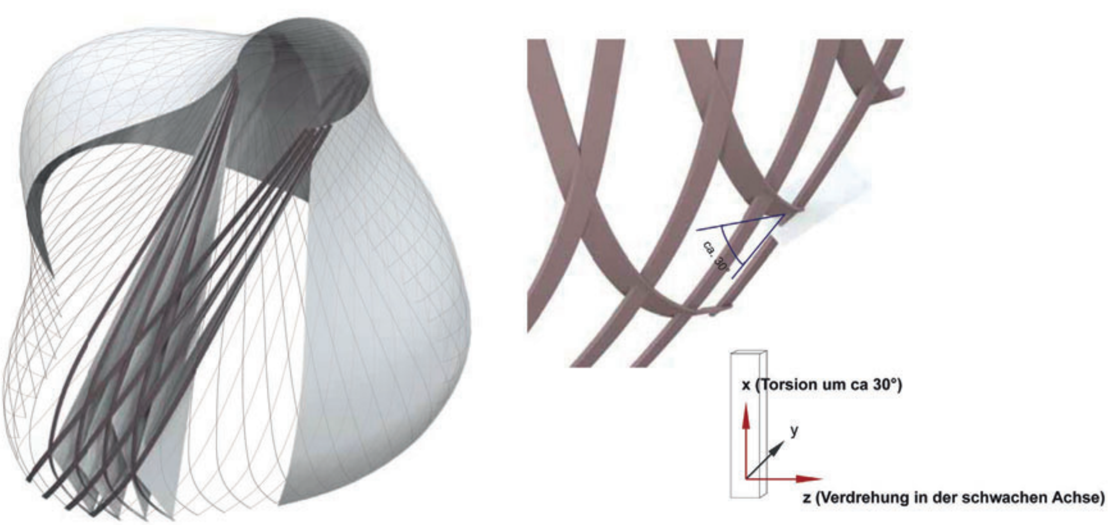


Figure 5.34 Laths aligned perpendicular to the cut surface twisted up to 30° at the nodes; model variant 2-1
Source: © Bollinger + Grohmann.

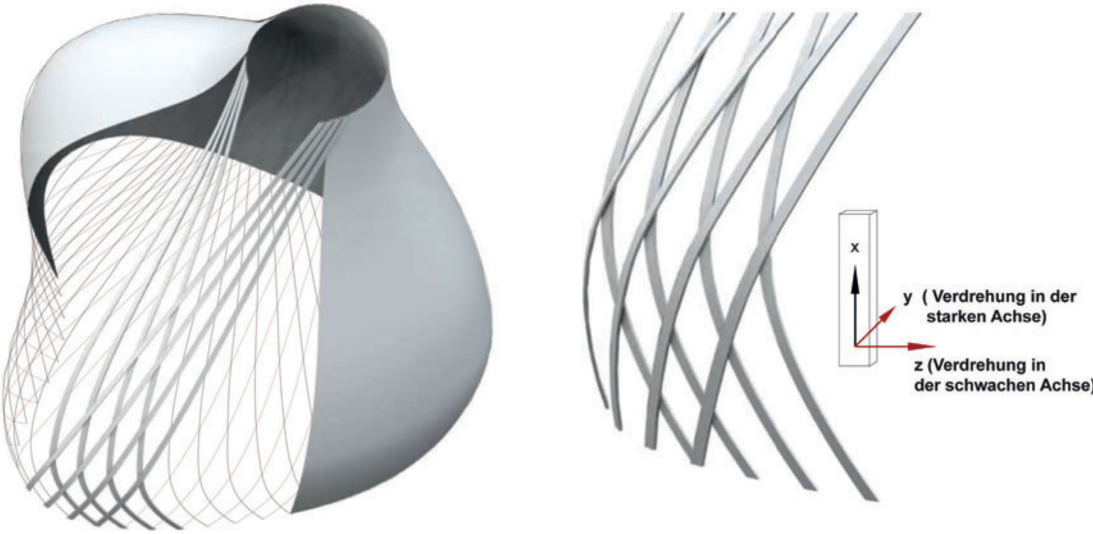


Figure 5.35 Laths aligned parallel to free-form surface have no relative twist at the nodes; model variant 2-2
Source: © Bollinger + Grohmann.

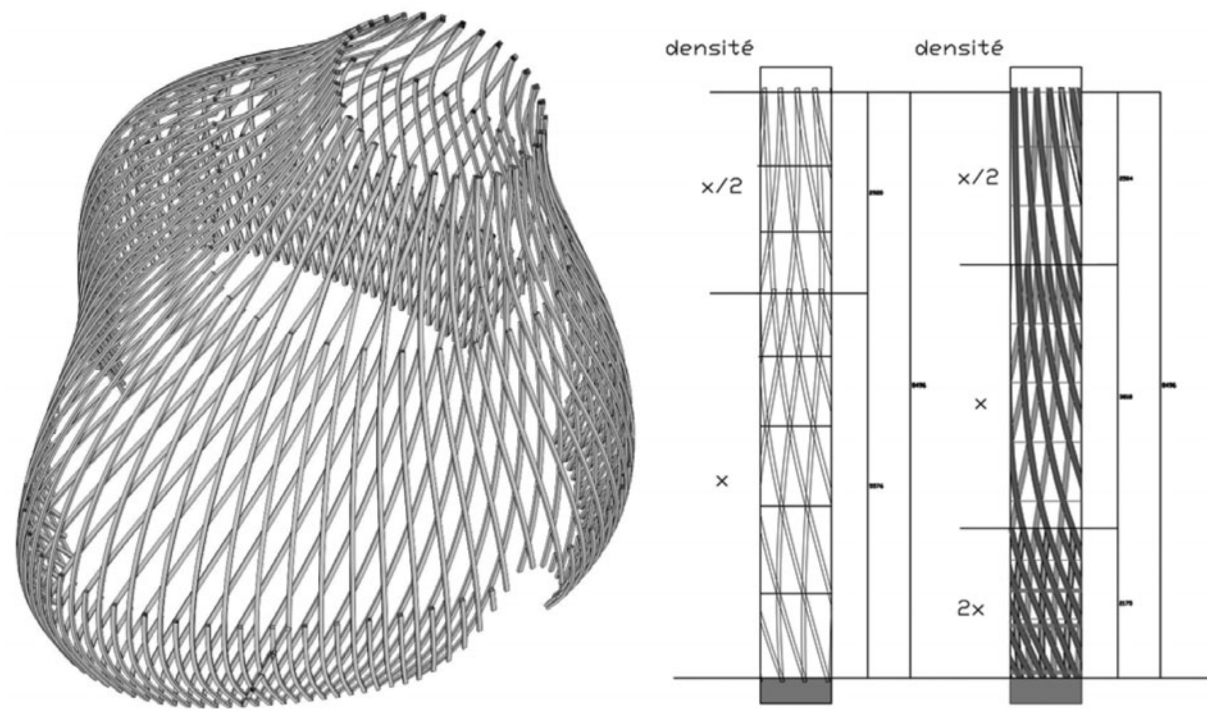


Figure 5.36 Variation of mesh density within the height of the 'bulle'
Source: © Bollinger + Grohmann.

Figure 5.37 (a) Pre-formed 60 x 40 mm, laminated battens; (b) batten detail
Source: © Bollinger + Grohmann.

Figure 5.38 Batten cutting patterns
Source: © designtoproduction GmbH.

5.39 (De Rycke and Bohnenberger, 2011). Sections of each gridshell were pre-assembled and glued before trial mounting on the installation rig at the workshop (Figures 5.40 (a) and (b)). Subsequently the 'bulles' were dismantled and re-erected on site, the node bolts were covered and final sanding and finishing took place.

It should be noted that the 'bulle' design was echoed in the balustrading of the monumental staircase, where steel frames were covered with smaller 40 x 28 mm laths. Together, the project illustrates the benefits of digital design and fabrication for complex free-form grids and reinforces the view that timber is perhaps the best material with which to realise them.

KREOD PAVILIONS, LONDON, UK, 2012

THE MULTIPLE AWARD-WINNING KREOD Pavilions, by architect Chun Qing Li of KREOD Architecture (formerly known as Pavilion Architecture) working with engineers Ramboll UK, were erected in Peninsula Square adjacent to the O_2 Arena (the former Millennium Dome), in London, in September 2012. Designed as temporary and demountable pavilions, these multiple award-winning structures illustrate an alternative method of generating a hexagonal patterned gridshell, using the reciprocal principle (Figure 5.41). According to the architects, the design promotes the use of sustainable building techniques and demonstrates the potential of digital design, fabrication and construction. Its modular and stackable components facilitate storage and transportation, and permit the gridshells to be

Figure 5.39 Template to control the curvature of the laminated laths during assembly
Source: © Bollinger + Grohmann.

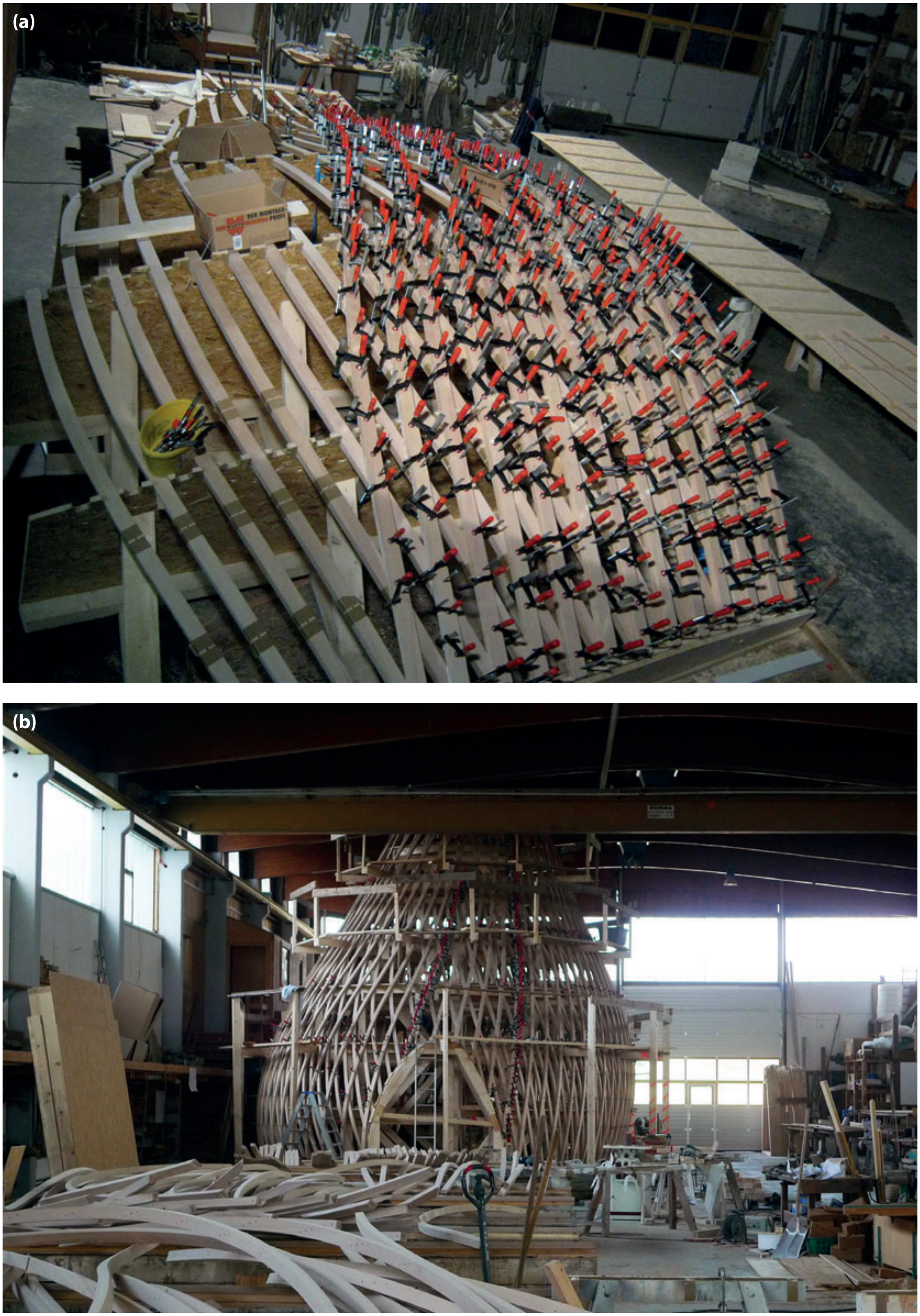


Figure 5.40 (a) Pre-assembled and glued section of gridshell on template; (b) trial installation in the fabrication shop
Source: © Bollinger + Grohmann.

easily assembled and dismantled for reuse (KREOD Architecture, 2015).

Resembling organic seed-like pods, the three pavilions, each of approximately 20 m² in plan (Figures 5.42 (a) and (b)), can be individually free-standing or combined in different ways to create an 'architectural landmark and an imaginative exhibition space' (ibid.) (Figures 5.43 (a) and (b)).

Selected as the Institution of Structural Engineers Small Project of the Year, in 2013, the structure exploited state-of-the-art parametric design software to define the complex geometry and digital fabrication methods to manufacture the timber components. Prototypes were tested to determine the strength of the node joint and method of assembly (Figures 5.44 (a) and (b)).

Given the number of joints in the structure, conventional fixings would have been prohibitively expensive. The architect was seeking a high-quality 'furniture quality' finish in the structure to be assembled and disassembled manually by untrained labour. As Stephen Melville, who worked on the project at Ramboll UK, has remarked, 'in theory every nodal connection would be different' (Format Engineers, 2015). The 'reciprocal' joints of the gridshell are assembled from precisely machined flat elements using just six through bolts. A slight offset of the individual Kebony planks in joints of the reciprocal grid generates the required double curvature of the grid, as can be seen in Figure 5.45.

Figure 5.41 The KREOD Pavilions, by architect Chun Qing Li of KREOD Architecture, displayed adjacent to the O_2 Arena, London
Source: © KREOD Architecture.

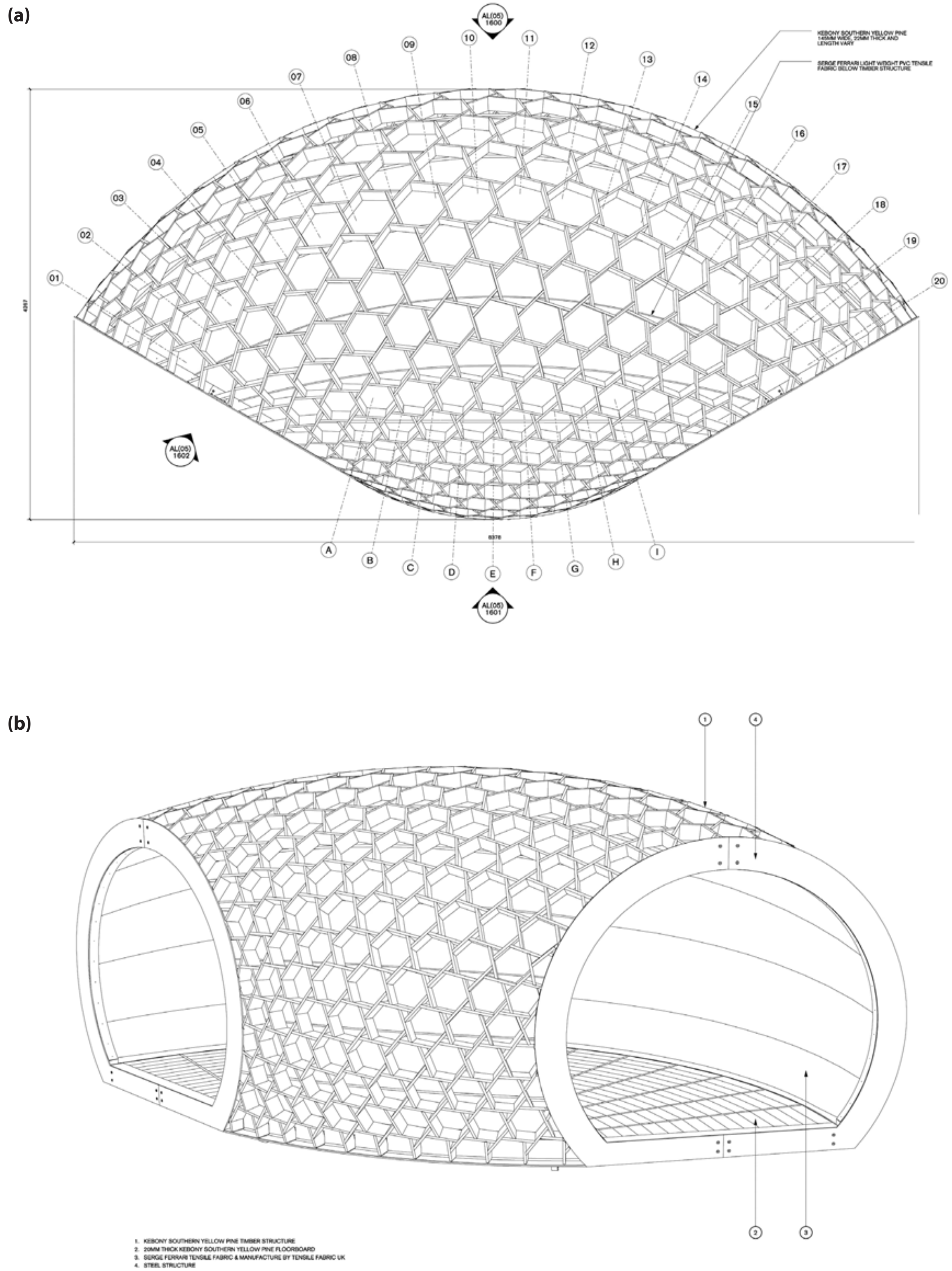
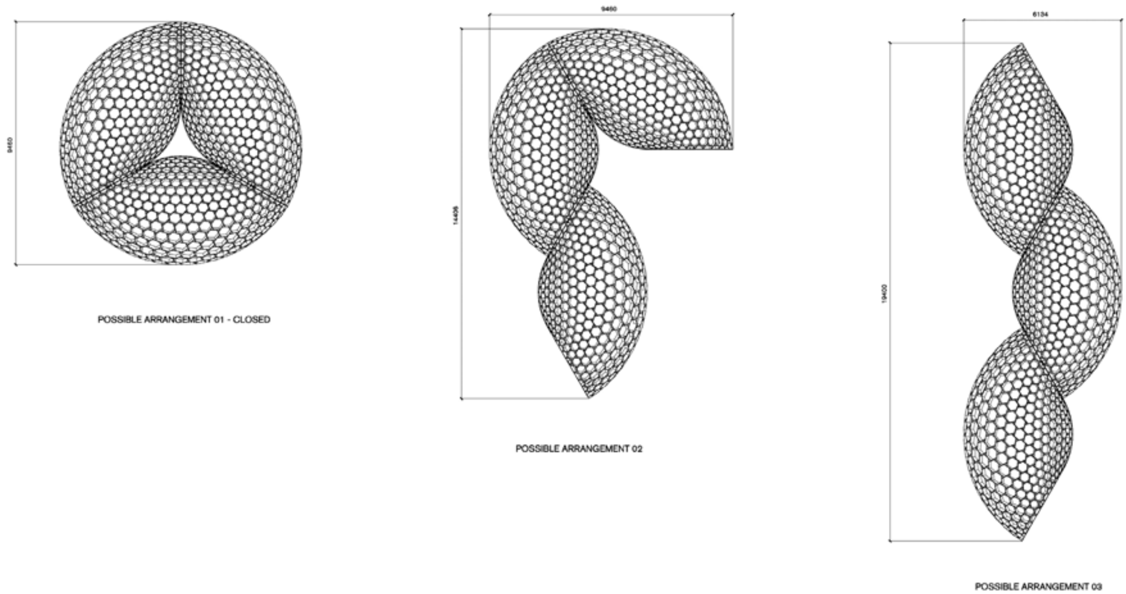


Figure 5.42 (a) Plan view; (b) axonometric of one of the KREOD Pavilion pods
Source: © KREOD Architecture.

(a)



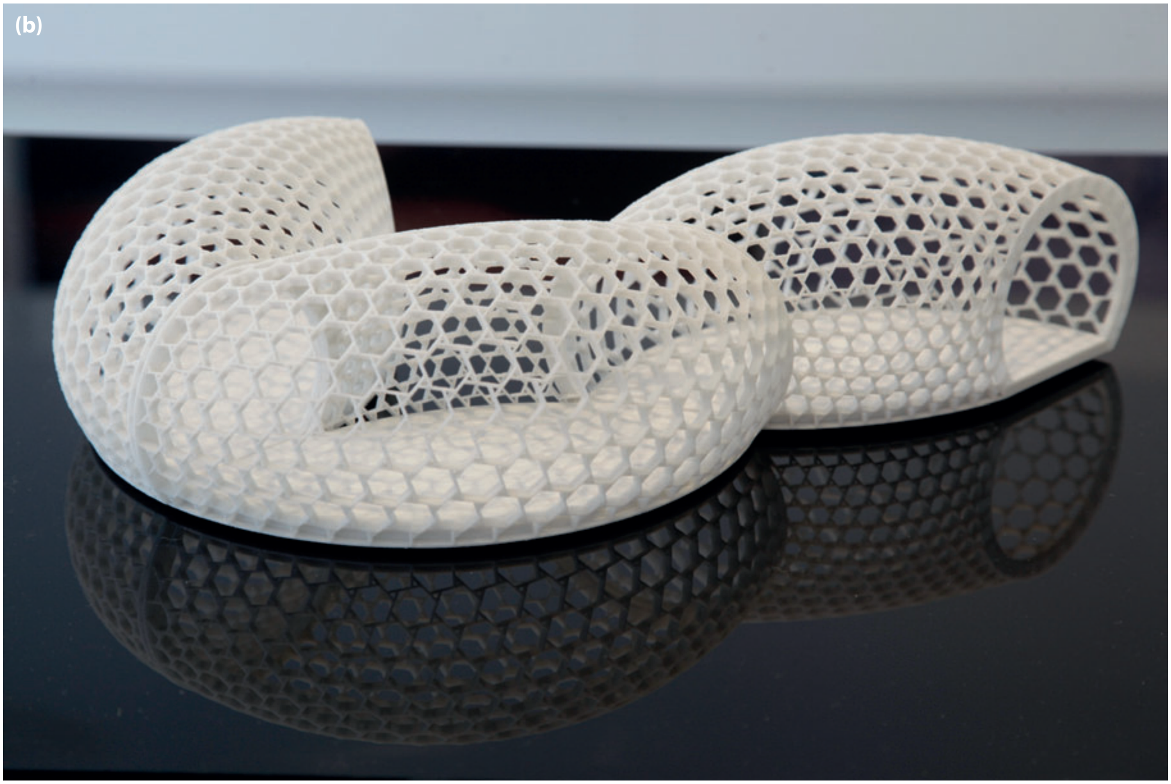


Figure 5.43 (a) Alternative arrangements of the KREOD Pavilions; (b) 3-D printed model of alternative shown centre in (a)
Source: © KREOD Architecture.

Figure 5.44 (a) Strength testing of typical joint; (b) trial assembly of reciprocal gridshell components
Source: © Ramboll UK.

Figure 5.45 Detail of the (weathered) hexagonal grid, in 2014, showing the slight offset of the individual planks in the reciprocal joint and, bottom centre, a suspension point for tensioning the membrane
Source: © John Chilton.

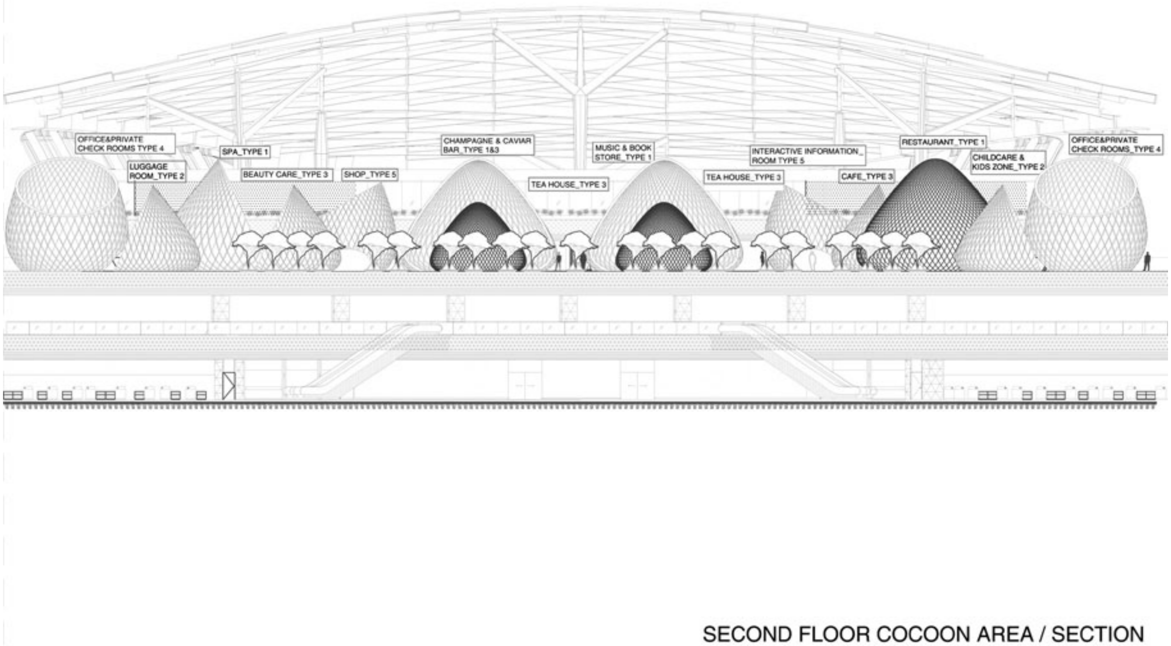
HEYDAR ALIYEV INTERNATIONAL AIRPORT TERMINAL, BAKU, AZERBAIJAN, 2014

AIRPORT TERMINAL BUILDINGS are often vast and impersonal architectural spaces. The contemporary interior architecture at the Heydar Aliyev International Airport Terminal, Baku, Azerbaijan, by Turkish practice Autoban, for client Azerbaijan Airlines (AZAL), is intended to mitigate this by the incorporation of the number of custom-made, gridshell-framed, timber-clad pods or cocoons (Figure 5.46 (a)).

Using the tactile qualities of the timber structure and cladding, five typologies of intimate nest-like cocoons accommodate the typical necessities of airport terminals and humanise what is often an uninviting environment. Three teardrop-like forms, struck through at an angle of 65° to the horizontal, have base diameters ranging from 3335 to 5720 mm and heights of 6518 to 10135 mm respectively. The remaining two, more bulbous basket-like forms, of 2605 and 3770 mm base diameter and up to 7290 or 10190 mm high, respectively, are truncated at 30° to the horizontal (Figure 5.46 (b)).

Diamond-shaped oak-veneered shingles of ayous wood (*triplochiton scleroxylon*) are used to clad some, but not all, of the gridshells (Dezeen, 2014), creating a stimulating interior environment of elegant shell and grids forms (Figure 5.47).

(a)



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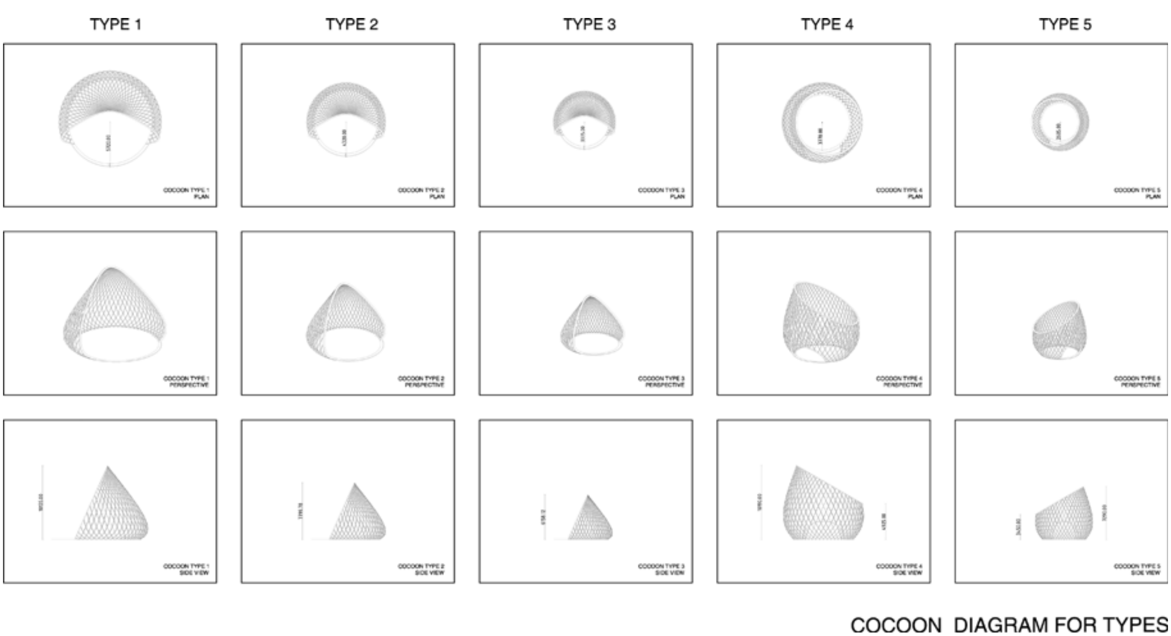

Figure 5.46 (a) Section through the Heydar Aliyev International Airport Terminal, Baku, Azerbaijan, showing the timber grid cocoons; (b) details of the five different cocoon types
Source: © Autoban.

Figure 5.47 Diamond-shaped oak-veneered shingles of *ayous* wood clad the gridshell forms
Source: © Kerem Sanliman/Autoban.

AHURIRI VALLEY LODGE, NEW ZEALAND, UNDER CONSTRUCTION IN 2016

ARCHITECTURE WORKSHOP, DESIGNERS of the Waitomo Glowworm Visitor Centre, described earlier in this chapter, are currently undertaking a further hybrid timber gridshell in collaboration with their engineer Alistair Cattanach. Located in the Ahuriri Conservation Park on New Zealand's South Island, the site is subject to a temperature range from -16°C to +40°C. Illustrating the increasing use of digital technologies even for relatively small projects, the complex roof geometry, described as a 'deformed composite' gridshell, has been developed using 3-D printing techniques (Figures 5.48 (a) and (b)).

Currently under construction, in 2016, the Ahuriri Valley Lodge is located in an area of great natural beauty, as can be seen in the project render in Figure 5.49, and requires an architectural design of great sensitivity. It is apposite, therefore, that the design solution incorporates a sustainable timber gridshell.

The roof profile is defined by 180 mm square, hollow steel tube section frames. Beneath these, a 70 x 90 mm hardwood lamella gridshell is bolted, referred to as 'screwlam' by the designers (Figure 5.50). According to engineers Dunning Thornton, the grid carries approximately 40 per cent of the roof loads, which include aluminium rainscreen scales attached to timber battens fixed to an 18 mm-thick, membrane-protected, plywood deck (Figures 5.51 (a) and (b)).

In this chapter we have described a variety of generally relatively small-scale gridshells. Chapter 7 introduces the practice of manufacturing gridshells directly as their final form by digitally controlled machining of solid engineered timber components.

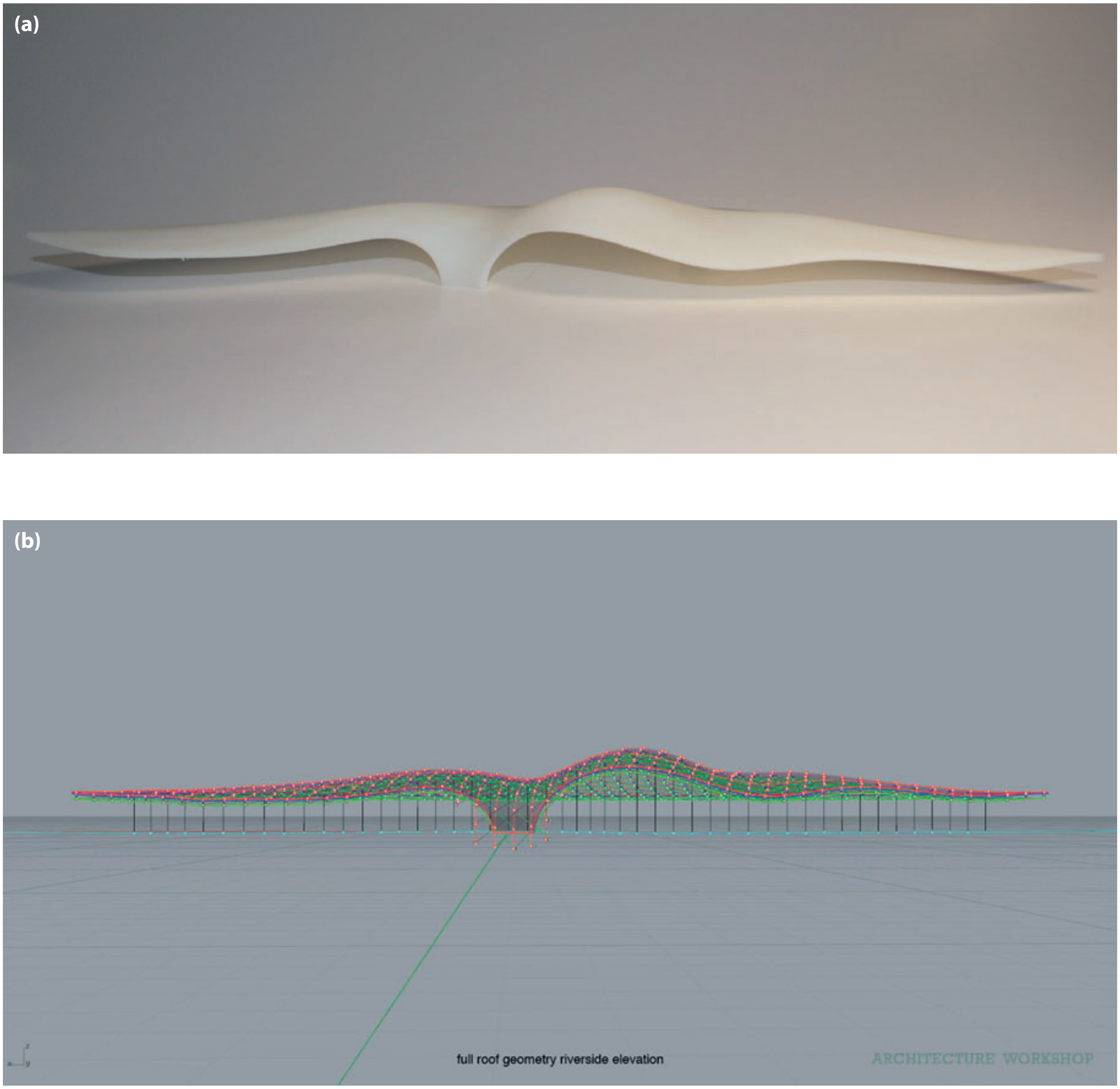

Figure 5.48 (a) 3-D printed model of Ahuriri Valley Lodge gridshell roof; (b) riverside elevation of final roof geometry
Source: © Architecture Workshop.

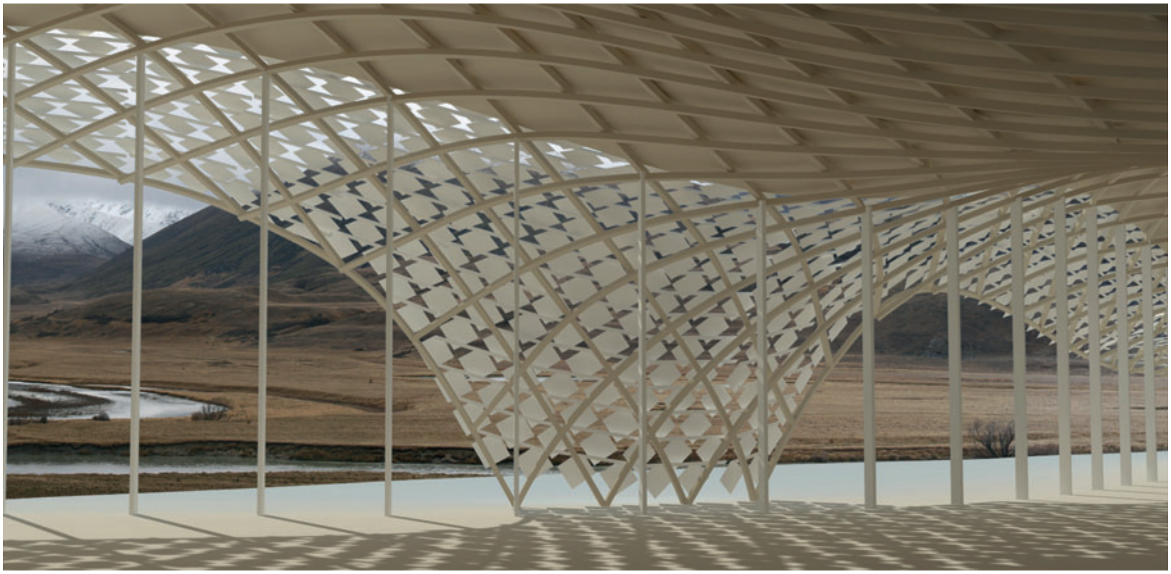

Figure 5.49 Internal rendering of the proposed Ahuriri Valley Lodge gridshell showing its highly sensitive location in the Ahuriri Conservation Park
Source: © Architecture Workshop.

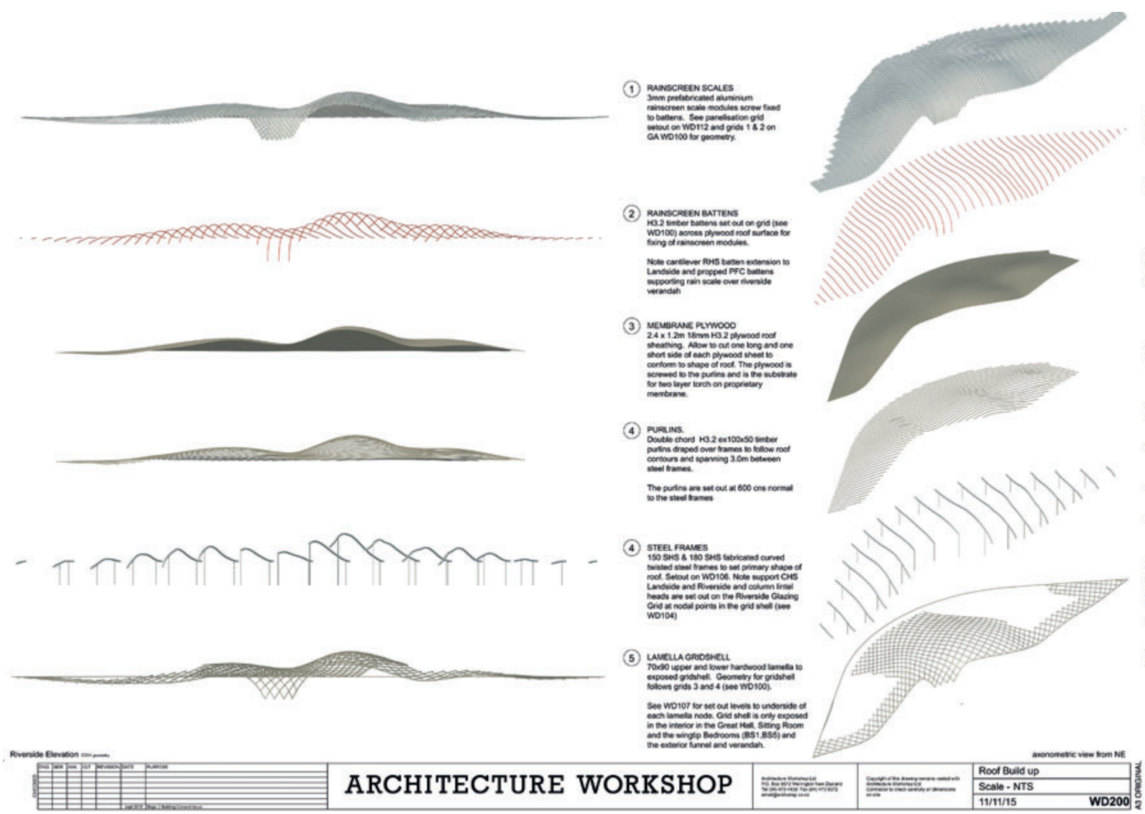

Figure 5.50 Gridshell roof build-up
Source: © Architecture Workshop.

Figure 5.51 (a) and (b) Mock-up of the proposed gridshell and aluminium rain-screen scales, Ahuriri Valley Lodge
Source: © Architecture Workshop.

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CHAPTER SIX

Recent small-scale projects and research experimentations

IN EARLIER CHAPTERS, we have seen timber gridshells used commercially in the construction of roofs, building enclosures and shelter on relatively large scales. Timber gridshells offered exciting possibilities with many high-profile projects such as the Weald and Downland gridshell (Chapter 3) evidencing the synergies and inter-disciplinary workings between architecture, structure and craft. Ateliers, smaller design studios and schools of architecture continue experimenting to perfect timber gridshell construction, ideas and techniques on a different scale. The exhilaration of timber gridshell design is therefore not limited to architects, engineers and builders involved in gridshell buildings, but one which is shared by designers and builders of small-scale gridshells in an experimental capacity as new ideas are tried, learnt and shared. Materially, components used in these tests are not restricted to regular machined timber but include new developments such as plywood, bamboo and new engineered timber products (Figures 6.1 (a) and (b)).

THE KUPLA GRIDSHELL, HELSINKI, FINLAND, 2002

IN 2002, HELSINKI Zoo welcomed a rare timber structure into its grounds. Set within the natural landscape looking out onto the waters of Helsinki, this bubble-shaped, two-storey-tall, timber look-out tower is encased in a timber gridshell (Figure 6.2). A winning design entry in a design competition organised by the Korkeassari Zoo and Wood Focus Finland, this project was designed and constructed by Ville Hare/Wood Studio workshop at the Helsinki University of Technology.

The organic shape of this gridshell earned the structure the affectionate name of 'Kupla' which means bubble in Finnish. Kupla measures 10 m high and sits atop a promontory 18 m above sea level. Inspired by the natural landscape, the gridshell responds to its surroundings and was positioned to follow an existing stone wall. It sits adjacent to a glade of birch trees (Hara, 2015).

Figure 6.1 (a) In 2011, the research team led by Juan Gerardo Oliva Salinas constructed a gridshell in bamboo at UNAM campus in Mexico City; (b) the bamboo was spliced together by bolts to create laths
Source: © Juan Gerardo Oliva Salinas.

Figure 6.2 The Kupla gridshell on the approach path, set against the skyline of the Finnish capital
Source: © Jussi Tiainen.

Looking through the gridshell, the structure and architectural components are clearly legible. This is not a big building – the two-storeyed timber structure consists of two floor plates measuring 82 m^2 in total, a linking access stairs and a free-form timber gridshell envelope (Hara, 2015) (Figures 6.3 and 6.4). The gridshell was constructed from 72 pieces of 60 x 60 mm battens bent and twisted on-site from seven pre-bent profiles secured together with 600 joints. Exposed to the harsh winter and summer conditions of Helsinki, this outdoor structure was treated with a linseed oil-based wood balm to protect it from harmful ultra-violet rays to prevent degradation.

Model-making and digital design

During a construction workshop between January and May 2001, scaled models were assembled by international students. The design was developed through the extensive use of scaled models and detail study.

A Plasticine model was used at the beginning to establish the structural form. The original geometry was free-form and irregular. Photographs of this model were taken and CAD drawings were made by tracing the curves digitally over these photographs. Level drawings were made and using these, a computer model was created by 'taping' curved battens to form the gridshell (Figure 6.5).

Figure 6.3 The Kupla gridshell
Source: © Jussi Tiainen.

Figure 6.4 Arriving at the top floor of the Kupla gridshell look-out tower, the connection to the landscape and sky is easily appreciated
Source: © Jussi Tiainen.

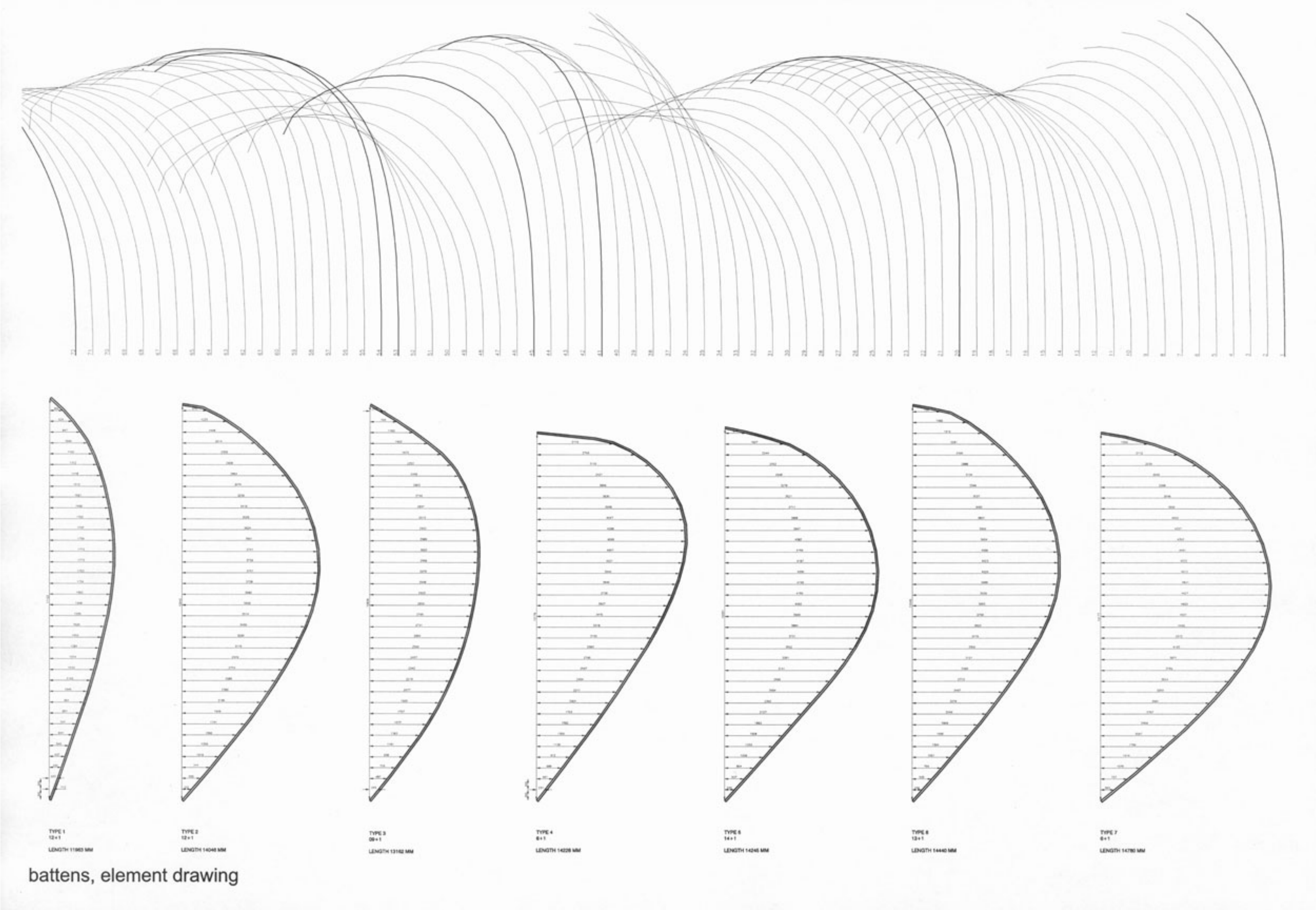

Figure 6.5 Batten drawings of the gridshell parts
Source: © Ville Hara.

Subsequently, this CAD model acted as the basis for the building of a 1:5 scaled physical model (Figures 6.6 (a) and (b)). Standing 2 m tall, this was made during a construction workshop at Helsinki University of Technology (now Aalto University) with international students, led by Jan Soderlund and the architect Risto Huttunen. The construction exercise simulated the process of the ensuing construction, drawing out aspects of design and construction that needed to be resolved at an early stage in the process.

Laminated timber and glulam testing

Following this workshop, full-scale test pieces of timber battens were laminated to understand their bending behaviour and the twisting tolerances of the gridshell timbers. When timbers resisted twisting, they were steamed to soften them – a practice similar to that used in traditional boatbuilding, growing from a working understanding of timber. Moisture tests were also carried out to study the effect of linseed oil-based wood balm while tension tests proved the durability of the joints (Hara, 2011). These battens were joined using simple applied-bolt connections stiffened with double-sided nail-plates.

Bending and curve forming

With the summer weather in Helsinki being hot and sunny, the timber battens dried quickly and resisted twisting. To counteract this, the battens were steamed again, becoming pliable (resembling cooked spaghetti) and workable again. With this outdoor summer weather prevailing, the softened wood hardened very quickly, hence curve-forming the timber elements had to be done promptly.

The construction

The full-scale structure was finally erected by a group of eight international architecture students. With construction materials sponsored, and with a limited budget, the assembly took place on site. Although the intersection points were predetermined and the location of the pilot holes was known, it was decided that the holes would be drilled on site as a conservative move to take into account movement tolerances in the summer heat (Figure 6.7).

Evidently, the Kupla is an exploration of form design on a smaller scale where timber laths are permanently deformed by steaming to achieve curvatures in three dimensions, albeit on a smaller scale by less skilled and less experienced craftsperson/constructors. Importantly, it showed how an organic timber gridshell form could be achieved without sophisticated software, but through simple logic of design and with a material understanding of timber. Although the structure is smaller in scale, the sensitive positioning of this belvedere responds sympathetically to the setting, an important measure of good design as much as the resolution of complexity in form, becoming a strong representation of craft (Figure 6.8).

ALISHAN BRIDGE, TAIWAN, 2003

THE DESIGN OF the Fen Qui Hu Bridge is part of a wider masterplan of visitor routes for developing cuisine tourism in the Alishan region of Taiwan, a mountainous rural district traversed by waterfalls with scenery of international repute. Designed by the American office Reiser + Umemoto, the scheme won first prize in an international competition in 2003 (Figure 6.9).

Following changes in economic emphasis, Taiwan is a country seeking to preserve and develop its natural landscape. This proposal considered the sensitive connection between the land and the economy through eco-tourism as a comprehensive tourist experience where micro-agriculture was proposed to support international cuisine tourism along the Alishan railway line (Figure 6.10).

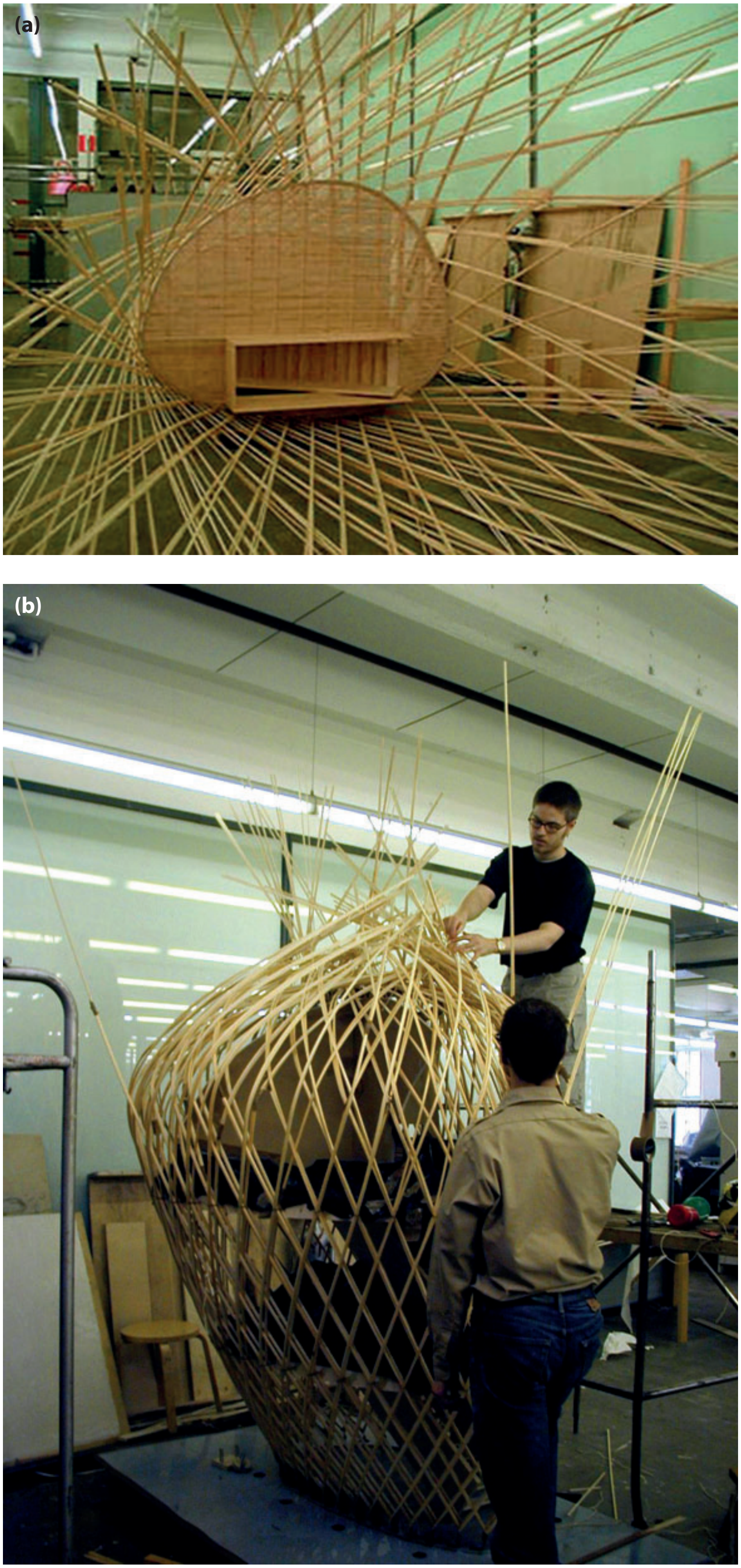

Figure 6.6 (a) The 2 m-tall wooden model was laid sideways on the ground; (b) nearing completion and standing upright
Source: © Jussi Tiainen.

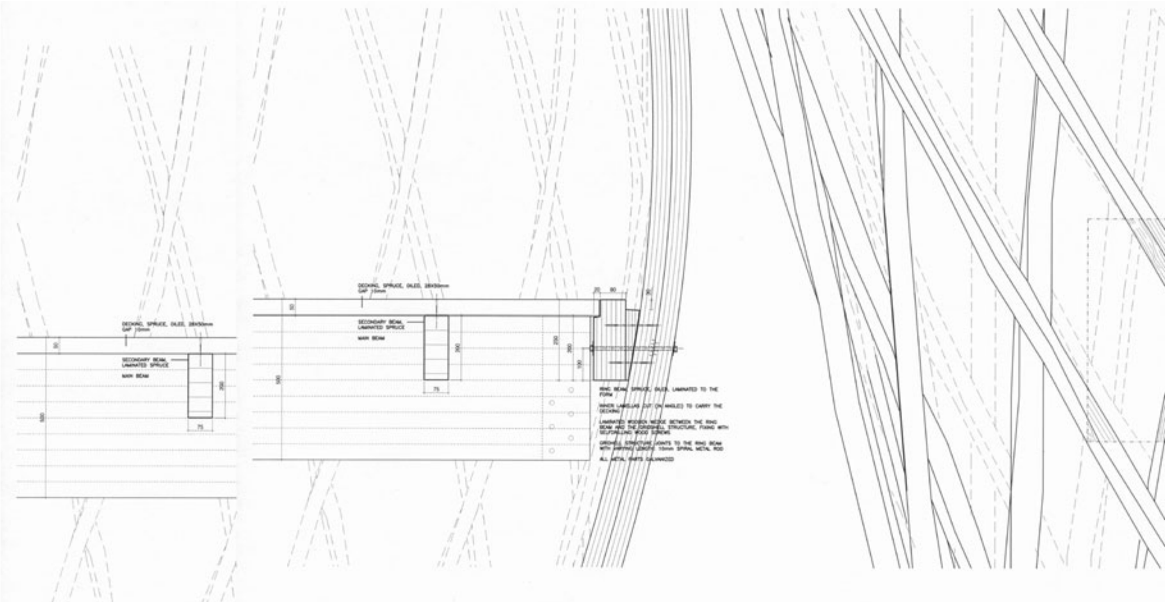

Figure 6.7 Detail connection of ring beam and the load-bearing gridshell structure
Source: © Ville Hara.

Figure 6.8 View of Helsinki from the intermediate floor
Source: © Jussi Tiainen.

Figure 6.9 Artist's impression of the proposed Fen Qui Hu gridshell bridge
Source: © Reiser + Umemoto, RUR Architecture.

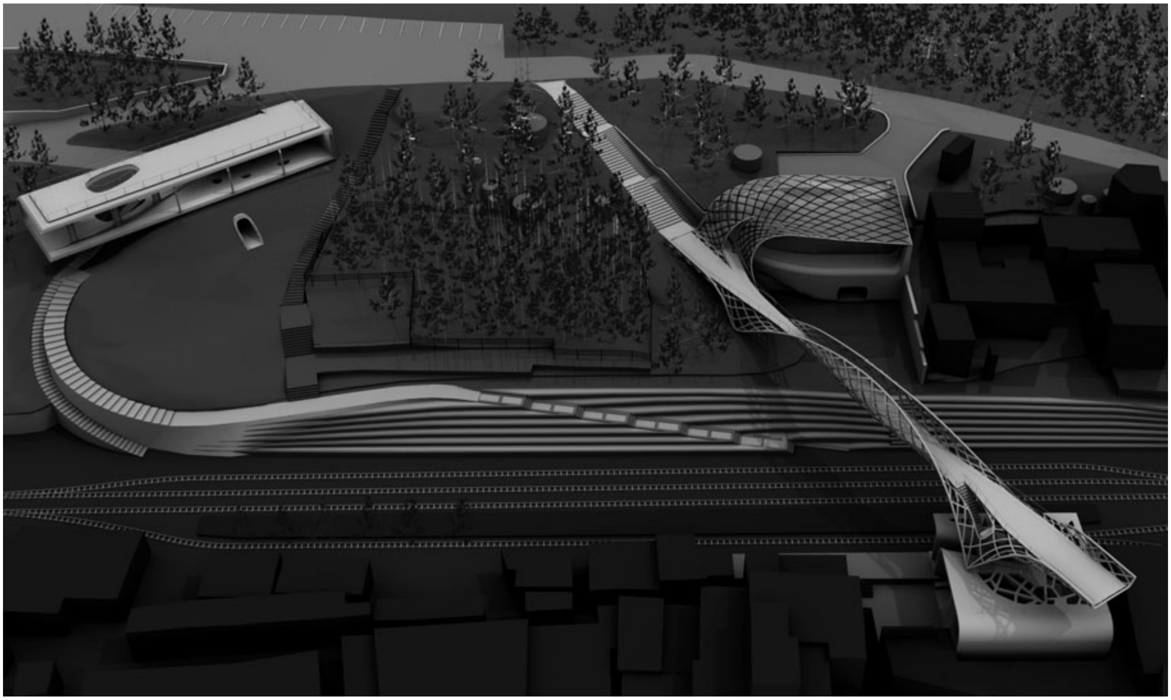

Figure 6.10 The gridshell bridge model showing its relationship to the railway tracks and surrounding buildings
Source: © Reiser + Umemoto, RUR Architecture.

The Fen Qui Hu site

The architects re-interpreted the offered site, a disused railway yard, as a piazza covered with grasscrete to blend in with the greenery of the surrounding bamboo forests. Due to the conditions of the topography, the architects proposed an event space in the form of an amphitheatre. A prominent feature is the design of a timber gridshell footbridge that arches over this area to announce this newly proposed public intervention.

The gridshell bridge was designed to be built of glulam timber. In close collaboration with Arups London, through computer modelling, form-finding was carried out digitally. This was a period when digital parametric design was in its infancy and when keen experimentation was carried out. Digital processes were starting to become generators of form rather than a checking tool (Figure 6.11).

Chosen to be exhibited at the 2003 Venice Biennale, the bridge was made of glulam timber (Figures 6.12 (a) and (b)). An ensemble of architectural interventions that defined this space, the gridshell bridges the rail tracks high up in the mountain region and lends visual drama. The gridshell can be compared to a tube whose wall has been peeled away, warped and deformed to produce a shell form to support the timber deck.

The 1:10 scaled timber model displayed in Venice was constructed by Cowley Timberworks in Lincolnshire, UK. Constructed of birch plywood ribs of varying thicknesses from 4 mm to 12 mm, all profiled and pre-drilled by a CNC machine, component sections were bolted together to form a model measuring 9.5 m in length.

The successful model construction was the result of the combination of mechanised precision and dexterity of the craftsperson. Speaking in 2012, Gordon Cowley reported the model took 543 hours to construct, subsequently it took a further 81 hours to assemble *in situ*.

Sadly, this project did not progress into the construction stages, as it would offer new opportunities in this exciting period to spearhead digital form-finding, construction and digital fabrication research in ways that other projects such as Pompidou Metz and the French Pavilion for the 2015 World Expo are pushing boundaries of timber gridshell possibilities. The built physical model was largely used for promotional purposes (Figure 6.13).

THE SWELLS GRIDSHELL, SHEFFIELD HALLAM UNIVERSITY, SHEFFIELD, UK, 2011

THIS WAS A couple of timber gridshells built during an experimental week-long student workshop organised at Sheffield Hallam University in 2011 (Figure 6.14). During the workshop, students worked with architects, engineers and technologists to explore and learn about their design and construction.

Form-found largely by using paper card cut into strips and pin-assembled to create gridmats, the workshop was themed on the notions of creative play and structural intuition advocated by the structural artists, Heinz Isler and Pier Luigi Nervi (Tang, 2013). The principles of the timber gridshell design and construction were based on the observation that by applying forces, a flexible gridmat could be manipulated to cause it to readjust and deform, resulting in three-dimensional shell forms (Figures 6.15 (a)–(d)).

The designed mat measured 18 m long by 9 m wide with each grid measuring 900 mm square. The final shell design consisted of two swellings rising from the flat plane. Both of these asymmetrical swellings had their front edge lifted off the ground. The smaller swell rose to a height of 1.2 m and the bigger swell rose to 3.5 m.

At the end of the week, double-layered pine laths bolt spliced together were built on soft grassed university grounds in Sheffield city centre by first creating a flat mat on the grassed area (Figure 6.16 (a)). The behaviour of flexing was first learnt from the scaled models. With students holding onto specific points within the mat (Figure 6.16 (b)), either moving away from or towards each other, shell forms were easily created. The deformation of grids from squares to diamonds allowed the flat mat to become three-dimensional.

The new shell forms were then made rigid by bolting additional laths to triangulate and freeze the geometry.

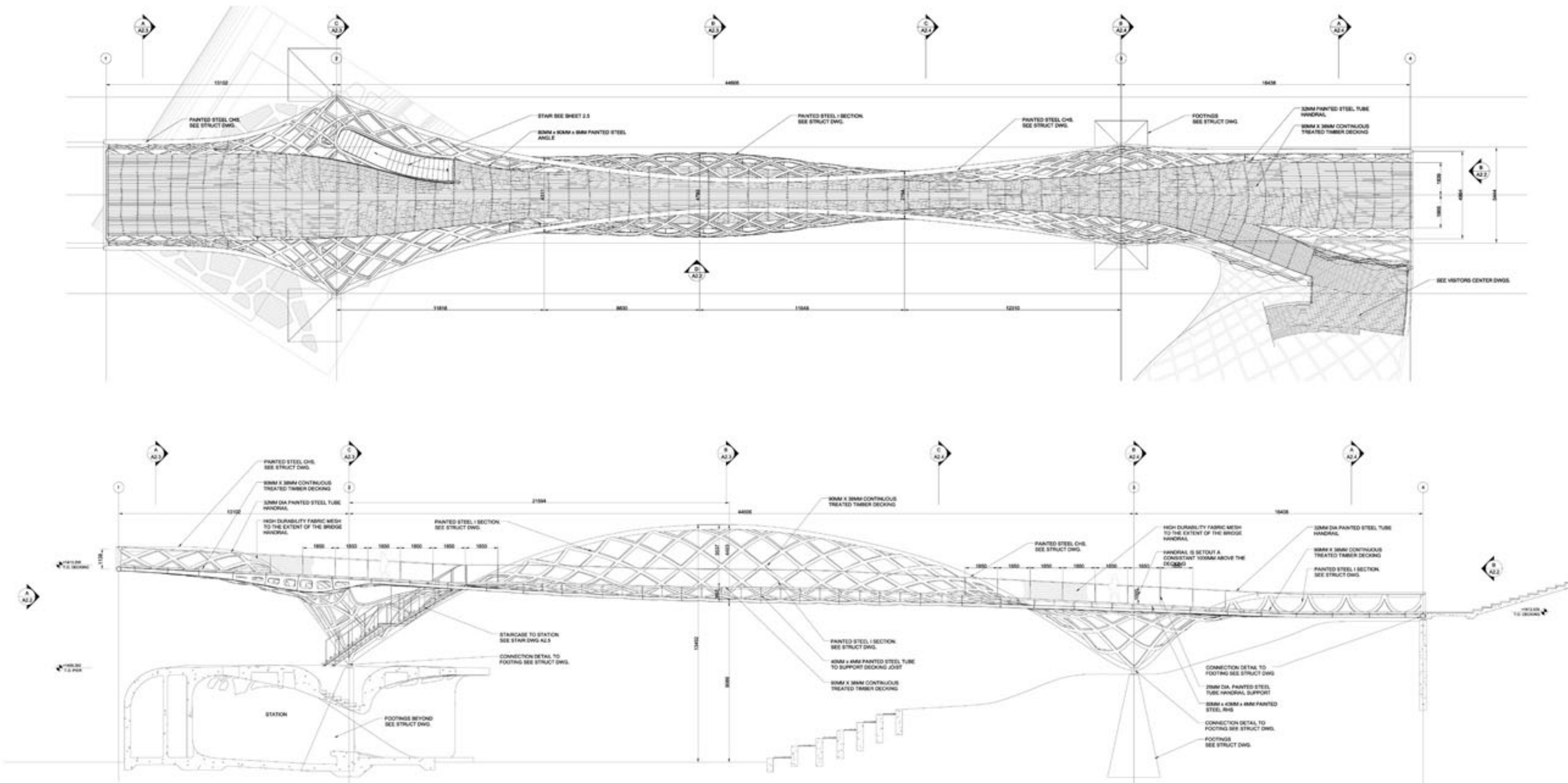

Figure 6.11 The Fen Qui Hu gridshell bridge on plan and on elevation
Source: © Reiser + Umemoto, RUR Architecture.

Figure 6.12 (a) Left: The 9.5 m-long model of the gridshell bridge is suspended from the ceiling of the exhibition room at the 2003 Venice Biennale; (b) right: seen from directly below
Source: © Reiser + Umemoto, RUR Architecture.

Figure 6.13 Another artist's rendering of the proposed unbuilt timber gridshell bridge
Source: © Reiser + Umemoto, RUR Architecture.

Figure 6.14 The timber gridshell, built as part of a construction workshop, rests gently on the grassed area in Sheffield city centre
Source: ©iD8 photography.

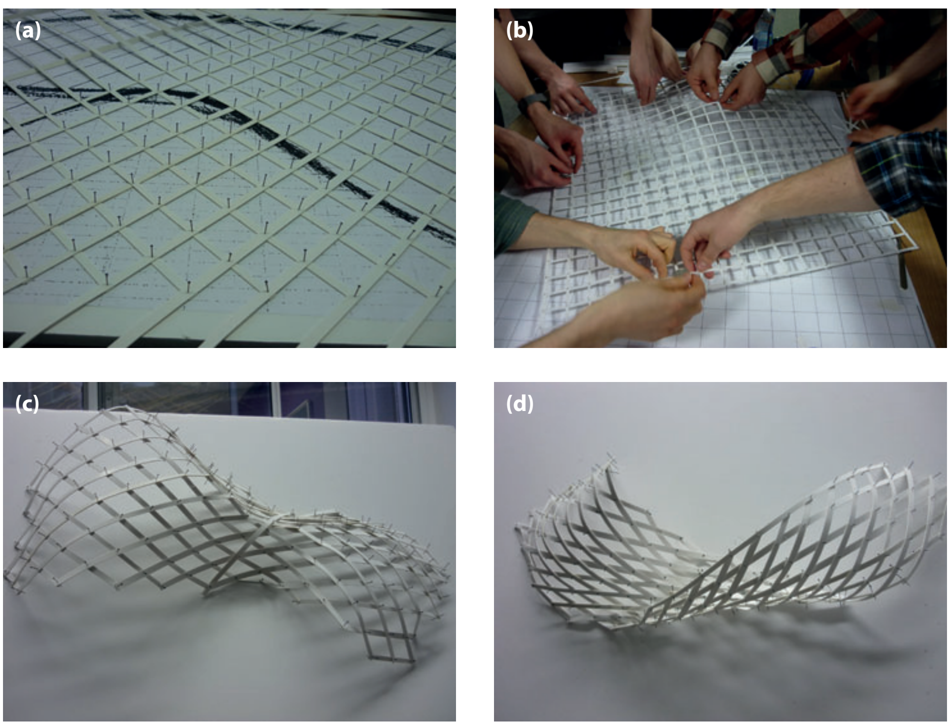

Figure 6.15 (a) The flat mat was made with paper strips laid at a diagonal in one direction. Another layer laid in the opposite direction was added on, with each intersection pinned with a model pin. (b) The gridmat is lifted up from base. (c) and (d) The grid mat is manipulated to create three-dimensional shells
Source: © Gabriel Tang.

Figure 6.16 (a) The gridmat measuring approximately 18 m by 9 m was constructed on the grassed area; (b) by picking up pre-determined points of the gridshells, students moved away from or towards each other to deform the gridmat into a three-dimensional gridshell
Source: © Gabriel Tang.

The structures were held down and anchored onto the ground by steel chairs and timber blocking pieces. These two timber gridshell structures were displayed in Sheffield city centre in England for a fortnight (Figures 6.17 (a) and (b)).

THE SHELLS OF SERGIO PONE

THE USE OF a deployable flat mat deformed to produce a three-dimensional timber gridshell was further experimented with in Italy by architect Sergio Pone and his research team at the University of Naples in Italy. Together with Sofia Colabella, Daniele Lancia and Bianca Parenti, he co-founded the Italian company GRIDSHELL.it. To date, they have built 13 gridshells, which they have managed entirely from conceptual design to construction.

Their work overlaps with research and practice, particularly by their experimentation in the areas of digital form-finding and construction. Numerous timber gridshell structures have been built at various locations in Italy and more recently in Melbourne, Australia, for purposes ranging from outdoor shelters for restaurants to smaller-scale outdoor courtyard shelters. The high level of student participation is highly encouraging with resulting structures reflecting the synergetic collaboration between architecture, structure and craft.

TOLEDO GRIDSHELL, NAPLES, ITALY, 2012

RESEMBLING AN INFLATED parachute, the gridshell appears to be suspended in mid-air by four concrete benches at each corner. The shape results in four arched openings which allowed visitors to walk under and through this shelter.

This construction project forms the basis of two Master's theses examining gridshell form-finding and construction. Built in the courtyard of the University of Naples 'Federico II' in 2012 (Figures 6.18 (a) and (b)), the structure covered an area of 75 m2 (Figure 6.19). It was constructed from a flat grid 156 m^2 made from 2130 m of spruce wood laths with a total volume of 2.13 m^3 (Pone *et al*., 2013a, 2013b). These were joined by 626 nodes which were each composed of a single bolt connection at each intersection point.

Form-finding was carried out via the *Gridshell Form Finding Tool* (GFFT), a special plug-in scripted and developed for visual scripting of Kangaroo developed for this exercise (Pone *et al*., 2013a).

First, timber was graded and then a flat grid was constructed before being pushed up towards target points drawn on the ground. The timber lattice was pulled by ropes at eight strategic points and propped up to create the shell form. Following the formation of curvature, it was propped up from below to achieve the required vertical displacement. Once the final shape was reached, diagonal members and shear blocks were added to lock the shape. Following that, the props were removed.

The intersection detail was different from previous timber gridshells. Two pieces of timber, each profiled 40 mm and 15 mm, were connected in the middle to produce a spur upon which timber members were then connected. This clever connection meant that shorter timber members could be used. Each end of the gridshell was then inserted and bolted into a 'boot' which was connected to a specially designed timber raft by a pin. This was further anchored onto concrete benches weighing half a ton each to counteract potential uplift.

The flat mat was lifted by a series of winches and pulleys placed at the four corners of a central tower (Figures 6.20 (a) and (b)). Four sections of ropes tie eight points on the flat mat identified as most suitable for receiving the imposed strain when pulling up the flat lattice to create the correct curvature. While the lattice is being lifted, the horizontal supports of the tower were removed for the gridshell to pass through the scaffolding tower. Winches were positioned at the base of the structure to control horizontal displacements (D'Amico *et al*., 2015).

The structural consultants for this project were architect Bernardino D'Amico, engineer Oreste Mammana and architect Raffaele Stabile.

Figure 6.17 (a) The Swells gridshell, located in Sheffield city centre, looks across to the train station; (b) the geometry of the gridshell is locked in place by bracing timber laths that triangulate the structure
Source: © Gabriel Tang.

(a)

(b)

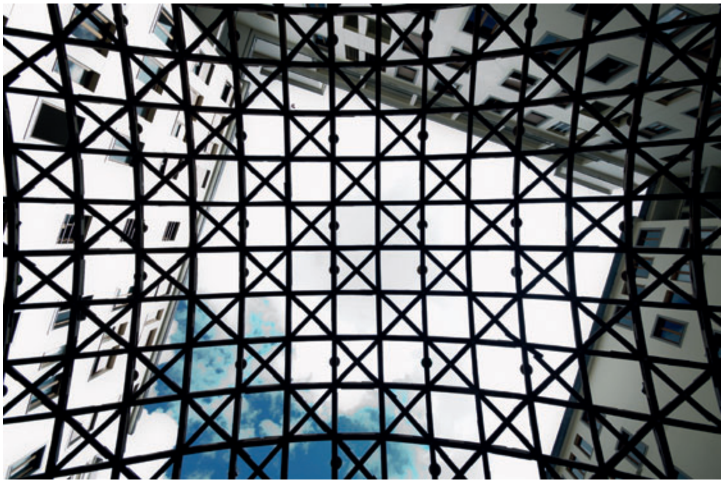

Figure 6.18 (a) The timber gridshell sits within the courtyard of the University of Naples 'Federico II'; (b) view of the gridshell skywards
Source: © Daniele Lancia.

Figure 6.19 The Toledo gridshell provides sheltered seating within the courtyard
Source: © Daniele Lancia.

Figure 6.20 (a) The flat gridmat is first constructed on the ground. Notice the scaffolding tower positioned in the centre of the gridmat. (b) The Toledo gridshell raised up from the ground by a system of pulleys and scaffolding
Source: © Daniele Lancia.

WOODOME GRIDSHELL, SELINUNTE, SICILY, ITALY, 2012

SINCE 2012, THIS insect-like free-standing gridshell has been stooping on a relatively flat area in the grounds of Parco Archeologico Marinella in Selinunte, Sicily (Figure 6.21). The Woodome gridshell is the result of an educational timber construction programme as part of a summer school.

The gridshell was constructed from five overlapping layers of timbers, four for the flat lattice and an additional one for the bracing system which lent stiffness to the overall gridshell with an interesting use of staggered connection joints between modules.

Being free-standing, and having no restrictions from adjacent architecture or buildings, there was creative freedom, although there were landscape issues to contend with as it was located within an archaeologically sensitive park. Similarities in scale can be drawn between this project and the gridshells at the Earth Centre, Doncaster (see Chapter 3).

Without any knots, the timber used was of first grade quality pine. The shape of the pavilion was made out of a cruciform-shaped flat mat first formed on the ground. The form-finding process was digitally aided by parametric design such as Grasshopper/Kangaroo as well as finite element software ABAQUS. Architect Bernardino D'Amico was the structural consultant for the project.

The gridmat was pushed up from the middle by the summer school student participants and propped up by timber members (Figure 6.22). The pavilion covered an area of 80 m² and was impressively constructed over five days. The structure was screw-bolted into the ground by metal bolts.

TRIO ENTRANCE ROOF, LECCE, ITALY, 2010

THE TRIO GRIDSHELL was designed as an entrance for a restaurant at Masseria Ospitale in Lecce (Figures 6.23 (a), (b) and (c)). Part of the perimeter of the gridshell was bounded by two straight edges of existing buildings. This highly expressive and dramatic gridshell was the culmination of the development of ideas from experimentation on the previous shells.

As the provision of a covered space for breakfast and lunch during summer was required, there was no requirement for this structure to be waterproof. Timber matchboards measuring 100 mm wide, 10 mm thick and 2 m long were used. They were flexible enough to follow the shape of the structure (Figures 6.24 (a)–(d)). As such, it was easy to fasten them to the structure.

This project was realised by GRIDSHELL.it in collaboration with architect Bernardino D'Amico and architect Filena Nigro with structural input from engineer Francesco Portioli.

CODA

COMPUTATIONAL DESIGN AFFAIRS (CODA) is a design consultancy/research group based at Barcelona Tech. With a focus on producing lightweight structural system and elastic deformation, through computational design, with special emphasis on digital manufacturing, the team has designed and built many interesting timber structures with the underlying aim of making efficient material use and reducing technological complexity.

JUKBUIN PAVILION, BARCELONA, SPAIN, 2012

IN 2012, A pavilion was built in Barcelona for the EME3 architecture festival. A system based on a tri-axial weaving technique borrowed from traditional Japanese basketry was used to create a timber gridshell in the Catalan city (Figure 6.25); the woven material exhibited isotropic behaviour. Through friction brought about by three interlocking axes, the gridshell self-stiffens, forming regular triangles and hexagons (Figures 6.26 (a)–(c)). Not only was this structure easily workable with

Figure 6.21 The timber gridshell in Selinute, Sicily, stands in the archaeological park
Source: © Gabriel Tang.

Figure 6.22 The timber gridshell was raised upwards by temporary timber struts
Source: © Daniele Lancia.

Figure 6.23 (a), (b) and (c) Restaurant entrance timber gridshell roof at Masseria Ospitale, Lecce, at various times of the day and in the evening
Source: © Daniele Lancia.

Figure 6.24 (a)–(d) Trio timber gridshell construction at various stages of completion
Source: © Daniele Lancia.

Figure 6.25 Jukbuin timber gridshell constructed in Barcelona for the EME3 architecture festival
Source: © Andrés Flajszer.

(a)

(b)

(c)

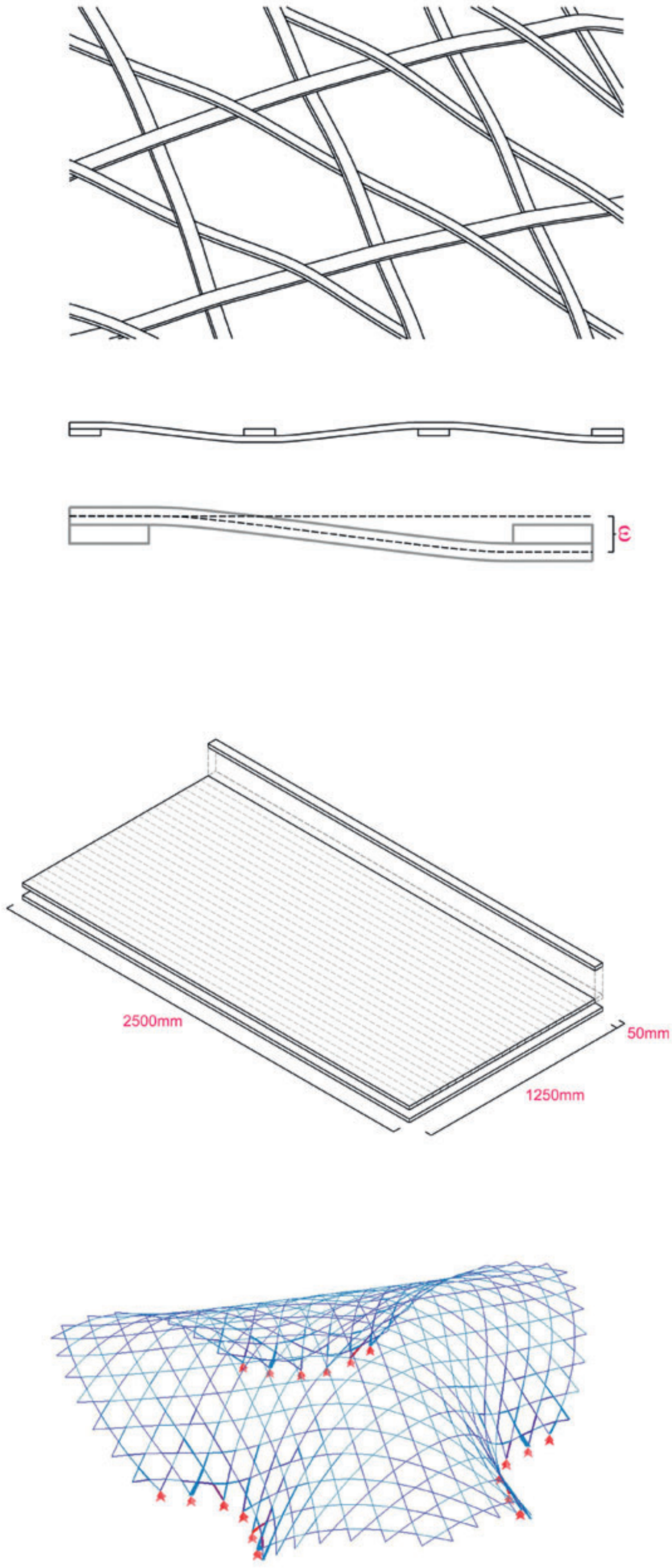

Figure 6.26 (a) The tri-axial weaving pattern is based on traditional Japanese basketry; (b) the timber elements are cut from 15 UPM WISA birch standard plywood boards sawn into 5 cm battens; (c) the physical simulation engine tool Kangaroo was used to model the behaviour of the woven fabric
Source: © Enrique Soriano and Pep Tornabell from CODA (Computational Design Affairs).

unskilled labour, held together by cable ties without the use of screws, it was easily repairable and dismantled by students.

Ratchet straps were used to retrain and form the shape. By subsequently shortening these cables, the points on the flat mat were drawn closer together at strategic points to create a three-dimensional form with a central rising apex. Following the successful erection, the strap supports were released and the shell stood up unaided.

The shell was made from 15 UPM WISA birch standard plywood boards sawn into 5cm battens (Figure 6.26 (b)); 280 pieces and 30 different sizes were used. The structure weighed a total of 257 kg and covered 93 m^2 and was built to a budget of €1500.

THE ALMOND, CATALUNYA, SPAIN, 2013

THIS TIMBER GRIDSHELL project was the result of the sponsorship of Incafust, the Catalan Timber Institute, who sponsored the project with sawn green pine timber (Figure 6.27). The project used sawn pine timbers to enhance its use. Considered misused as fruit boxes and for pallet making, the same timbers as 15 mm green deformed plank were used here where they were bent easily with low curvatures (Figures 6.28 (a) and (b)).

The shape of the timber gridshell, resembling an almond, was form-found by placing two arbitrary curves scanned by photogrammetry to generate a parametric model (Figure 6.29). The strategy was to create a multiple layer gridshell of conjugate geodesics. These curves have the virtue of being able to be built out of flat and straight planks, and have as well the advantage of sharing the normal on every intersection, thus simplifying the resolution of coplanar joints, when crossing strips.

With the timber delivered onto site, physical experimental bending tests were carried out to introduce minimum curvature restrictions that defined the curved surface. This method of timber use and construction while in its green state avoids time- and energy-consuming glulam technology. To gain shell stiffness, the elements become rigid by drying in the sun, resulting in a structure consisting of two cross-layers of timber sections, members in tension in the top layer and a lower layer acting in compression.

SINGAPORE UNIVERSITY OF TECHNOLOGY AND DESIGN GRIDSHELL, SINGAPORE, 2013

SINGAPORE HAS RECENTLY established a new educational establishment, SUTD (Singapore University of Technology and Design). A timber gridshell was designed and commissioned as part of a project in the research laboratory to build an outdoor shelter on a sloping grass bank between the library and a busy highway. The shelter provided space for staff and students to mingle and integrate and in the evenings acted as a venue for outdoor evening guest lectures.

The shelter took the form of a plywood gridshell covering an area of 200 m^2. The structure bends around a corner. The gridshell resembles an armadillo with metallic cladding on the outside (Figure 6.30). Inside, the gridshell structure is clearly visible (Figure 6.31). The structure is marked out with triangular cells milled digitally from 12 mm-thick marine grade (7 ply) plywood bolted together into a complex matrix (Figure 6.31). The cladding is made from 2 mm galvanized rolled steel tiles and all connecting bolts and nuts are made from stainless steel. The asterisk-shaped inner reinforcement straps used to secure the structure were also made from 2 mm rolled steel.

The design process

The design of the gridshell took a period of 10 months and was constructed by the use of simple two axes-routers (Figure 6.32). The process of manufacture and assembly had an important bearing on the design process and available technologies. It was interesting to note that although the primary designers from northern Europe were familiar with the extensive and economical

Figure 6.27 The Almond timber gridshell
Source: © Andrés Flajszer.

Figure 6.28 (a) and (b) The Almond timber gridshell under construction
Source: © Andrés Flajszer.

Figure 6.29 Drawing showing how cross-layers are sequenced to create the gridshell
Source: © Enrique Soriano and Pep Tornabell from CODA (Computational Design Affairs).

Figure 6.30 The timber gridshell in Singapore is encased in an overlapping layer of steel tiles
Source: © Philipp Aldrup.

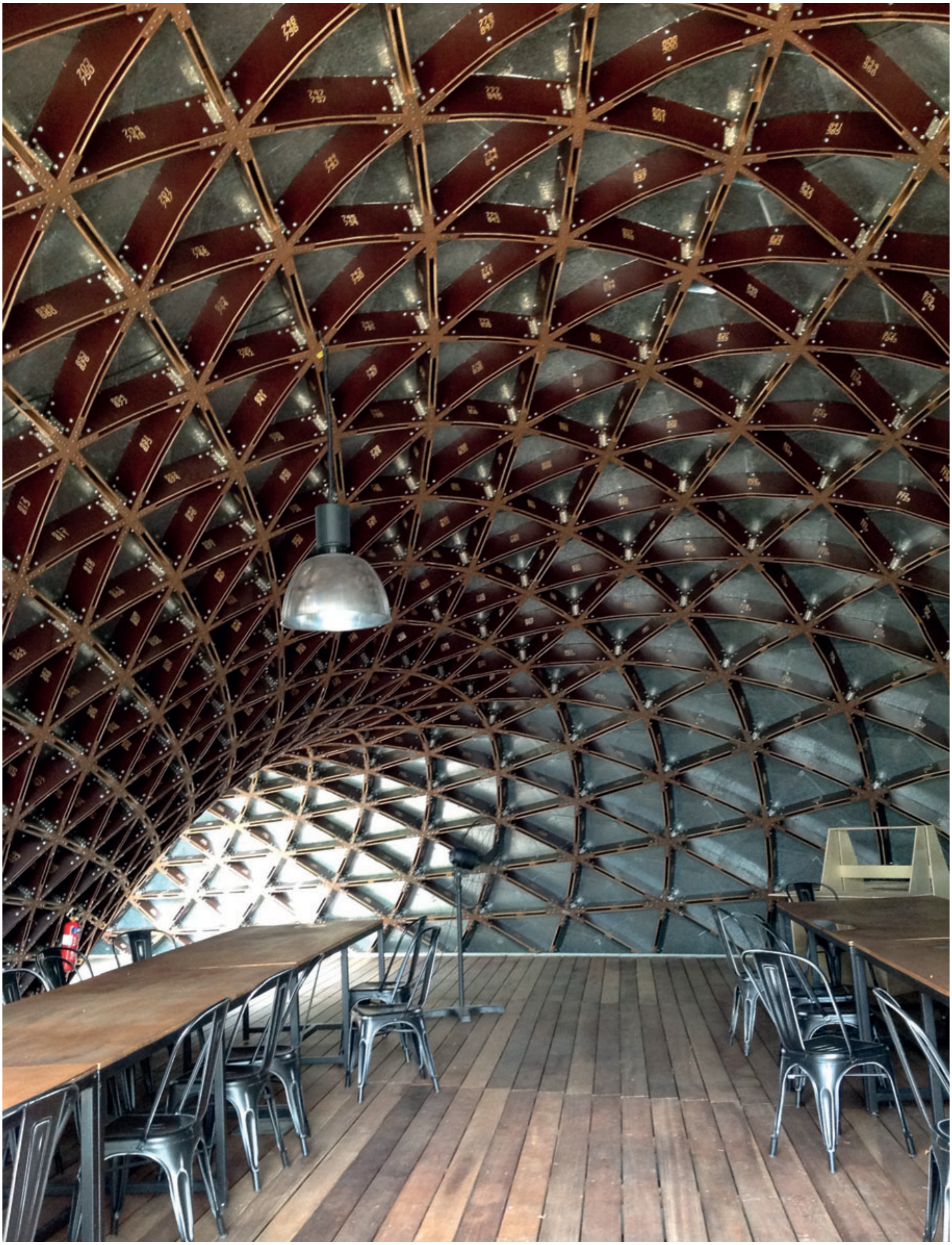

Figure 6.31 The interior of the gridshell displays intricate patterning, made possible by digital fabrication
Source: © Gabriel Tang.

use of timber products, the high price of plywood products in Singapore did come as a surprise (Sevtsuk and Kalvo, 2014). In this instance, however, plywood was chosen for its excellent structural performance, stability and ease of working with available digital fabrication technology. Because it was a structure unfamiliar to the local regulatory bodies, like the use of paper tubes in the 2000 Japan Pavilion (see Chapter 3), extensive structural testing had to be carried out.

The principle of gridshell design is closely linked to the way that it was constructed. Using 3-D line network software, the shell was geometrically broken down into triangles (ibid.). The algorithm turns the shape into a double-wall structure while keeping all vertical elements planar and the component outlines vertical. This enables these components to be cut easily using the 2-D cutters. All the 3012 panels were CNC-cut and engraved with a specific number (Figure 6.34 (a)). Some panels have a slight curvature that accommodates some changes in geometry.

Three panels are connected together to form a triangle using standard 4-inch stainless steel door hinges which also address associated shear loads. Six of these triangles are then joined together to form a hexagonal node with M8 bolts on the sides (Figure 6.33 (a)). Plywood packings 25 mm thick were used as spacer blocks (ibid.). The node was then covered with a tile at the top (Figure 6.33 (b)) and secured at the bottom with a reinforcement strap.

According to the designers, the choice of cladding material was decided at a late stage in the design. Singapore has a hot, humid climate with sunshine and torrential rain. For this building to perform its intended function, keeping rain out was imperative. The decision to use rolled steel to form the building envelope was a practical one premised on cost and fire resistance, with polycarbonate considered, but quickly dismissed due to fire safety concerns (ibid.). Each hexagonal tile is composed of two sections machine laser cut and bolted together. The tectonic is fully expressed internally (Figure 6.34 (b)).

Assembly and erection

The assembly of the modules was carried out by student volunteers off-site (Figure 6.35), before being brought on site. In sections, these were assembled by professional contractors. The process of assembly was straightforward and required the co-ordination of matching numbers as all the pieces had been numbered accordingly. All the components were machine cut, the holes were pre-drilled and the matching numbers engraved, therefore, no craft skill was required in this instance as it was a matter of manual assembly to complete the gridshell. With the involvement of different statutory agencies, this was executed as a building construction project where building contractors with craning equipment were engaged.

Unsurprisingly, life-sized proof testing had to be carried out with a safety factor of between 4 and 5 to satisfy building regulations. The safety officer mandated a load test, thus a cable was hung and loaded with a 200 kg weight, which simulated the weight of two workers and a tool box, i.e. 200 kg. The sturdiness of the structure was verified to a small acceptable deflection between 2–4 mm (ibid.).

Digital advances mean construction with a precision that was previously achievable only by materials such as steel and glass can now be applied and expected with timber. Another example of how digital design impacts on gridshell design, the realisation of an intricate assembly of straight plywood board components to create a curved surface, is made possible because of scripting and parametric design development. With grid sizes easily made irregular, reinforced by the ease of translating these into components through digital pre-fabrication, this case study evidences a new way of making timber gridshells. This heralds a departure from the early methods devised in the 1960s, with a change of craft emphasis from the artisan to digital technology, thereby changing the form and tectonic expression.

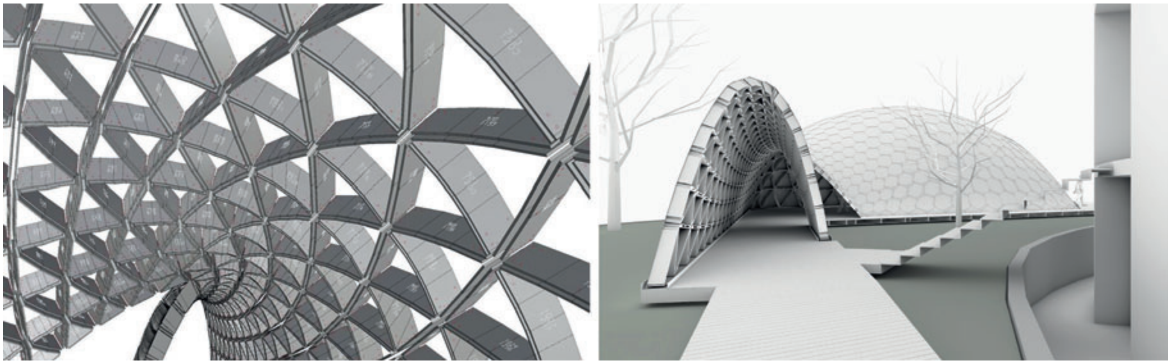

Figure 6.32 Computer-generated images of the design
Source: © City Form Lab.

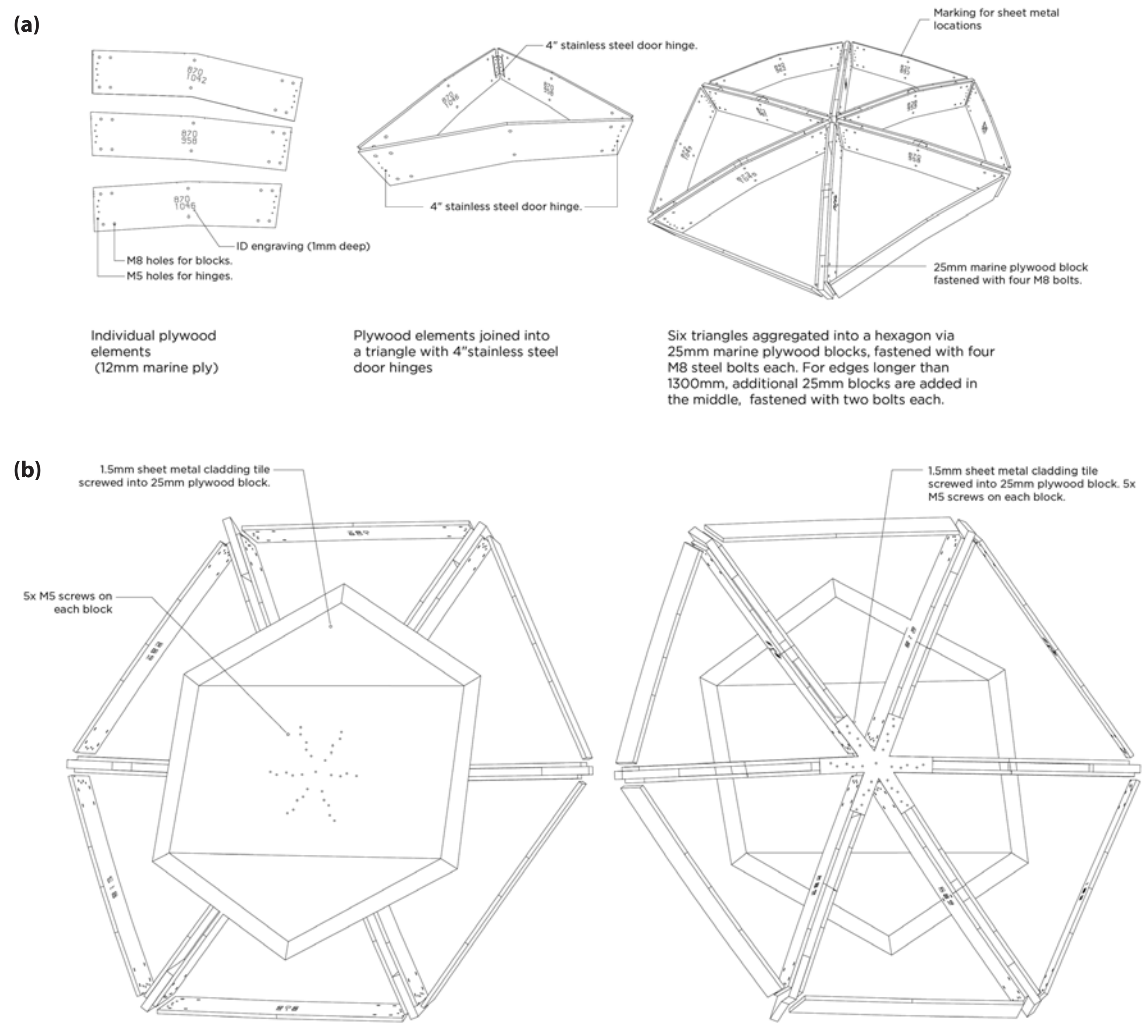

Figure 6.33 (a) Drawing describing how milled boards are connected to first form triangles, then bigger hexagonal units; (b) drawing showing positioning of single steel tile over gridshell
Source: © City Form Lab.

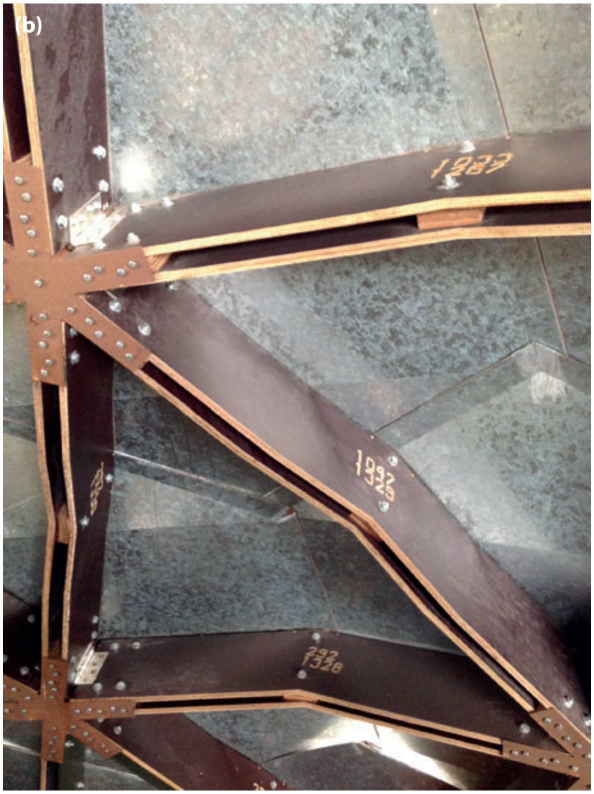

Figure 6.34 (a) Components of the gridshell are arranged to optimise the material usage; (b) the tectonics of construction are clearly expressed and celebrated
Sources: (a) © City Form Lab; (b) © Gabriel Tang.

Figure 6.35 An exercise in construction, students help to build up the triangular modules first
Source: © City Form Lab.

Further reading

Colabella, S., Lancia, D., Repola, L., Memmolo, R. and Pone, S. (2015) 'A monitoring system for wooden post-formed gridshells', in *Proceedings of the International Association for Shell and Spatial Structures (IASS)Symposium 2015*.

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CHAPTER SEVEN

Made to measure

Digital fabrication

SINCE THE BEGINNING of the twenty-first century, rapid advances in the ease of digital processing of complex geometry, structural modelling and digital manufacturing have revolutionised the design and manufacture of free-form timber gridshell structures. The workability, wide availability, sustainability and well-mannered material properties of sawn timber allowed craftsmen of the past to fashion, for example, clinker-built hulls of ships. In recent years these advantages have been extended through the availability of engineered timber with enhanced properties and improved understanding of the material's behaviour. There have been similar advances in the digital design and fabrication process – computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), including the development of more sophisticated computer numerically controlled (CNC) fabrication techniques. Bespoke, curved, glue-laminated timber beams can now be manufactured and rapidly processed on multi-axis milling machines to produce high-precision, double-curved components. Handworking craft has become digital craft. A direct consequence of this is that designers are no longer dependent on the deformation of a regular square or rectangular mesh to create double-curved gridshell surfaces. Such double-curved surfaces can now be specified and built directly. In this chapter we review some inspiring applications of these new technologies in medium- and large-scale gridshells, while current practice is reviewed in Chapter 8.

SOLEMAR THERME, BAD DÜRRHEIM BRINE BATHS, GERMANY, 1987

BUILT IN 1987, the suspended timber gridshell roof of the health spa in Bad Dürrheim in the Black Forest region of Germany was designed by Geier and Geier in collaboration with the engineers Wenzel, Frese and Barthel, with form studies by Klaus Linkwitz (Herzog *et al*., 2004: 265) (Figure 7.1). The project sees the use of glulam ribs assembled to form gridshells draped over five glulam columns (trees) between 9.1 m and 11.5 m tall spaced 20 m apart. With a surface area of 2500 m² (Linkwitz and Veenendaal, 2014: 147), the roof covers a floor area of 1500 m² (Herzog *et al*., 2004: 265).

The forms were generated digitally and follow approximate stress trajectories (ibid.: 265). The shells are formed from a combination of meridians hanging to natural catenary lines between the five glulam trees and annular ring beams of between 6 and 8 m in diameter (of 80 x 80 or 120 x 140 mm sections) radiating out from the columns (Woodcampus, 2015: 26) (Figure 7.2). With each rib being held together by finger-jointing, each rib can withstand both tension and compression forces. The meridians, measuring 200 mm x 205 mm in section, connect columns and edge boundaries of the structure (ibid.: 26). The annular rings are spaced at 800 mm centres. These two systems are connected together using true pins (ibid.: 26).

To create the complex double curvature and sometimes twisting elements, the glulam ribs are built up from a number of laminates. They were at first curved in one direction but flat in the other. These pieces were then bonded a second time to create the double curvatures required. They were assessed for strength and reliability of the ends joints (ibid.: 26).

Special durable fixings in the wet humid environment were used as hardwood dowels to connect the tenons within the branching tree structures. These columns constructed from glulam segments can be lifted up by jacks. Adjustable pads connect the shell to the tree supports to encourage the production of membrane forces, with lattice shell forces being minimised. Two layers of diagonal timber boarding give the shell its shear strength and the roof is eventually covered with PVC membrane (Herzog *et al*., 2004: 265).

TOSKANA THERMAL SPRINGS, BAD SULZA, GERMANY, 1999

IN GERMANY, TIMBER gridshells are gaining popularity as a structural solution for indoor spas and thermal springs facilities. Another timber gridshell used to provide a tempered environment is the Toskana Therme Bad Sulza in Bad Sulza, Germany (Figure 7.3 (a)).

Constructed in 1999, the free-form ribbed shell, resembling a wave frozen in motion, was designed by Ollertz Architekten and structurally engineered by Trabert und Partner. It was constructed to cover the thermal bath facilities and pools at Bad Sulza. Located on the gently rising terraces of former vineyards, the gridshell defines a continuous uninterrupted space without any use of intermediate supporting column (Figure 7.3 (b)).

Using the Zollinger or reciprocal principle, the gridshell was assembled from individual timber members each measuring approximately 160 mm x 240 mm to create a grid size measuring approximately 1600 mm x 1600 mm (Herzog *et al*., 2004: 247). With steel connections being kept to a minimum to reduce the possibility of corrosion in the humid environment (ibid.: 247), wooden dowel connectors were used (Figure 7.4 (a) and (b)).

The roof was initially form-found using a computer program that replicates the principles of the inverted hanging chain (Figure 7.3 (b)). A digital suspended cable net was subsequently inverted so that all cables originally in tension would then act in pure compression under self-weight loading (ibid.: 247). The ability to form-find digitally on the same principles is a far cry from the physical form-finding methods used in the Mannheim Multihalle in the 1970s (see Chapter 2), also seen in the laboriously ingenious hanging chain model-making practices of Antoni Gaudí. Subsequently, the inverted hanging form was adjusted to accommodate functional and design considerations (Figures 7.5 (a) and (b)).

Double-curved edge beams then carry the interconnected glulam beams and their compressive forces to transfer them into their inclined concrete abutments (ibid.: 247) shown in Figures 7.3 (b) and 7.6 (a), (b) and (c).

This project sees the fabrication process moving towards a mechanised basis and the structure is braced at their intermediate surfaces. Like the Solemar Therme, Bad Dürrheim, described earlier, with wooden ribs and

Figure 7.1 The gridshell form at the Solemar Therme, Bad Dürrheim Brine Baths, creates an extensive roof draped over five columns
Source: © Solemar Therme.

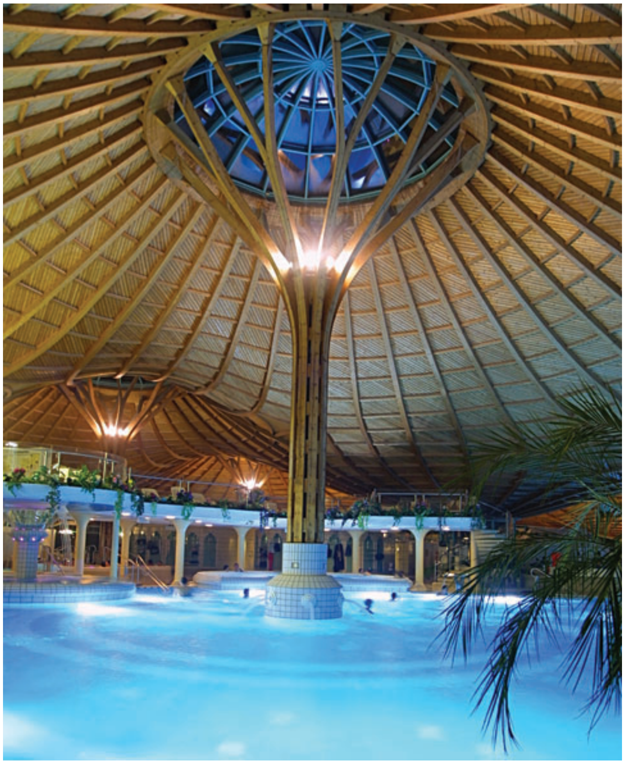


Figure 7.2 The spectacular and dramatic hanging timber gridshell roof displays the close workings of architecture, engineering marvel, the craft skills of the builder and the influence of digital technology in form-finding and fabrication advancement. The gridshell structure is clearly expressed
Source: © Solemar Therme.

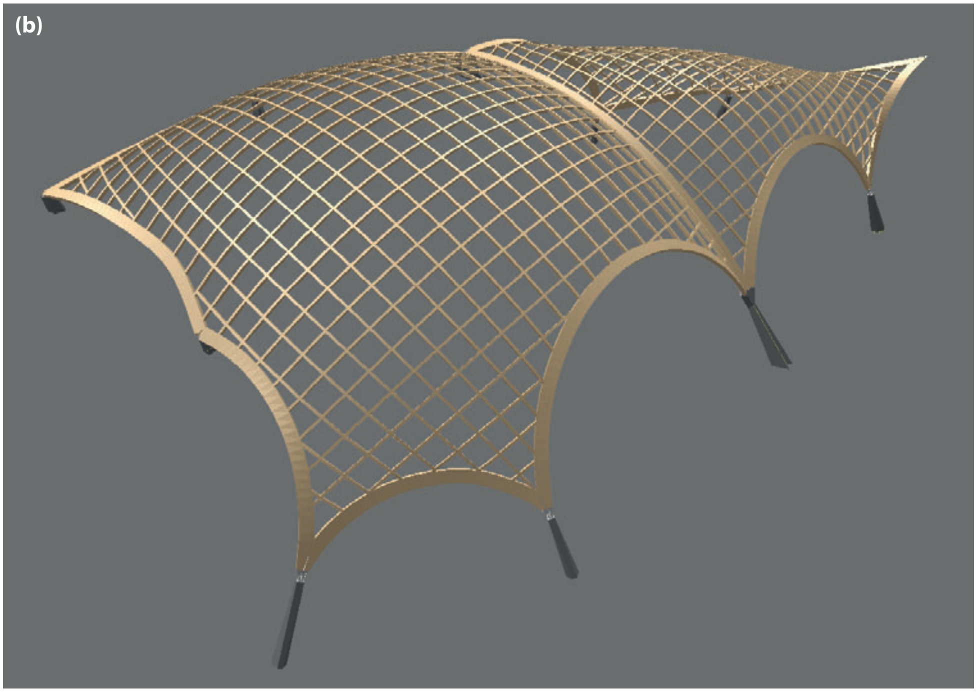


Figure 7.3 (a) An aerial view of the timber gridshell roof. Notice that skylights are designed to follow the grid openings of the gridshell. (b) The form of the gridshell roof at Bad Sulza was form-found digitally from an inverted cable net. Notice that the gridshell load is in fact transferred into inclined reinforced concrete abutments
Source: © Ollertz Architekten.

(a)

(b)

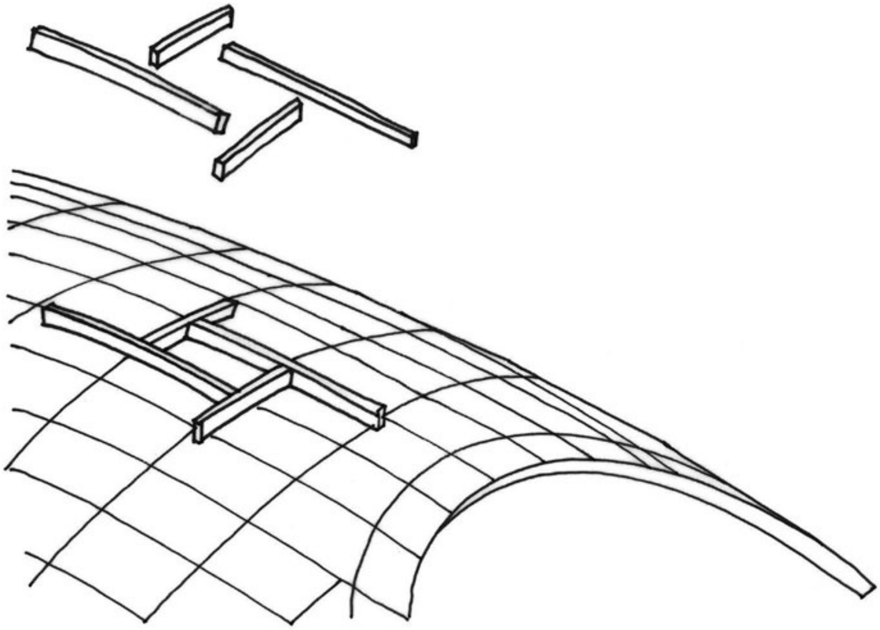


Figure 7.4 (a) The grid units were assembled from individual timber members connected with timber dowel connectors in an arrangement using the Zollinger or reciprocal principle; (b) the design of a unit which forms the entire gridshell
Sources: (a) © Ollertz Architekten; (b) © Gabriel Tang.

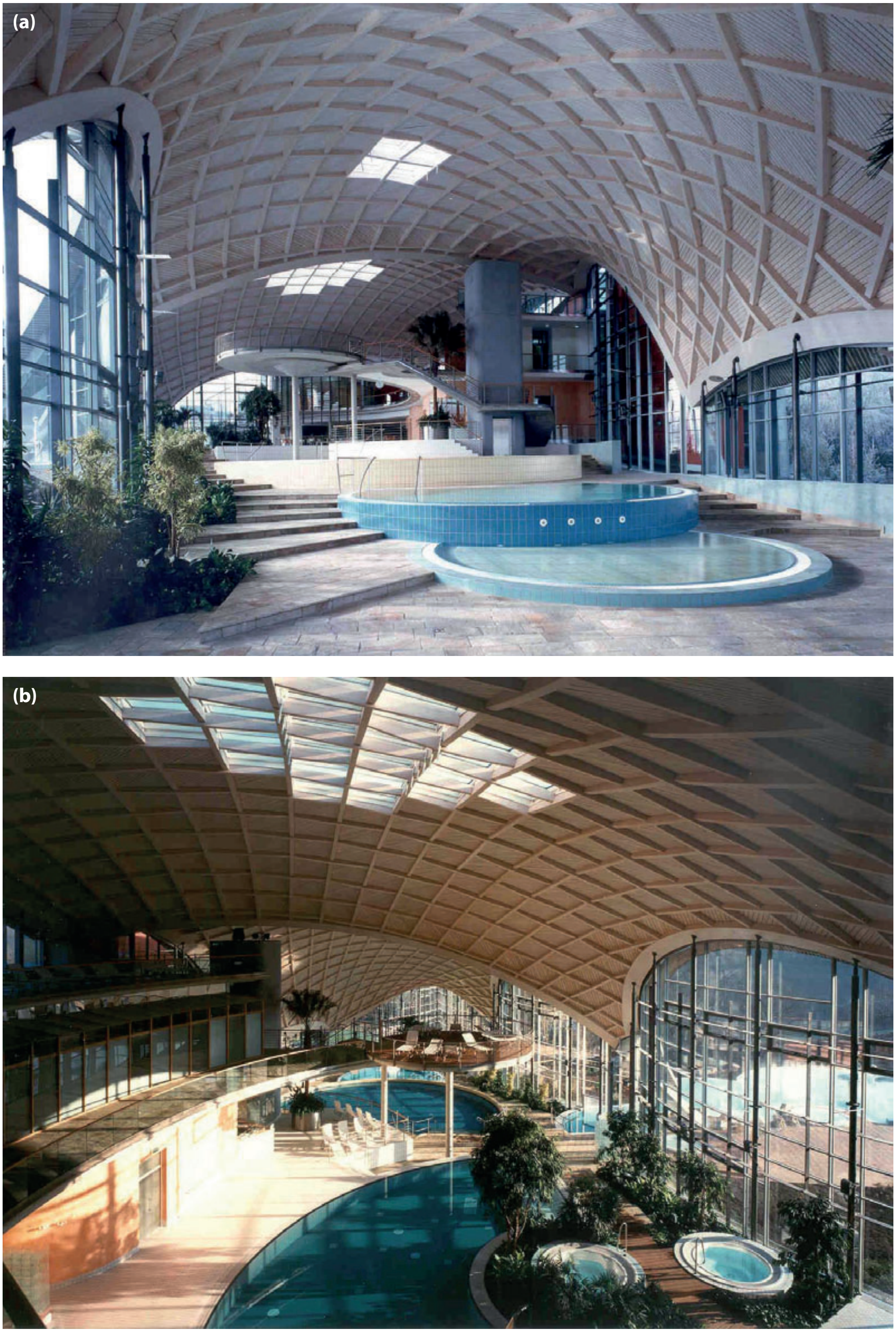


Figure 7.5 (a) and (b) Interior views of compression gridshell roof in Bad Sulza
Source: © Ollertz Architekten.

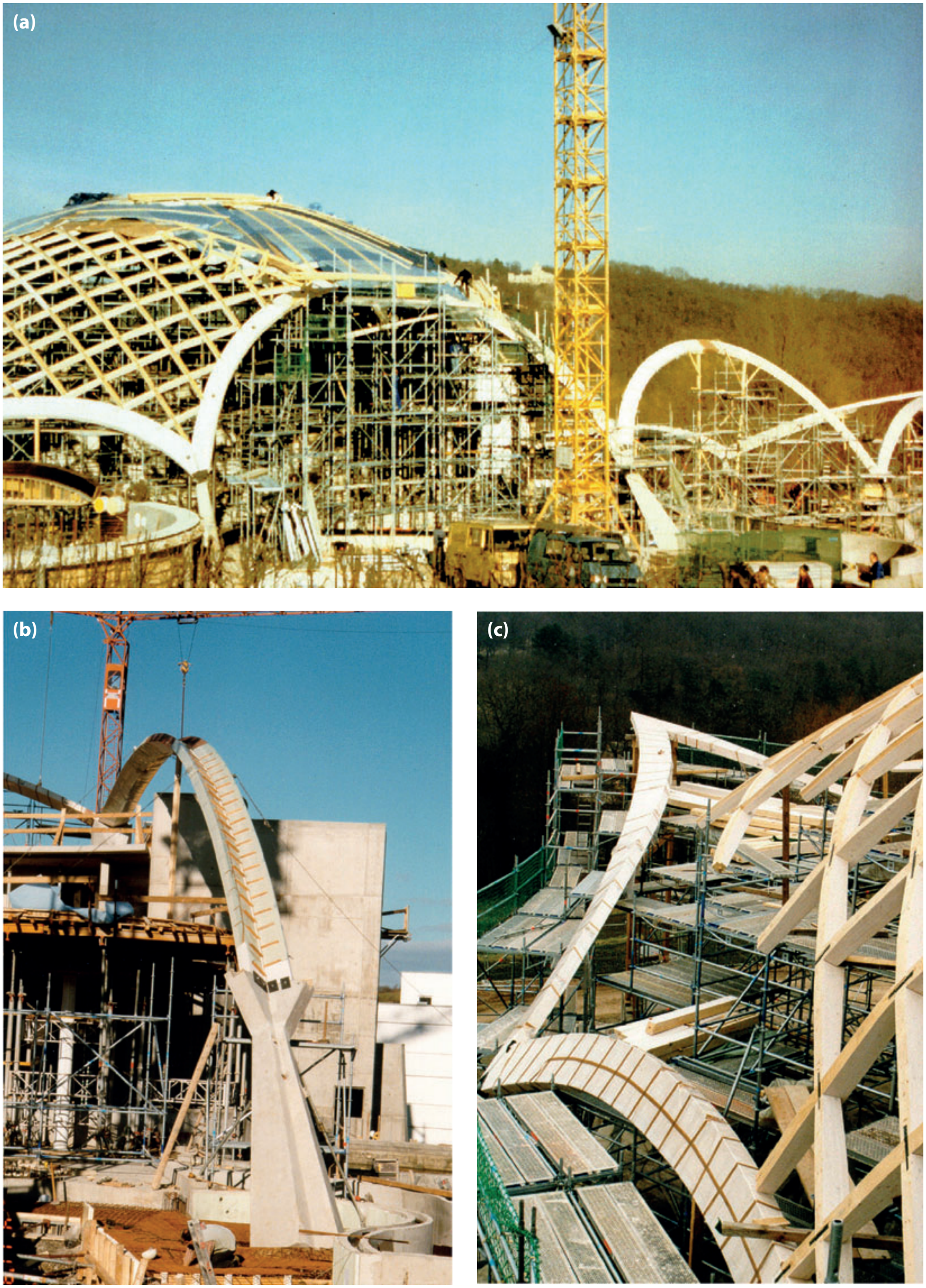


Figure 7.6 (a) Made from glulam timber, the doubly-twisted timber arches are raised, supported by temporary scaffolding providing edge stability to the finished structure; (b) concrete abutments were constructed in readiness to receive the twisted glulam arches; (c) the gridshell eventually develops a synclastic surface defining the space below
Source: © Ollertz Architekten.

inner boarding layer exposed on the underside, the materials were chosen for their aesthetic quality to fully exhibit all the appeal of a timber gridshell.

The roof grid is stabilised by two layers of conifer board (30 mm) covered with a vapour barrier and two layers of mineral fibre insulation, and then topped with a high-quality polymer sealing membrane. To ensure that this complied with the free-form roof contours, discrete strips were made up on site, mechanically fixed to resist wind uplift, and then welded to form a continuous waterproof envelope (DuPont, 2015).

TOSKANA THERMAL SPRINGS, BAD ORB, GERMANY, 2009

IN 2009, ANOTHER gridshell roof was constructed for Toskana Thermal Springs at Bad Orb, 275 km south-west of Bad Sulza (Figure 7.7 (a)). Designed by the same architects, Ollertz Architekten, the timber shell takes a free-form mode, which resembles 'a wave frozen in motion' (Figure 7.7 (b)). With eight border beams, the roof is assembled from 682 timber ribs and 682 individual acoustic elements (HESS, 2015). Although erected using the same Zollinger/lamella/reciprocal principle, compared to the gridshell at Bad Sulza, it displays more advanced morphological complexities resulting from developments in digital form-finding and digital fabrication (Figures 7.8 (a) and (b)).

Covering an area of 2200 m^2 (HESS, 2015), the gridshell used double-curved and twisted beams that can be noted in Figure 7.9, in particular in the area where the grid meets the ground on the right. These components were fabricated using cutting-edge digital manufacturing technology developed by HESS TIMBER GmbH who also provided services of planning, production, assembly and delivery of the roof shell timber structure.

Construction of the Toskana Bad Orb gridshell necessitated the extensive use of temporary scaffolding platforms (Figure 7.10 (a)). As the roof does not achieve full structural integrity or its final shape until all components are installed, temporary props were used to define the profile of the double-curved surface and to carry the self-weight of the gridshell structure until it was able to support itself (Figures 7.10 (b)).

CENTRE POMPIDOU-METZ, METZ, FRANCE, 2010

OPENED IN MAY 2010, and seven years in the making, the Centre Pompidou-Metz, is the result of a competition-winning design conceived by architects Shigeru Ban Architects, Jean de Gastines, Paris, and Philip Gumuchdjian with structural engineers Arup, London, Terrell, Boulogne-Billancourt, Paris, and Herman Blumer, Waldstatt. It is crowned by a free-form, double-curved, timber gridshell structure, which is loosely modelled on the form of a traditional woven Chinese hat, a concept presented by Shigeru Ban at a design team meeting in August 2003 (Lewis, 2011: 21). Clad with a translucent PTFE/glass fabric membrane, the roof has the appearance of being draped over the building (Figure 7.11).

Having a hexagonal plan with side length of 52 m, the roof, of approximately 7000 m^2 in plan, has a maximum width of 104 m; however, the roof structure spans a maximum of around 50 m. Although the initial design concept envisaged a reciprocal/lamella grillage system of discontinuous, mutually supporting elements with simple connections (ibid.: 22), similar to that used in the Toskana Spa roofs described above, the final solution, reminiscent of a Chinese hat, is a hybrid gridshell of laminated timber. It is tessellated with a pattern of hexagons and triangles. These have a side length of around 1.57 m (derived by subdivision of each roof edge by 33), resulting in a three-way grid having beams spaced at about 2.7 m centres (Figure 7.12). The whole is supported on four inverted conical, or funnel-shaped, downward extensions of the gridshell which reach to the ground, a circulation core which maintains the central peak of the roof at a height of about 36 m, and oval steel rings where solid building elements (the exhibition galleries) punctuate the envelope (ibid.: 20–21; Anon, 2010), see the section shown in Figure 7.13.

(a)

(b)

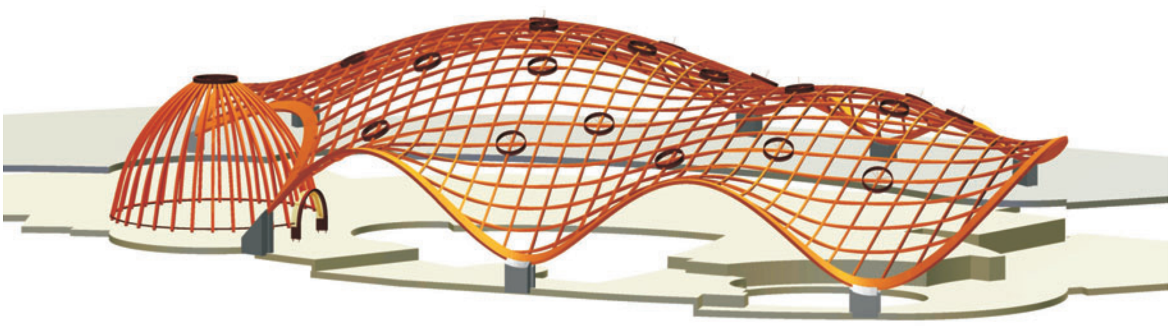
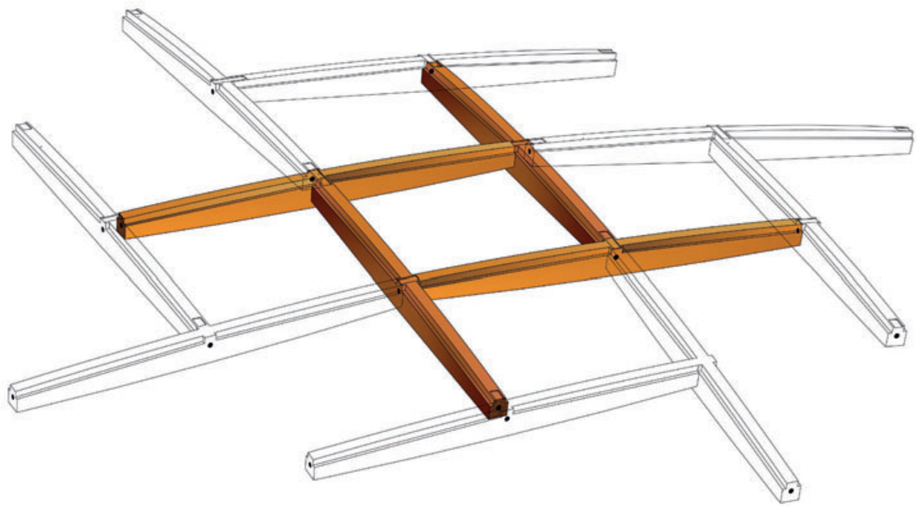


Figure 7.7 (a) The Toskana Thermal Springs, Bad Orb timber gridshell as built; (b) a digital model describing the geometry of the grid
Source: © Ollertz Architekten.

(a)



(b)

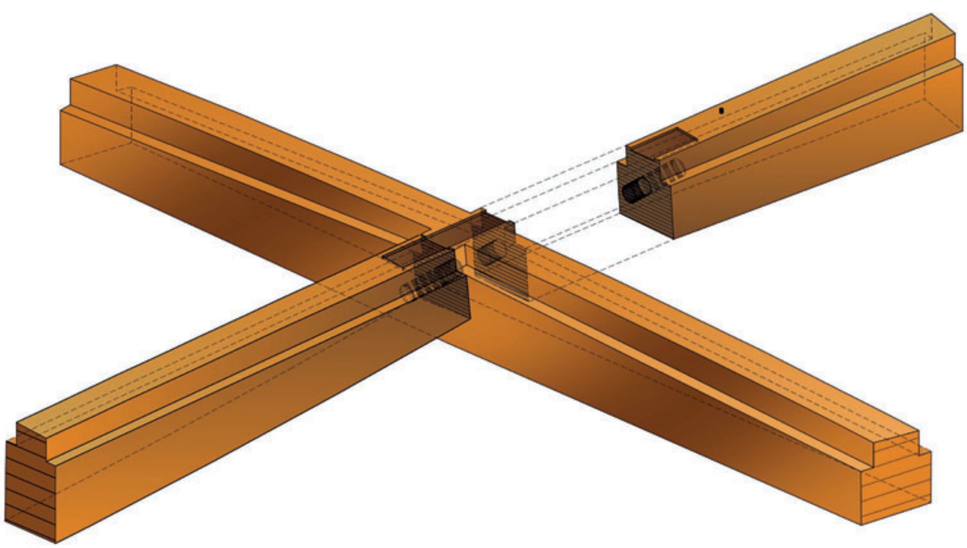


Figure 7.8 (a) Glulam timber elements assembled in the Zollinger/lamella/reciprocal principle form the 'building blocks' of the gridshell surface; (b) detail drawing of connection details
Source: © Ollertz Architekten.

Figure 7.9 The completed interior of the free-form timber roof. Note the curved beam components in the area where the grid meets the ground. Notice also the reflection of the structure in the still pool waters
Source: © HESS TIMBER GmbH & Co. KG.

Figures 7.10 (a) and (b) The construction of the Toskana Bad Orb gridshell shows the extensive use of temporary scaffolding platforms on which props support the gridshell structure until it gains its final shape and structural integrity
Source: © HESS TIMBER GmbH & Co. KG.

Figure 7.11 Translucent PTFE/glass fabric roof membrane on the timber gridshell of the Centre Pompidou-Metz
Source: © Koffi Alate, Taiyo Europe.

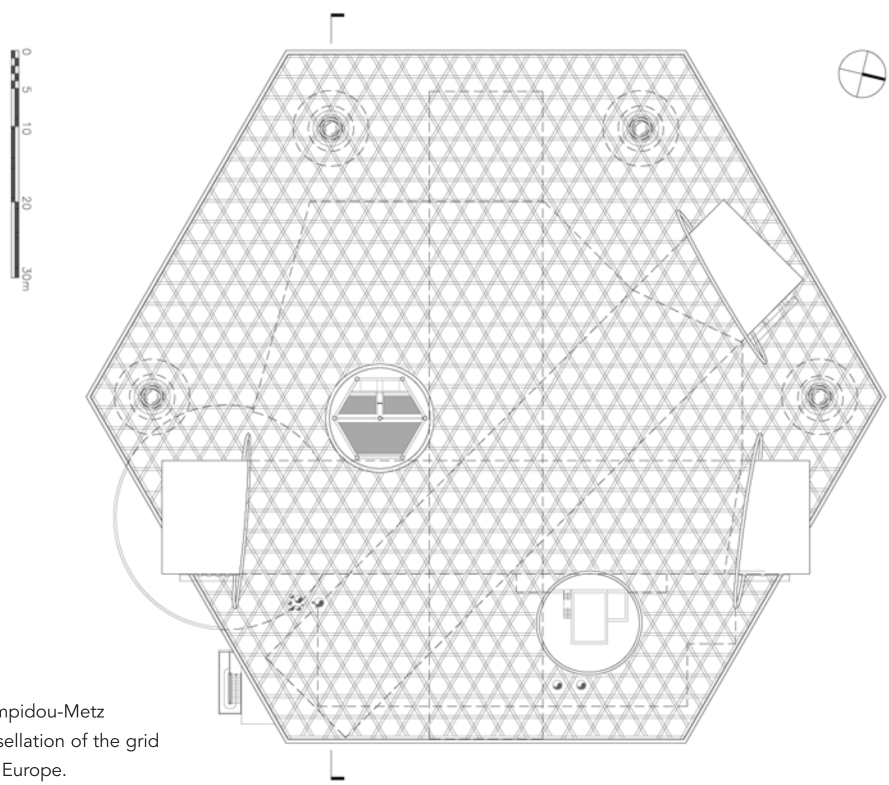


Figure 7.12 Roof plan Centre Pompidou-Metz showing hexagonal/triangular tessellation of the grid
Source: © Shigeru Ban Architects Europe.

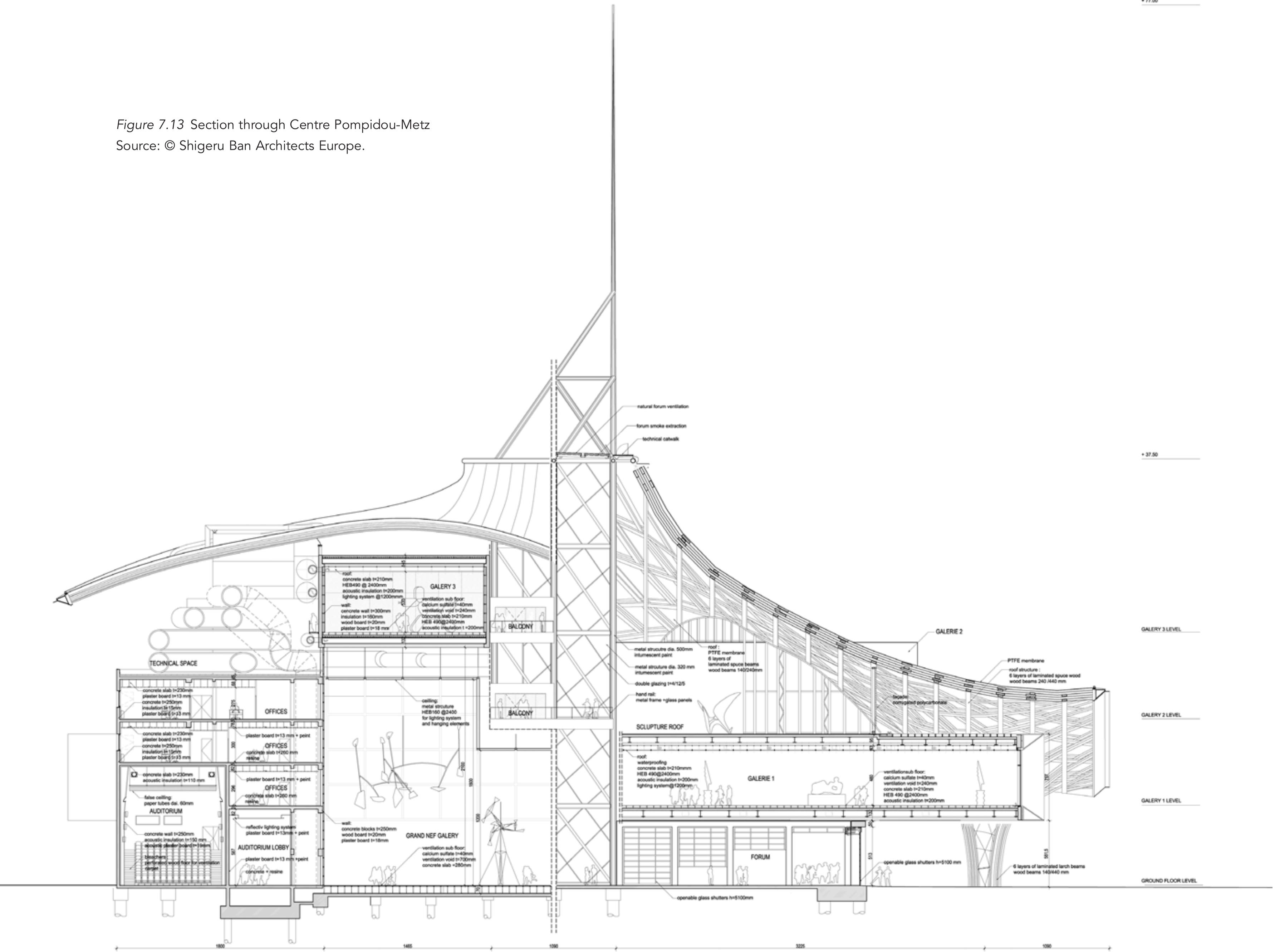


Figure 7.13 Section through Centre Pompidou-Metz
Source: © Shigeru Ban Artists Europe.

Initially form-found as a minimum surface using Arup's 'in-house' GSA software, in a manner similar to that used to derive the form of a tensile membrane or cable net, the surface was refined through iteration and collaboration between architect and engineer until an architecturally acceptable shape and grid density was defined (Lewis, 2011: 21). Subsequently, the structural system required to construct the free-form shape in timber went through a process of gradual refinement. Initially each grid line was conceived as three planks of 350 mm wide x 81 mm thick Kerto-S LVL separated by spacer blocks 12 mm deep to allow weaving of the three intersecting grid directions. Subsequently, considerations of cost and fabrication complexity resulted in a reduction in the number of planks and a change to a cheaper but weaker material – two 500 mm-wide x 200 mm-thick softwood glue-laminated planks. The increased grid depth – 800 mm for the gridline beams and 1200 mm at intersections had structural benefits – increased bending stiffness and reduced deflections (ibid.: 22–23).

During the detailed design by Arup the ribs of the gridshell had been envisaged to be glue-laminated timber elements prefabricated with double curvature and twist. However, the German timber contractor, Holzbau Amann GmbH, proposed an alternative method of manufacture using CNC milling equipment to fashion components from initially-oversized glue-laminated blanks. Although this might be considered a less efficient use of an expensive engineered material and perhaps wasteful of natural resources, the waste generated is used to produce wood fuel pellets. This method was found to be cheaper, faster and to yield more accurately dimensioned components (Figures 7.14 (a) and (b)).

Because the grain of the timber would, in some parts, no longer be parallel to the axis of the member, a reduction in design strength was imposed for some elements. Nevertheless, a re-evaluation of wind and snow loadings enabled a reduction in the size of the plank ribs to 440 mm wide x 140 mm thick (ibid.: 25). To some extent this compensated for the more material-hungry fabrication technique.

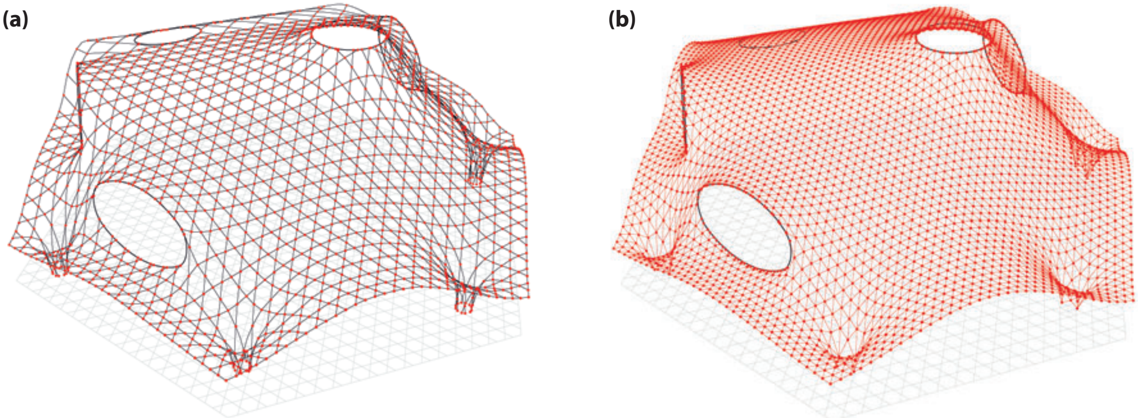
In total, around 18000 m of double-curved timber ribs up to 14 m in length – shorter in areas of high curvature – had to be manufactured and installed. Hence, given the preferred fabrication technique, a highly important aspect of the project was the cost-effective realisation of the complex geometry, an area which in recent years has been assisted by the rapid development of digital design and fabrication software. Fabian Scheurer has suggested this process is not necessarily as simple as it seems. To expect to be able to merely supply a fabricator with a 3-D CAD model and to receive the structure as a kit of finished mass-customised components at a later date 'is downright utopian' (Scheurer, 2010b: 93). It is a matter of tolerances. Those of the computer model have to be more precise than those of the CNC equipment that will be used for manufacture: 'accuracy must be in the range of a few hundredths of a millimetre' (Scheurer, 2010a: 380). For the Metz grid, specialist consultants designtoproduction GmbH, who have offices in Zürich and Stuttgart (designtoproduction GmbH, 2012), assisted by programmers iCapp, also from Zürich, provided Holzbau Amann with reference geometry for the curved elements. Using a NURBS model, they generated a precision reference surface, starting from the basic digital model comprising node points (defined by co-ordinates) connected by straight line elements (Scheurer, 2010a: 380; 2010b: 90) (Figures 7.15 (a)–(d)).

Individual pieces of the grid planks were connected longitudinally by concealed 5 mm-thick twin steel plates fixed by dowels. Assembled on temporary falsework, the six plank layers forming the grid were joined at each intersection by a single 24 mm diameter (M24) bolt (Figure 7.16). These were installed through tolerance holes pre-drilled in spigots glued into each plank. Pre-stress was applied to the bolts using 125 mm spring washers, in a similar way to the nodes of the Mannheim Multihalle constructed 35 years earlier, see Chapter 2.

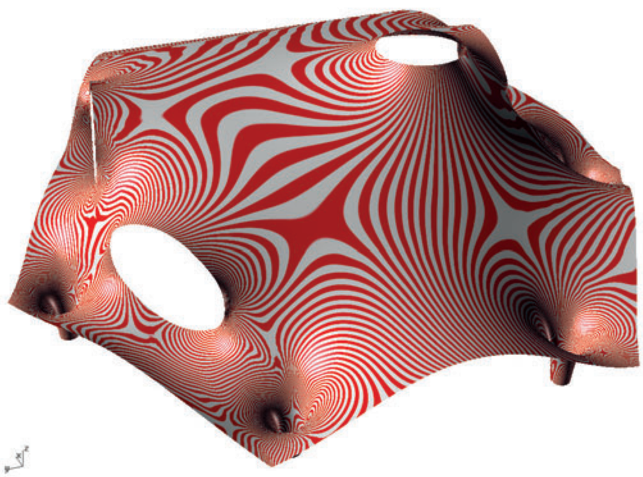
As with the Mannheim gridshell, the structure was covered with a translucent membrane, in this case, PTFE/glass. To minimise the possibility of condensation on the inner surface of the membrane coming in contact with the timber gridshell, the fabric strips were tensioned between reinforced channels raised on steel chairs fixed to the upper layer of the gridshell (Figures 7.17 (a) and (b)).

Figure 7.14 (a) Digitally derived component geometries; (b) oversized glue-laminated sections machined to form curved planks
Source: (a) © designtoproduction GmbH; (b) © Holzbau Amann GmbH.

(a) (b)



(c)



(d)

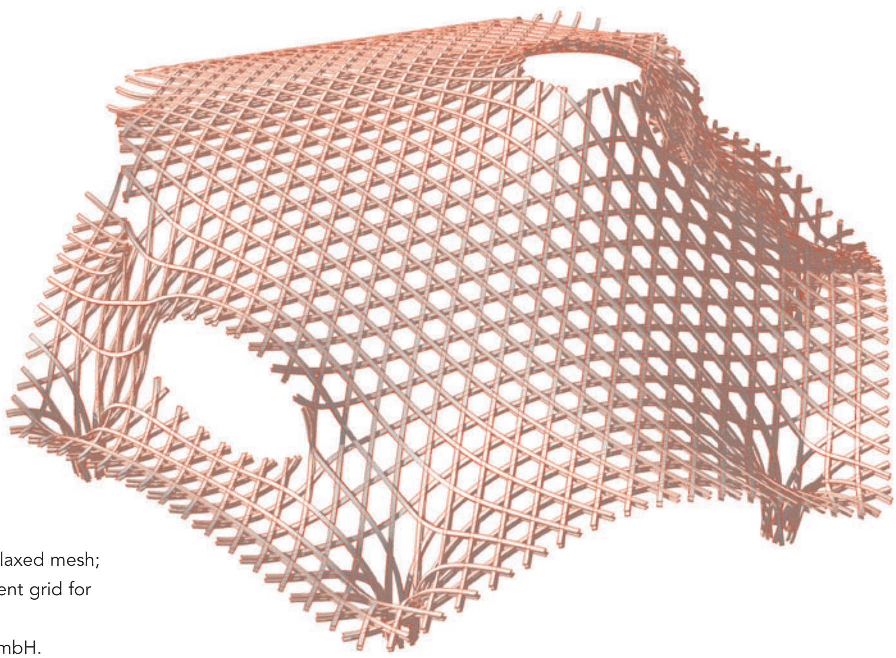


Figure 7.15 (a) Input mesh; (b) relaxed mesh; (c) reference surface; (d) component grid for the gridshell surface
Source: © designtoproduction GmbH.

Figure 7.16 Gridshell assembled on temporary falsework. The plank layers were joined at each intersection by a single 24 mm diameter (M24) bolt.
Source: © Holzbau Amann GmbH.

It has been commented that the translucent membrane covering perhaps detracts from the delight of the timber grid when viewed externally during the day: 'In the day the roof is opaque. Press photographs show an appealing glowing mass, but these surely mourn the loss of the initial proposal's fundamental transparency' (Hunter, 2010). Nevertheless, the translucent membrane creates a light and airy interior that 'allows soft natural light to filter into the interior' (Shigeru Ban Architects, 2012a) and illuminates the grid so that its geometry can be appreciated once inside the building (Figure 7.18).

A more transparent cladding might have revealed the structure from the outside but the timber grid would then not have been so clearly defined against an off-white background. Glass would have loaded the grid more heavily, with a consequent increase in structure, whereas parts of the tessellation are rather small for ETFE cushions and the necessary distributed inflation system would have had to be detailed carefully not to conflict with the purity of the timber grid. Rainwater run-off from the large roof area is accommodated through inverted membrane cones half-concealed within the funnel columns (Figure 7.19).

An important consideration in the design of gridshells is the interface between the double-curved timber grid and the more rectilinear elements of the building. In this case, detailing is simplified as the enclosure is not fully sealed. Here, corrugated polycarbonate walls are supported by vertical steel trusses to resist imposed wind loads and stop short of the timber structure (Figure

Figure 7.17 (a) Steel chairs fixed to the upper timber beams to raise the roof membrane above the gridshell; (b) strips of PTFE-glass membrane being installed
Sources: (a) © Holzbau Amann GmbH; (b) © Koffi Alate – Taiyo Europe.

Figure 7.18 Interior showing the diffuse light and clear geometry of the timber grid contrasting against the translucent membrane
Source: © Koffi Alate – Taiyo Europe.

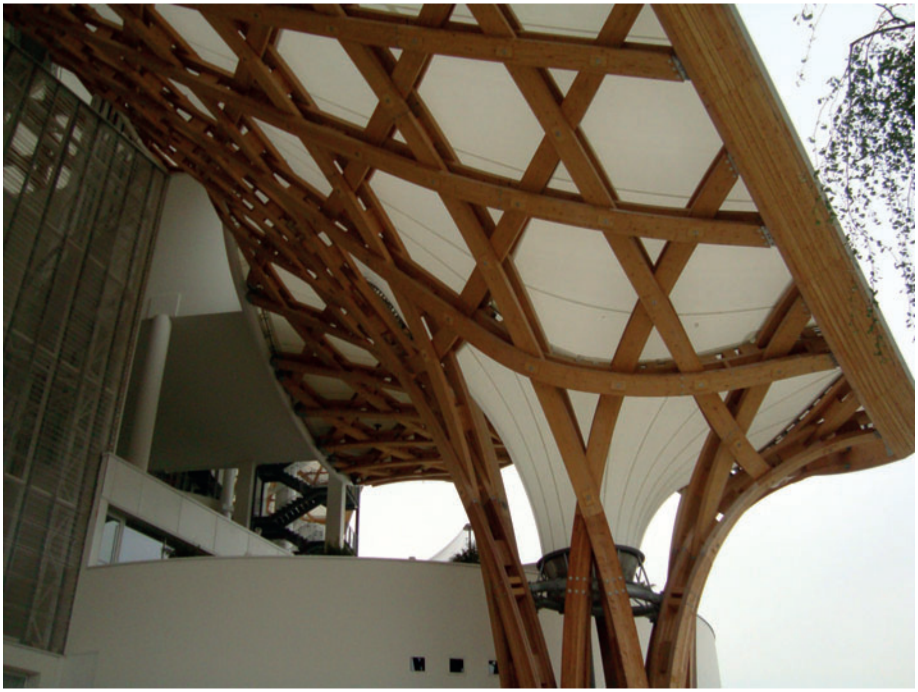


Figure 7.19 Rainwater run-off from the large roof area is accommodated through inverted membrane cones half-concealed within the funnel columns
Source: © Koffi Alate – Taiyo Europe.

7.20). This ensures that the roof load is not transferred to the façade. A steel ring reinforces and supports the roof grid around the penetration of the exhibition galleries (Figures 7.21 (a) and (b)).

The geometry of the timber grid and its similarity to the weaving of the Chinese hat are revealed at night (Figure 7.22).

CLUBHOUSE FOR THE HAESLEY NINE BRIDGES GOLF RESORT, YEOJU, SOUTH KOREA, 2010

PERHAPS LESS WIDELY known than the high-profile Centre Pompidou-Metz, similar digital design and production techniques were used in the Clubhouse for the Haesley Nine Bridges Golf Resort, Yeoju, South Korea, architects Shigeru Ban Architects and Kyeongsik Yoon (KACI International), South Korea. Here a gridshell 36 m x 72 m in plan, again of laminated timber members on a hexagonal-triangular grid based on a traditional Korean basket-weaving pattern, is held aloft by 21 tree-like columns, in three rows of seven (Figures 7.23(a), (b) and (c)). At three storeys high, the filigree columns and their supported grid suggest a forest roof canopy (Figure 7.24). The size of the timber structure was limited to comply with Korean regulations (Shigeru Ban Architects, 2012b) and timber sections were oversized to comply with fire resistance requirements.

Broken down into 32 elements, each of 9 m x 9 m, of which there are five distinct types, the roof structure has an element of repetition not present in the Centre Pompidou-Metz grid (Scheurer, 2010a: 380) (Figure 7.25).

Instead of the several crossing independent layers of the Pompidou-Metz gridshell, in that of the Nine Bridges Golf Resort, half-lap joints are cut in the timbers where they cross so that three layers of continuous timber elements in the hexagonal-triangular grid form a single interlocking surface – much like an extensive wooden puzzle (Figure 7.26). The geometry for the 467 discrete grid component types and more than 2000 different joints was derived automatically, using a parametric algorithm devised by designtoproduction GmbH, so that digital descriptions of each could be supplied to the fabricator Blumer-Lehmann AG (Scheurer, 2010a: 380–381) (Figures 7.27 (a) and (b)). The surface generated is composed of around 3500 individual pieces and requires almost 15,000 lap joints (Scheurer, 2010b: 77).

As for the grid of the Pompidou-Metz, individual curved and double-curved components were manufactured by CNC-machining to remove surplus material from oversized blanks. Hence, an important consideration was how component sizes had to be adjusted to minimise the volume of timber blank required for machining each curved element and to reduce material wastage. Individual component geometries were established by designtoproduction GmbH (Figure 7.28). Glue-laminated timber blanks were then cut and milled to create the complex 'puzzle' pieces (Figures 7.29 (a)–(d)).

With components prefabricated in Switzerland by Blumer-Lehmann AG, realisation of the gridshell structure comes from the close collaboration between designtoproduction GmbH (digital modelling), SJB Kempter Fitze (engineering) and Lehmann Timber Construction (for the fabrication) (Scheurer, 2010a; 2010b). Unlike the gridshell of the Centre Pompidou-Metz, in this case, 9 m x 9 m sections of the roof were pre-assembled on timber formers, to shape the correct geometry (Figure 7.30). Complete 81 m^2 sections were then craned into position and connected to the filigree columns and previously installed sections of the roof grid (Figures 7.31 (a) and (b)). A bird's eye view of the gridshell under construction is shown in Figure 7.31 (c).

This is a major departure from the techniques used in the Centre Pompidou Metz. Instead of a single bolt fixing at the intersection of grid members, which allows some rotation between grid layers, and the introduction of connecting shear blocks, the interlocking of the timber elements allows no rotation at the intersections. With direct connection between the lapped layers in the grid, see Figure 7.26, there is no requirement for shear blocks.

Figure 7.20 Corrugated polycarbonate walls supported by vertical steel trusses stop short of the timber structure
Source: © Holzbau Amann GmbH.

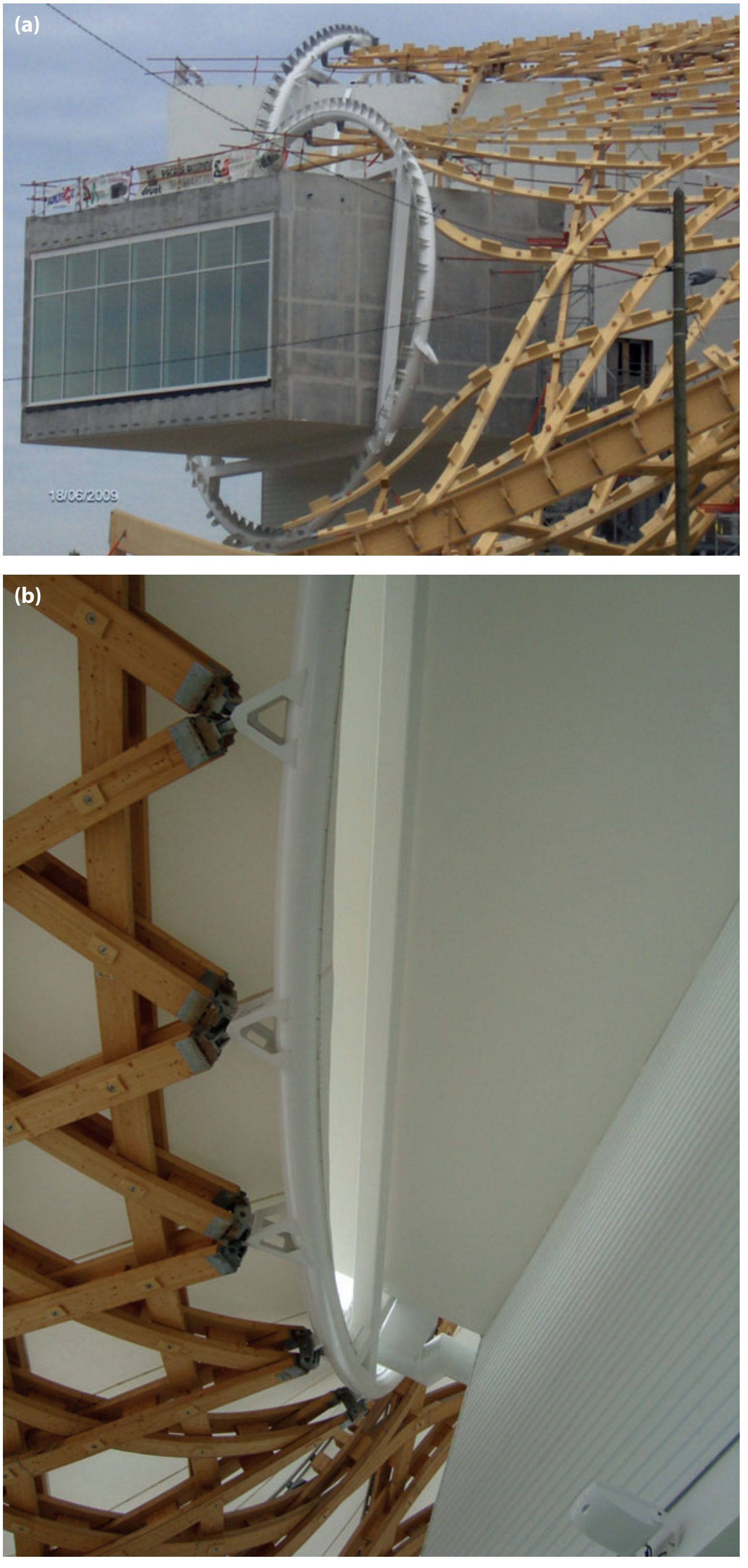


Figure 7.21 (a) A steel ring reinforces the timber grid around the gallery penetration of the roof; (b) connection of the timber grid to the steel ring
Sources: (a) © Holzbau Amann GmbH; (b) © Koffi Alate – Taiyo Europe.

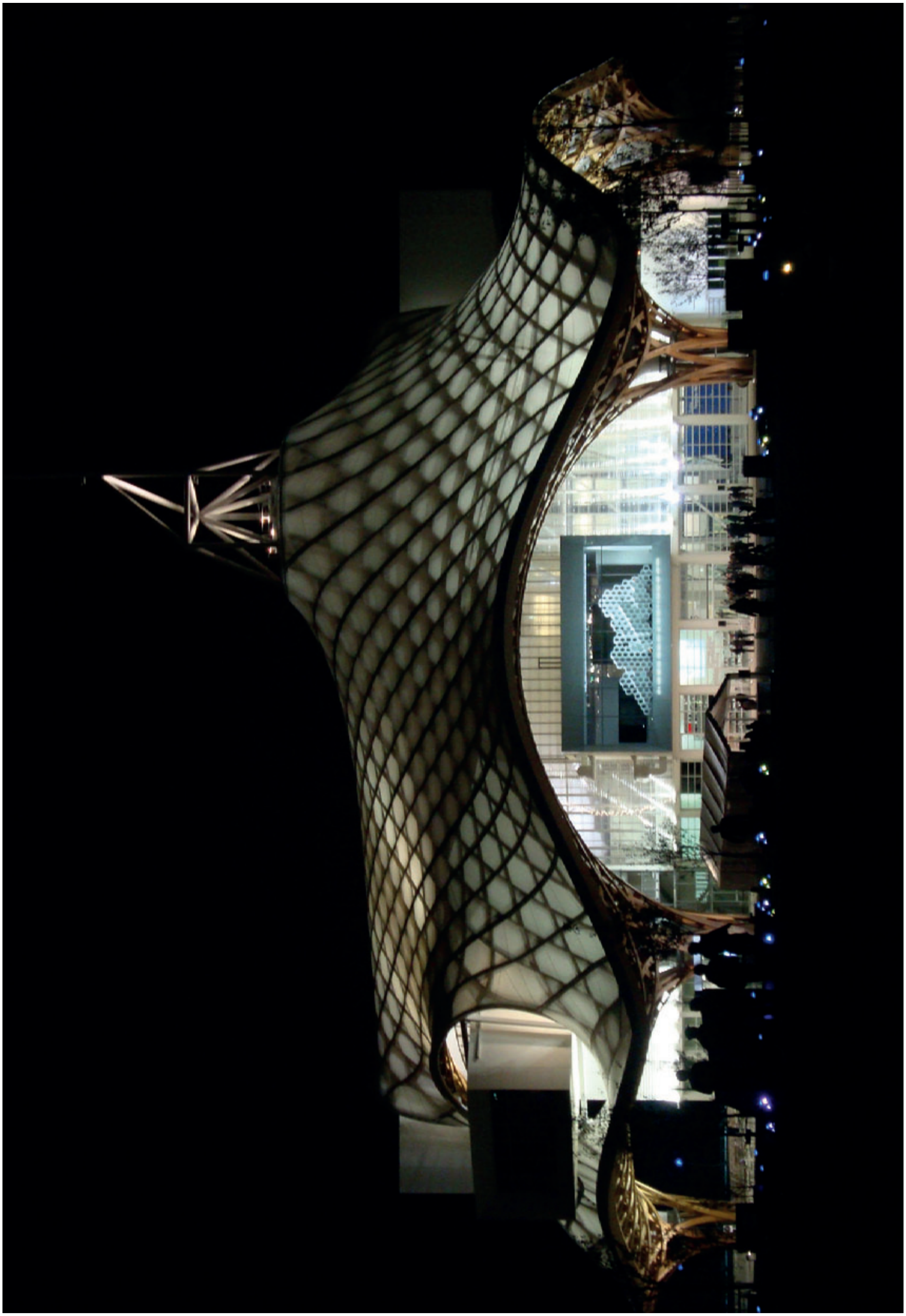
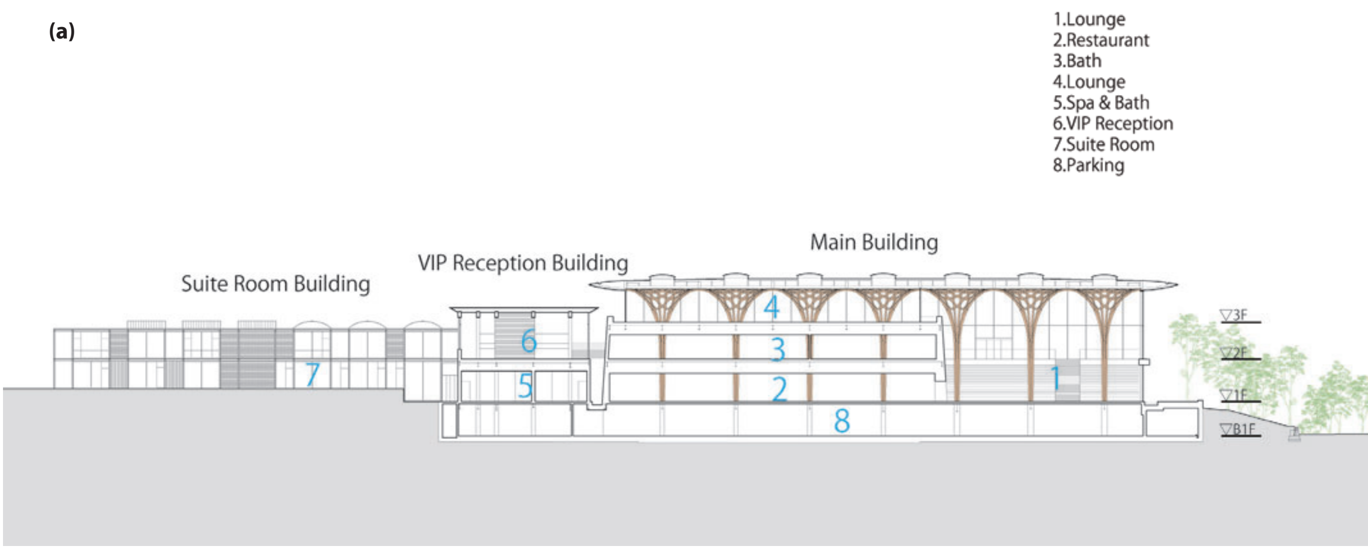


Figure 7.22 Night view of the timber grid
Source: © Koffi Alate – Taiyo Europe.

(a)



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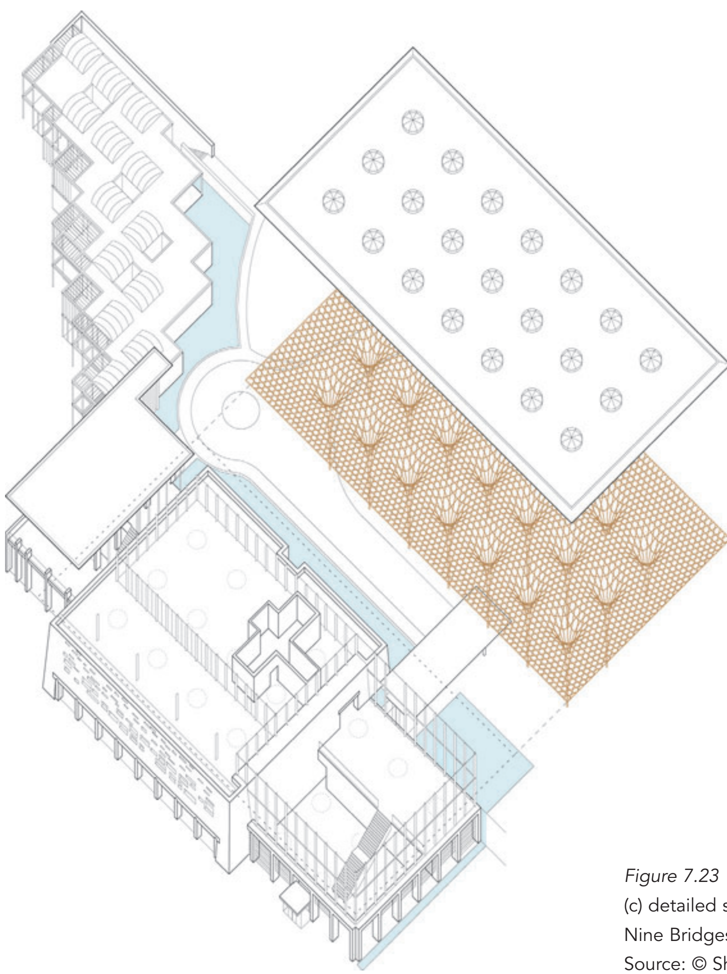


Figure 7.23 (a) Long-section; (b) axonometric; (c) detailed section of the Clubhouse for the Haesley Nine Bridges Golf Resort, Yeoju, South Korea
Source: © Shigeru Ban Architects.

(c)

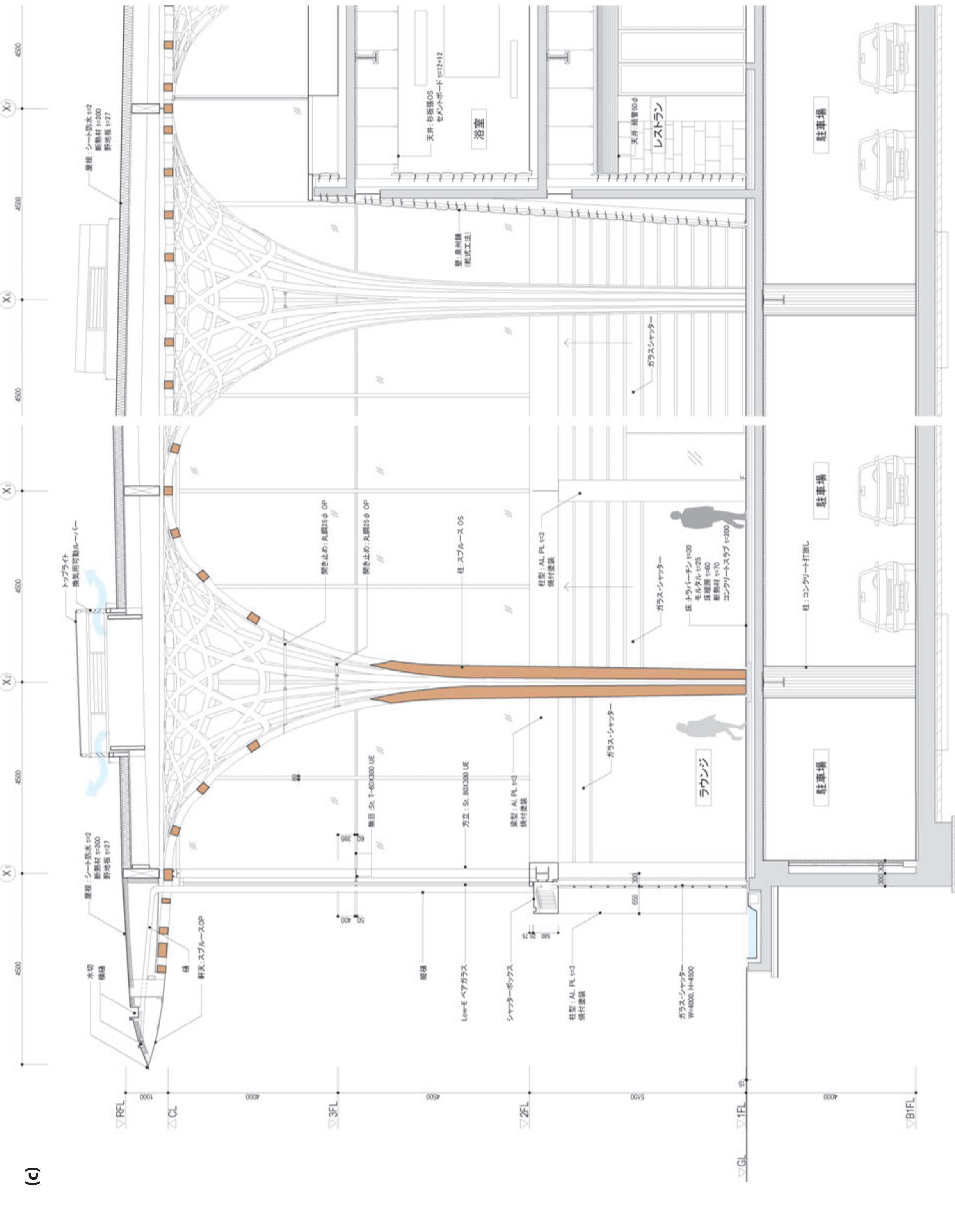


Figure 7.24 Interior view of the gridshell, Haesley Nine Bridges Golf Resort, Yeoju, South Korea
Source: © Blumer-Lehmann AG.

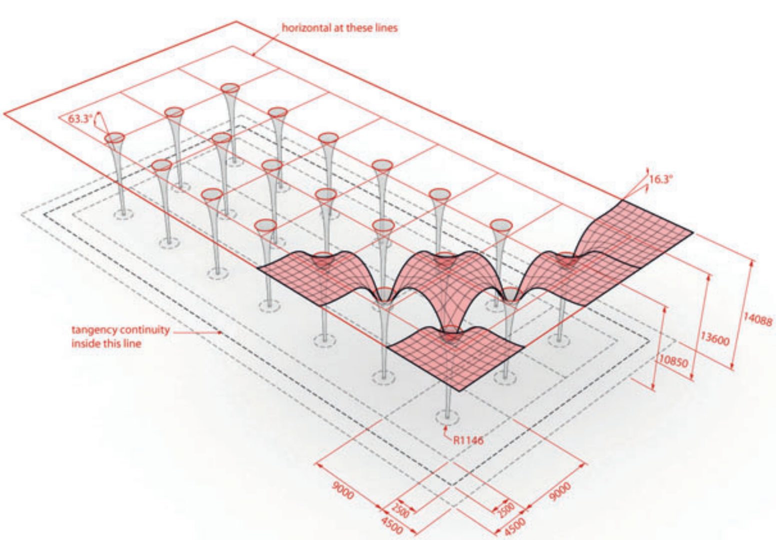


Figure 7.25 Reference surfaces for the five gridshell element types
Source: © designtoproduction GmbH.

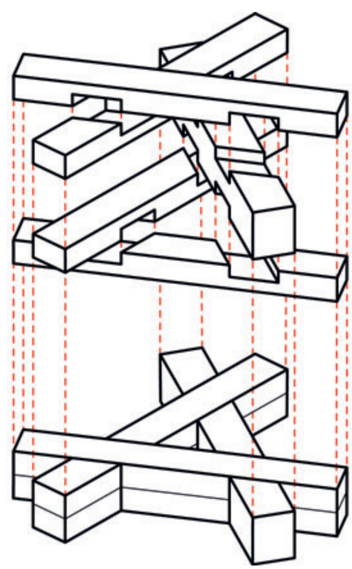
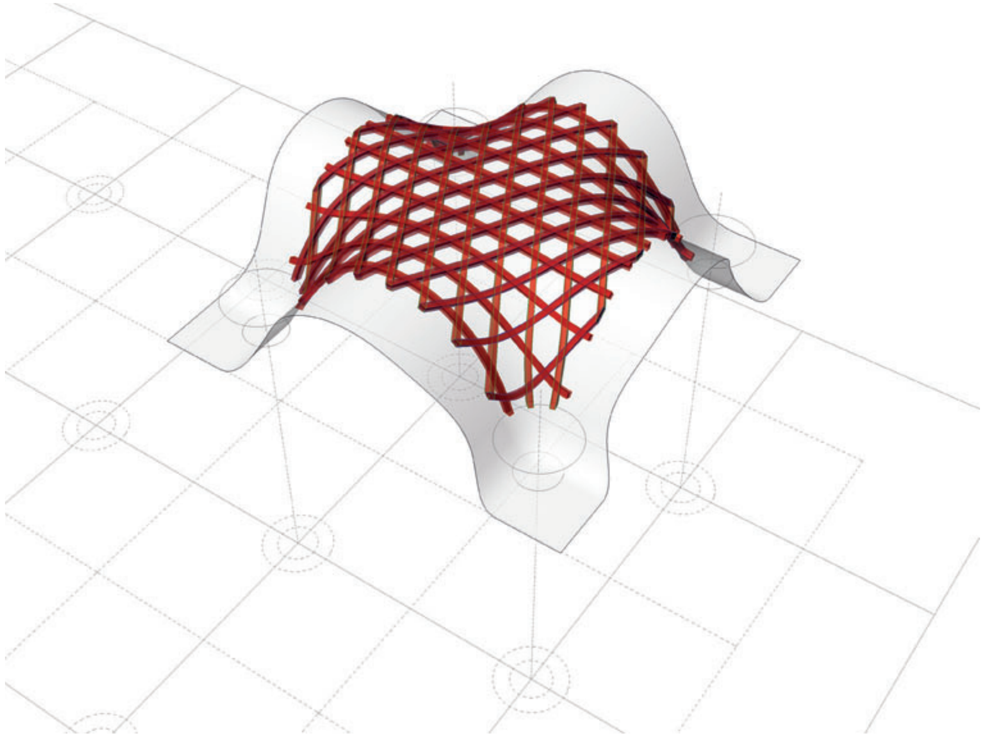


Figure 7.26 Multiple lap-jointed components assembled to form a continuous single-layer gridshell surface
Source: © designtoproduction GmbH.

(a)



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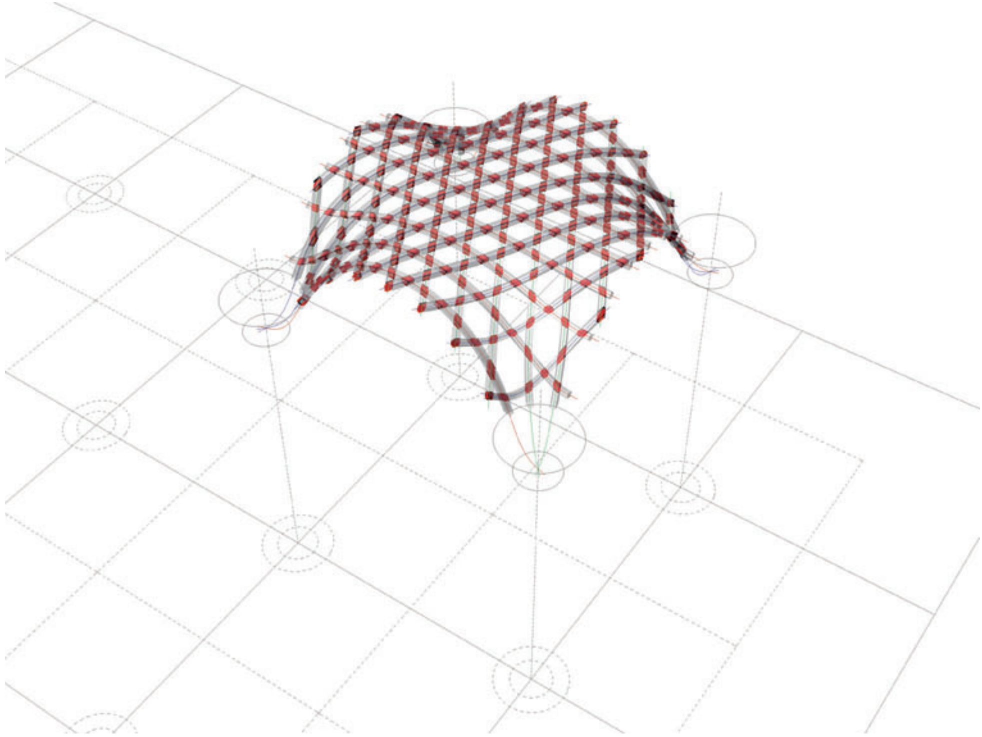


Figure 7.27 (a) Girder grid geometry used to determine the joints; (b) the geometry of individual lap-jointed components required to form a single-layered gridshell surface
Source: © designtoproduction GmbH.

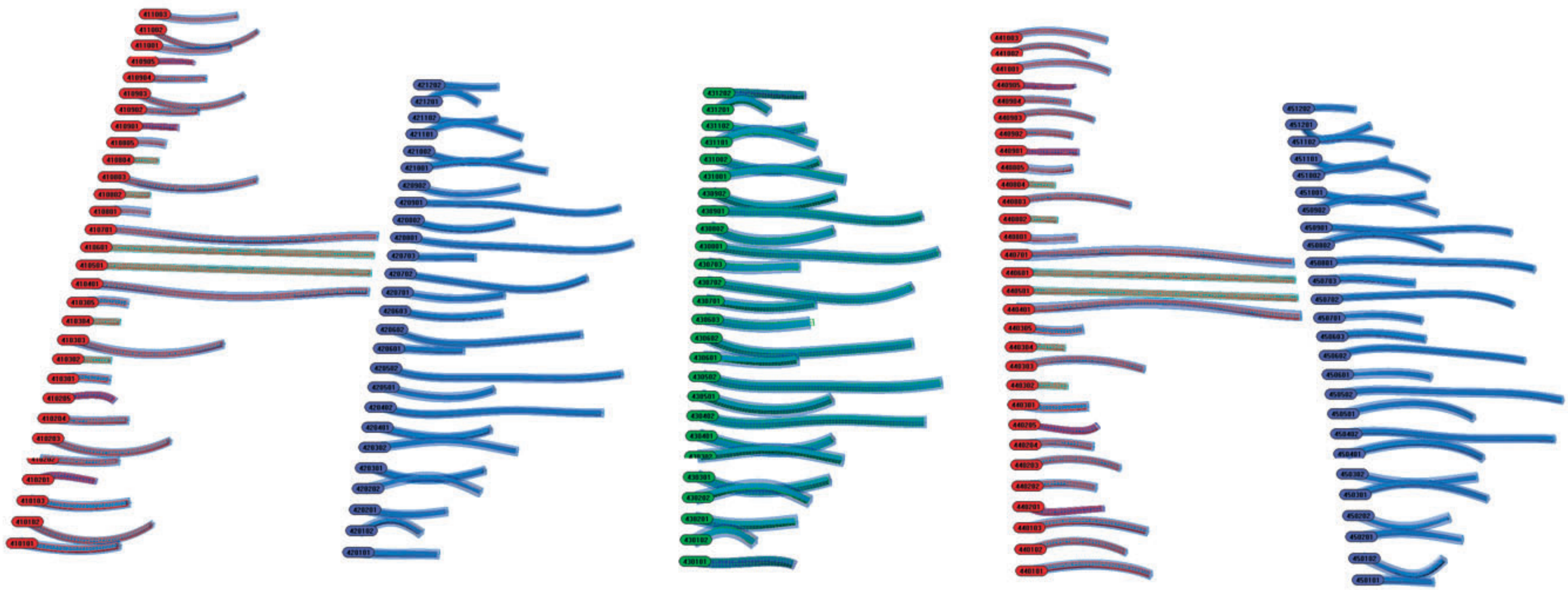


Figure 7.28 Individual component geometry used for CNC machining
Source: © designtoproduction GmbH.

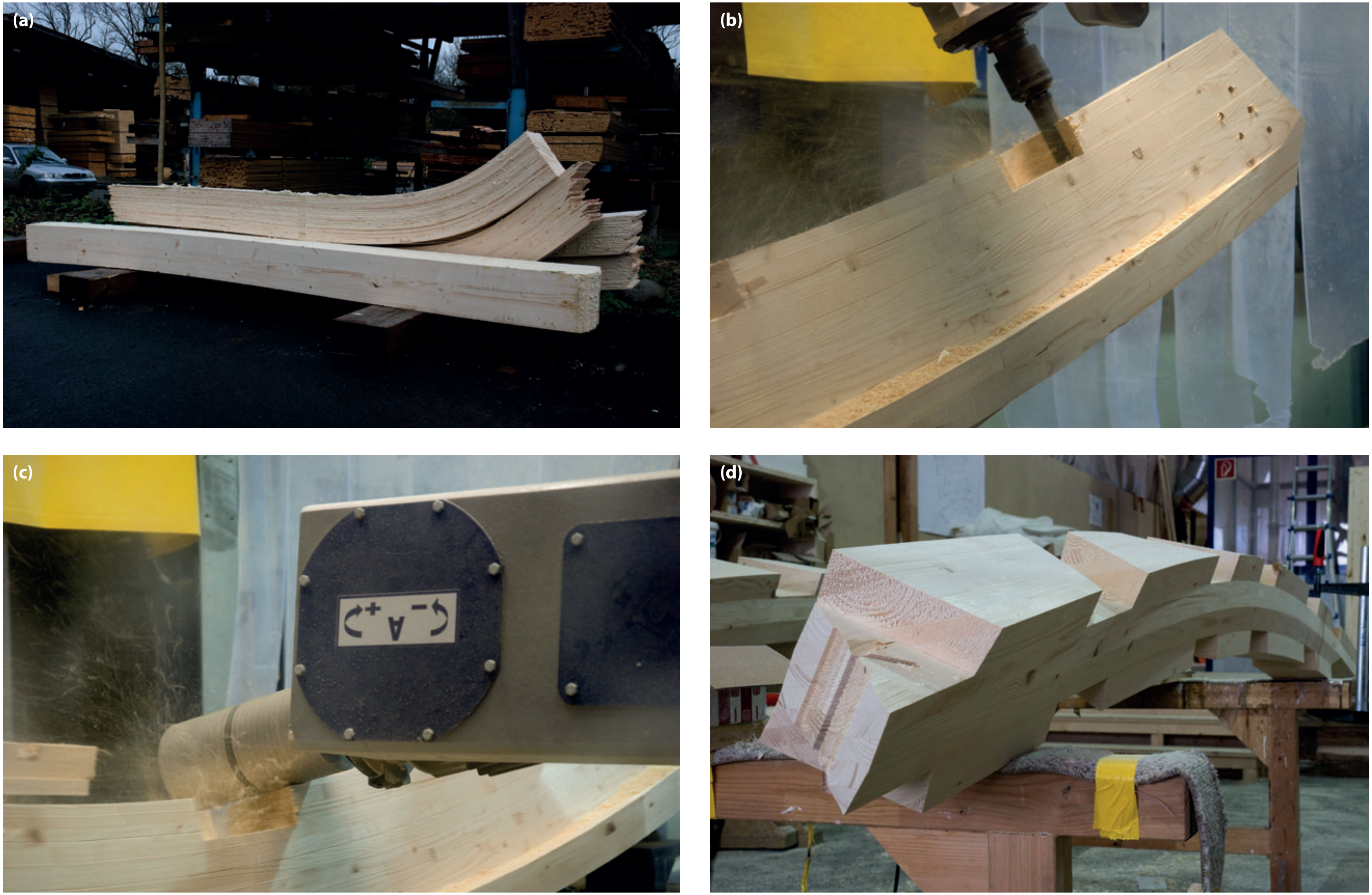


Figure 7.29 (a) Glue-laminated timber blanks being (b) cut and (c) milled to form (d) complex CNC-machined components
Source: © designtoproduction GmbH.

Figure 7.30 Assembly of components on timber formers to shape one of the 32 roof elements
Source: © Blumer-Lehmann AG.

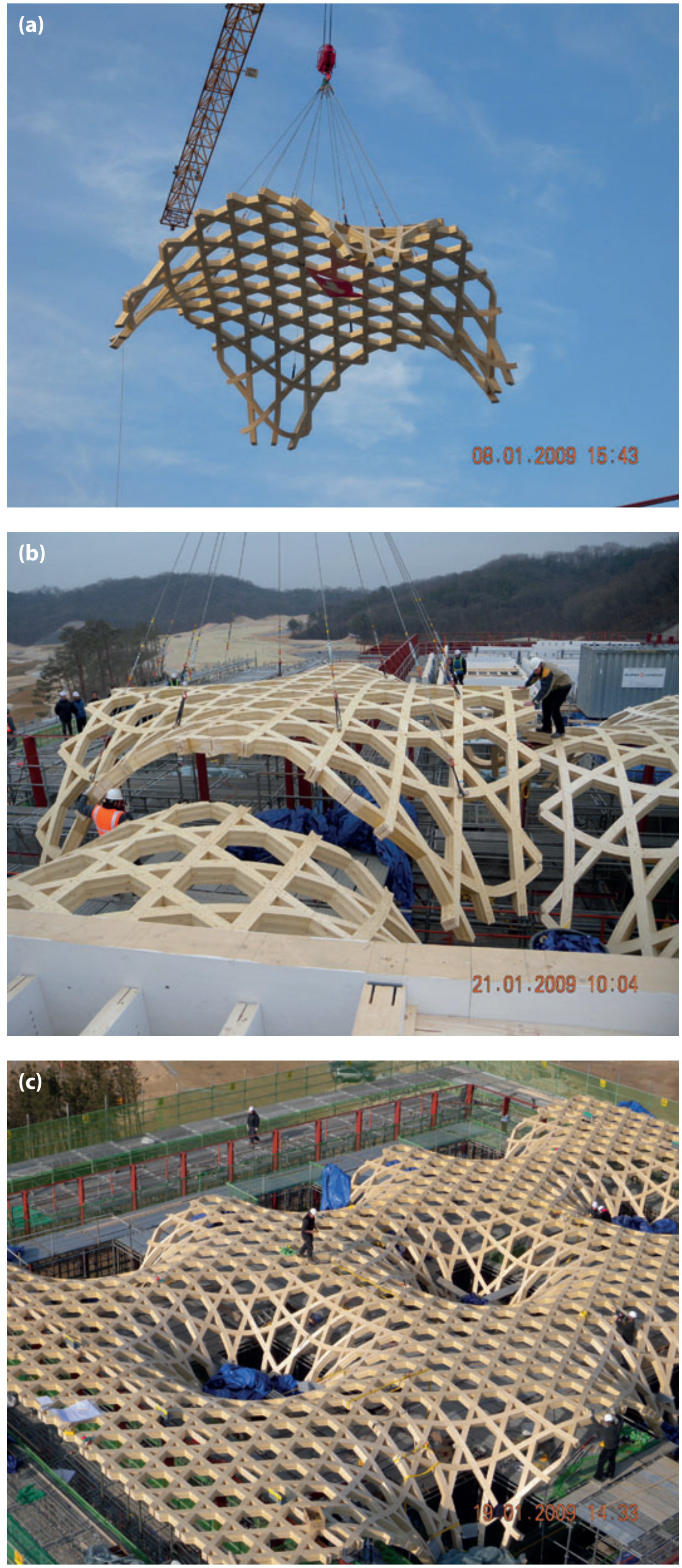


Figure 7.31 (a) and (b) Prefabricated roof sections being craned into position; (c) bird's eye view of the gridshell during construction
Source: © Blumer-Lehmann AG.

The grid structure provides sufficient lateral stability to eliminate the need for bracing in the building façades.

The regularly spaced basket woven tree forms flow freely into the roof grid 15 m above and create a light and airy social space. When illuminated from above, the gently filtered light echoes the environment beneath a rainforest canopy (Figure 7.32).

METROPOL PARASOL, SEVILLE, SPAIN, 2010

INCREASINGLY, DEFINITIONS OF structural typographies are becoming blurred and merging with developments in digital technologies. Imaginable structures are now constructible. A related structure to the gridshells described above, the Metropol Parasol is an expansive outdoor timber structure on an urban scale setting in the historic heart of Seville (Figure 7.33). At first glance, the structure does not look like a gridshell, but the idea of the grid imposed on the structure is highly discernible.

The structure, consisting of six mushroom-shaped parasols billowing up to 28 m high into the skies and 150 m in total length, shown in plan and section in Figures 7.34 (a) and (b) respectively, shades the Plaza de Encarnación in Seville, an exuberant city in Southern Spain where it is almost always hot and sunny. Other than shelter from the sun, the structure accommodates numerous other building functions, namely, an underground archaeological museum that houses recently uncovered Roman mosaics; a 2155 m^2 market place consisting of the existing market and new stalls at ground floor level; an elevated public square which includes bars and restaurant, and a spectacular panoramic walkway 250 m long at 21.5 m above the plaza. Serviced by lifts in concrete towers hidden within the expressive timber gridded waffle structure and snaking at 'treetop' level, the elevated promenade presents the visitor with an unusual and surprising roofscape of old Seville (Figures 7.37 and 7.38).

The structure is the realisation of a winning competition entry submitted by Jürgen Mayer H Architects in collaboration with engineers at Arup in 2004 (Figure 7.35). Garnering much public support, the concept of shady trees in the neighbouring park together with the cascading roof forms of the Gothic Cathedral was something that the Sevillianas can relate to very easily (Webb, 2011).

Completed in 2010, it took six years to build. No mean feat, it measured 150 m at its longest, 70 m at its widest and 28 m at its highest (Koppitz *et al*., 2012: 250). This sprawling building also spills into the plaza on plan and bridges over a road at the southern tip of the building.

Form-finding and structural design

Inspired by the conceptual form of six trees with canopies that coalesced into a single volume, the shape of the structure was generated digitally. Following that, this single volume was vertically 'cut' in an orthogonal grid measuring 1.5 x 1.5 m, a process which generated the individual cutting pattern of each laminated veneer lumber (LVL) element (ibid.: 250).

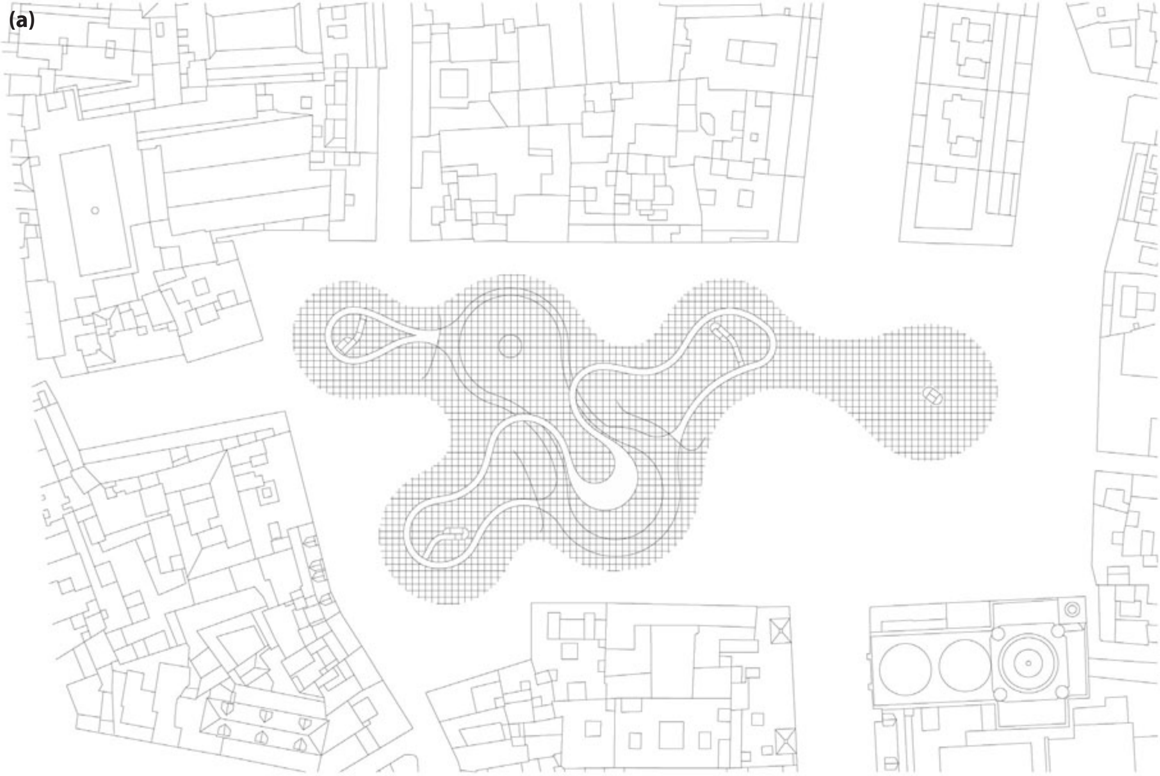
Delving into the structural design, within this structural forest was in fact a series of different structural strategies in response to various architectural functions. Foundations and the cylindrical lift shafts or 'trunks' with a diameter of roughly 15 m (Kaltenbach, 2011: 644) were made from concrete (Koppitz *et al*., 2012). The museum underground and shops on the ground floor and the elevated plaza level were constructed from composite steel trusses of steel and reinforced concrete, while the restaurant on the roof level bears on to hollow steel sections in slanted struts that resembled branches of a tree. The building was stipulated not to exceed the 28 m ridge height of the cathedral (Kaltenbach, 2011).

The impressive bulk of the building, an intriguing matrix of board-like material, is in fact made of CNC milled Finnforest Kerto Q laminated veneered lumber, ranging in thickness between 68 mm to 311 mm (Koppitz *et al*., 2012), milled in Finland and transported to Aichach in Bavaria for further processing (Kaltenbach, 2011: 643). Arup, the consulting engineers, had previously

Figure 7.32 From below the illuminated gridshell echoes the impression of light filtering through the forest canopy
Source: © Blumer-Lehmann AG.

Figure 7.33 The Metropol Parasol seen from the street level provides visual interest to the city of Seville, Spain
Source: © Gabriel Tang.

(a)



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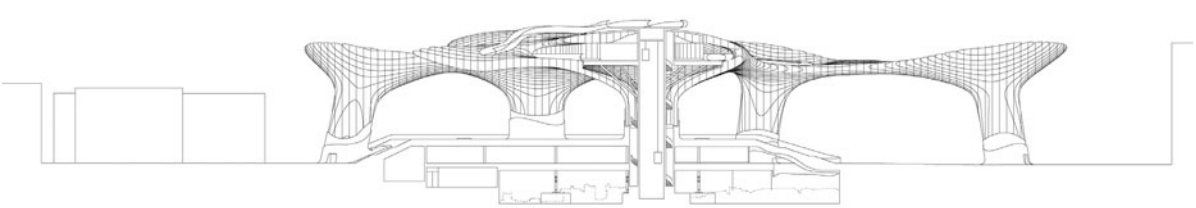


Figure 7.34 (a) Roof/walkway plan; (b) section of the Metropol Parasol, Seville
Source: © J. MAYER H. Architects.

Figure 7.35 The Metropol Parasol strikes a morphological contrast to the old Seville street plan
Source: © nikkolrot fotografie for Holcim Foundation.

considered the use of steel before deciding on timber for the main structure because of economy (ibid.: 640). The sizes of LVL vary up to the largest single sheet measuring 16 m x 3.5 m x 0.14 m used in the 'trunk'. The gridded waffle was assembled like a three-dimensional jigsaw puzzle of about 3400 segments, and with 40,000 connection points used a volume of 3,500 cubic metres of laminated veneer lumber (Kaltenbach, 2011: 643; Koppitz *et al*., 2012). Providing shade, the structure does not have a roof covering. As such, it was imperative to cross-brace the quadratic structure to stabilise the wooden structure. An intelligent arrangement of steel cables was incorporated to provide bi-directional shell action within this wooden grillage.

To waterproof the structure, the timber elements are sprayed with 2K polyurethane between the thickness of 2–3 millimetres. This prevents fissures from developing in the wood. With a 3 mm PUR layer sufficiently vapour-permeable, and with the application of a top coat of ivory paint, the project sets a precedent for a new way of treating timber (Kaltenbach, 2011: 642). Considering the heat of Seville, the epoxy resin for bonding the connections to LVL was tempered to be approved for 80°C (Koppitz *et al*., 2012).

With all connections being exposed, joints needed to be visually non-intrusive (Figures 7.36 (a) and (b)), yet still able to support bearing forces of up to 1.3 MN (Kaltenbach, 2011: 642). Also, with limited bearing capacity on the foundations, the minimising of these connection joints imparts benefits. In total, 35,000 threaded rods were used. These are designed to be modular and adjustable to bespoke angles of jointing to accommodate the large numbers of connections.

Structural analysis

As with the number of connections, bolts and corners, the process of structural analysis is a computational challenge. With a single run of iterative convergence process taking several days to complete, a special software was developed in Arup to automate and make this process more efficient. This new software also takes into account the weight and load-bearing capacity, through thickness, height and geometric fibre orientation of the timber (Koppitz *et al*., 2012). Upon completion of this digital iteration, the architects and contractors receive the information to carry out detail checks. The checked data is then used directly for fabrication.

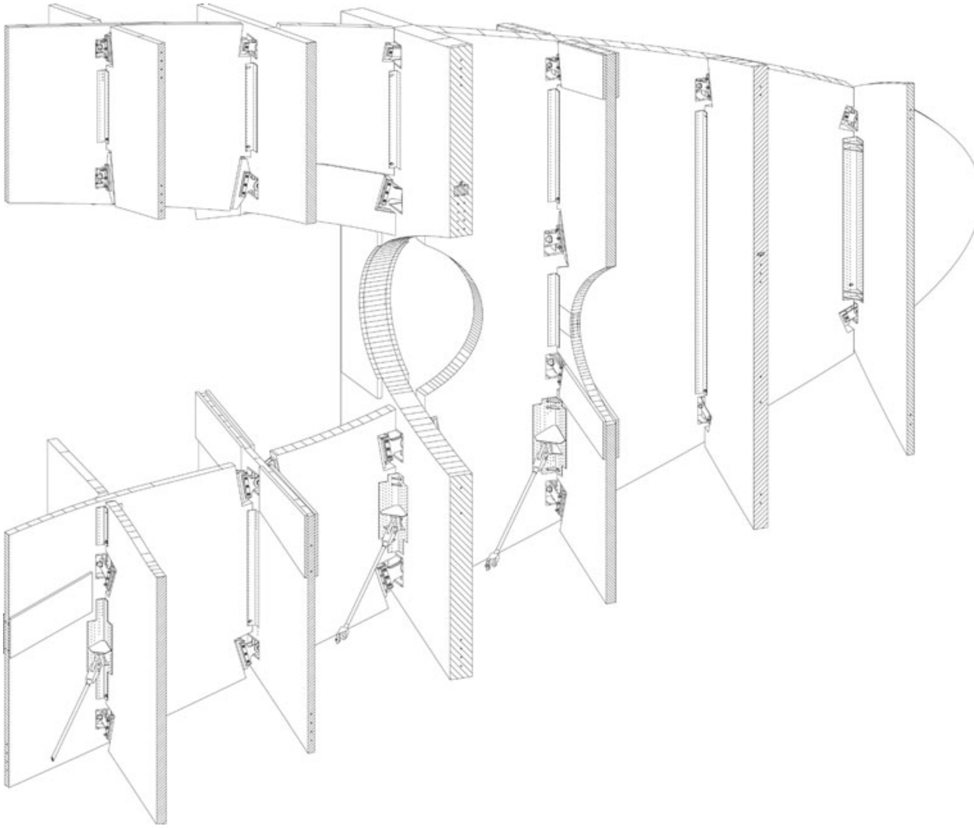
Twenty engineers were involved in the scheme (Kaltenbach, 2011: 642). To manufacture each piece, a CAD team manually arranges the LVL sheet on a CNC trimming robot which mills the elements with millimetre precision and cuts the pieces out like a cookie cutter. Again, a complex matrix of scaffolding was required, and special bespoke assembly baskets were made for workers to gain access to work during the bolt assembly stage (Koppitz *et al*., 2012) (Figure 7.37).

The CNC-milled Kerto is held together by steel-threaded rods up to 660 mm long (Kaltenbach, 2011: 644) as well as high strength glue developed by the Fraunhofer Institute. This glue hardens inside the custom engineered points where steel connectors penetrate the wood (ibid.: 642).

To provide cross-bracing and lateral stability, this waffle grid is cross-braced by steel-threaded rods glued into timber with a special epoxy glue that withstands the high temperatures under the Andalusian sun. The entire timber structure was then coated with a special cream-coloured polyurethane paint before the final assembly. This polyurethane paint provides additional protection to the timber and gives a more monolithic feel to the entire structure (Figure 7.38). Steel flitch plates support the section of the canopy that bridges across the road (Koppitz *et al*., 2012) (Figure 7.39).

The project is a result of the advances in computer and building technology fuelled by the fertile and daring imagination of architects and structural designers. This vision, combined with seamless and synergetic collaboration between architects and contractors, has culminated in the development of new structural ideas, crossing the boundaries of straightforward definitions of structures, be it by its form, its structure or its construction method. Enabled by advances in new digital fabrication technologies, we see a hybrid timber

(a)



(b)

Figure 7.36 (a) and (b) Exposed connections need to be visually non-intrusive yet adjustable to accommodate different joint configurations
Sources: (a) © MERK Timber GmbH; (b) © nikkolrot fotografie for Holcim Foundation.

Figure 7.37 Support scaffolding for assembly of the Metropol Parasol – beyond the completed structure
Source: © J. MAYER H. Architects.

Figure 7.38 The rooftop walkway on the Metropol Parasol of Seville allows locals and tourists alike to see the city from another perspective
Source: © nikkolrot fotografie for Holcim Foundation.

Figure 7.39 Realisation of the project required various systems hidden beneath the apparent singular structural system
Source: © J. MAYER H. Architects.

structure being realised to enrich the built environment, making impossible landmark buildings a reality, giving an opportunity to enhance our built environment and enrich the experiences of those who live in it.

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CHAPTER EIGHT

Current practice

SINCE THE FIRST gridshells designed by Frei Otto in the early 1960s there have been many advances in timber technology, digital design and fabrication techniques. In this chapter a number of recent completed projects and projects under construction are reviewed to demonstrate the current state of the art of timber gridshell architecture, advanced structural systems and the digital craft that is used to manufacture them.

CROSSRAIL PLACE, CANARY WHARF, LONDON, UK, 2015

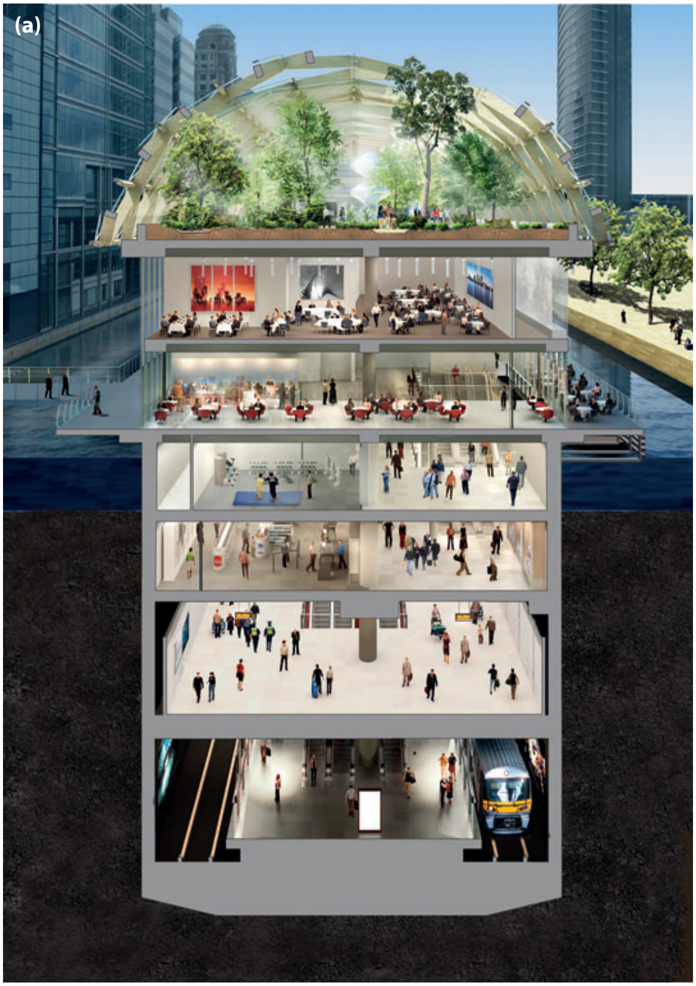
DESIGNED BY FOSTER + Partners, the 310 m-long roof of Crossrail Place, Canary Wharf, London, cantilevers out 30 m each end over the waters of North Dock (Figure 8.1). At the centre of the design, the glulam timber roof arches over 12 m above a large landscaped park. The spruce beams support large triangular ETFE cushions which are inflated by a network of air pipes. The roof is partially open for views out and for natural irrigation while also providing sheltered spaces to comfortably enjoy the park all year round (Figures 8.2 (a) and (b)).

The visual simplicity of the roof design is the result of subtle variation in the underlying geometry. The axis of each successive diagonal beam twists as it coils around the roof. As timbers extend in length towards the cantilevered ends, the incoming angles at nodes become successively more acute and asymmetric and the cushion triangles lean increasingly outwards (Figures 8.3 (a) and (b)). While all but four of the 1418 glulam beams are straight, they vary according to structural grade, depth, length and visual quality. Straight beams were fabricated in an almost 100 per cent automated process (Rabagliati *et al*., 2014). To achieve this geometry, the geometric twist in the axis of each successive diagonal beam needed to be taken up in the node.

The degree of geometric complexity of the steel node connections is therefore large. Additionally, the configuration of openings in the roof means that nodes with two, three, four, or five connecting beams sit

Figure 8.1 Crossrail Place: the timber gridshell appears like a vessel sitting in London Docklands
Source: © CentralPhotography.com.

Figure 8.2 (a) Rendered section; (b) plan and long section through Crossrail Place at Canary Wharf
Source: © Foster + Partners.



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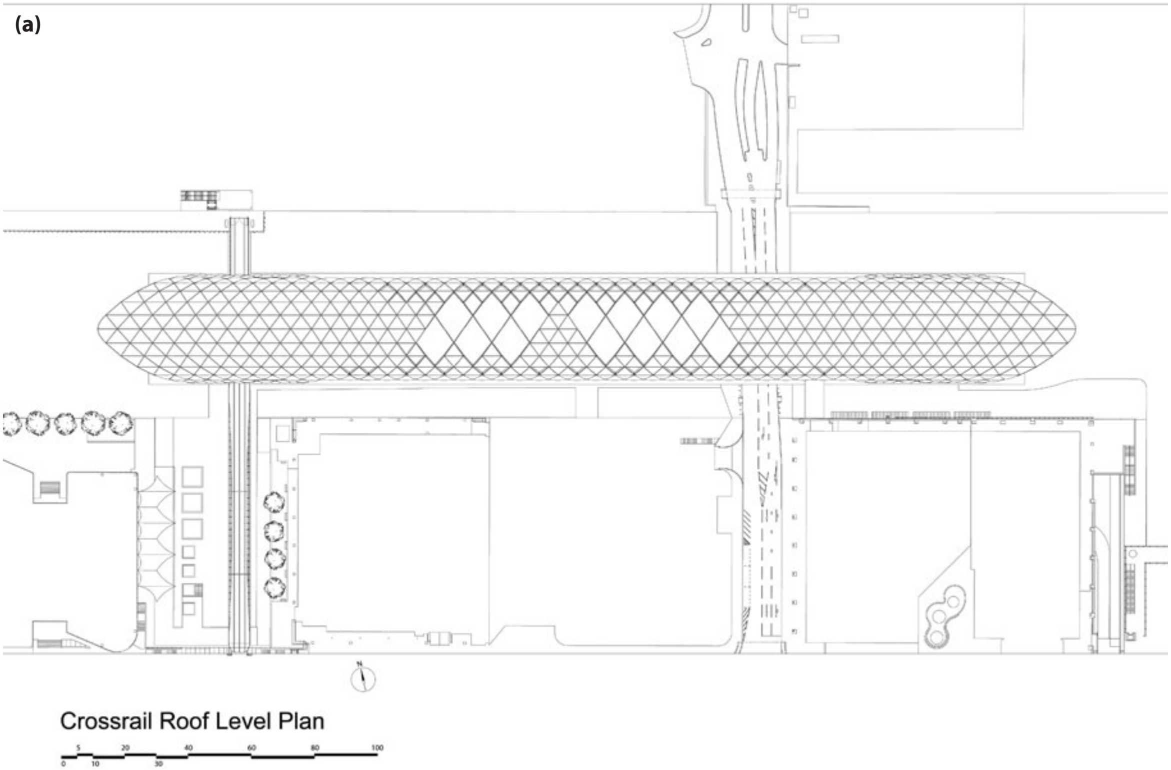

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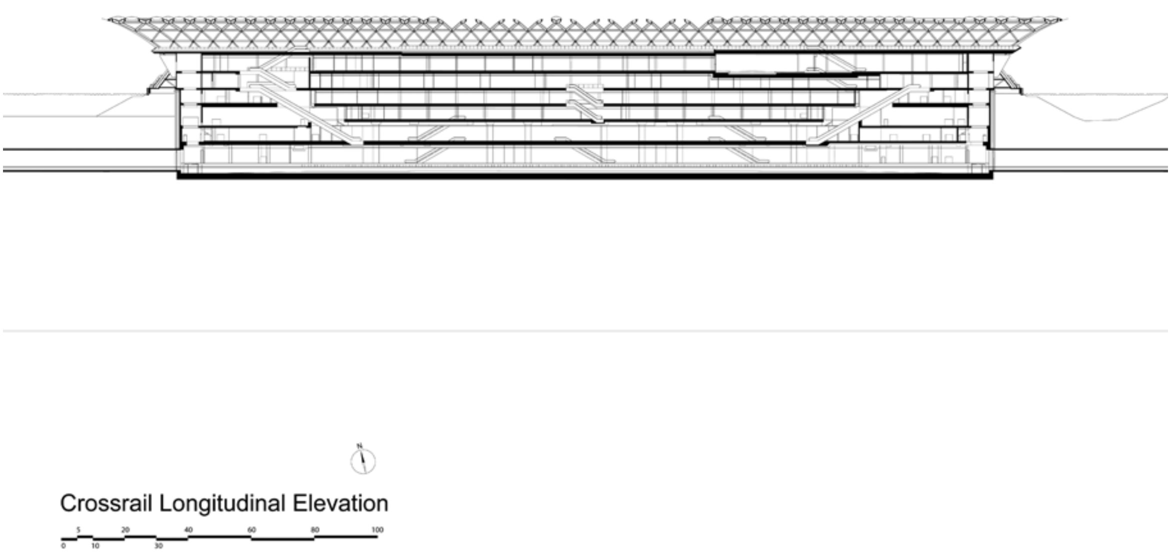


Figure 8.3 (a) Roof plan; (b) south longitudinal section. Both reveal how the triangular grids clearly distort as they move towards the end cantilevers
Source: © Foster + Partners.

alongside the nodes with six connections. The result is that, of the 564 nodes, over half are unique in geometry, but crucially, all the nodes were designed as one family with geometric rules that would adapt to each condition. Similarly, variation in the 777 ETFE cushions, which occupy 302 different-shaped triangles, is almost imperceptible. The air pipes supplying the cushions, for example, pass through the brackets behind the timber beams supporting the ETFE frames (Figures 8.4 (a) and (b)).

Using scripting and a flexible parametric model, the design team was able to prototype the design logic at each stage of its development. The whole roof was designed with this systems approach, allowing the design logic to be refined even while dimensions were still being updated according to structural analysis. With geometric rule sets and design data shared easily via algorithms and spreadsheets, knowledge of material capabilities, construction logistics and assembly practicalities could be built into relational digital models. By developing close collaborative relationships with the fabricators, the flexible system permitted adaptions and refinements right up to point of fabrication.

Prototyping was a vital process in the realisation of the roof. By building full-scale prototypes into the design schedule, it allowed for innovations whose performance could be tested, fine-tuned and successfully delivered. Two full-scale mock-ups were built to test the performance of the ETFE cladding to test water tightness, snow loading, impact of a large body falling on it and re-inflation times if the air supply was cut off. These performance tests gave important feedback and demonstrated the robustness and resilience of the design system to the client. Two full-scale prototypes were built for the node connections, which allowed the design to be refined with each iteration.

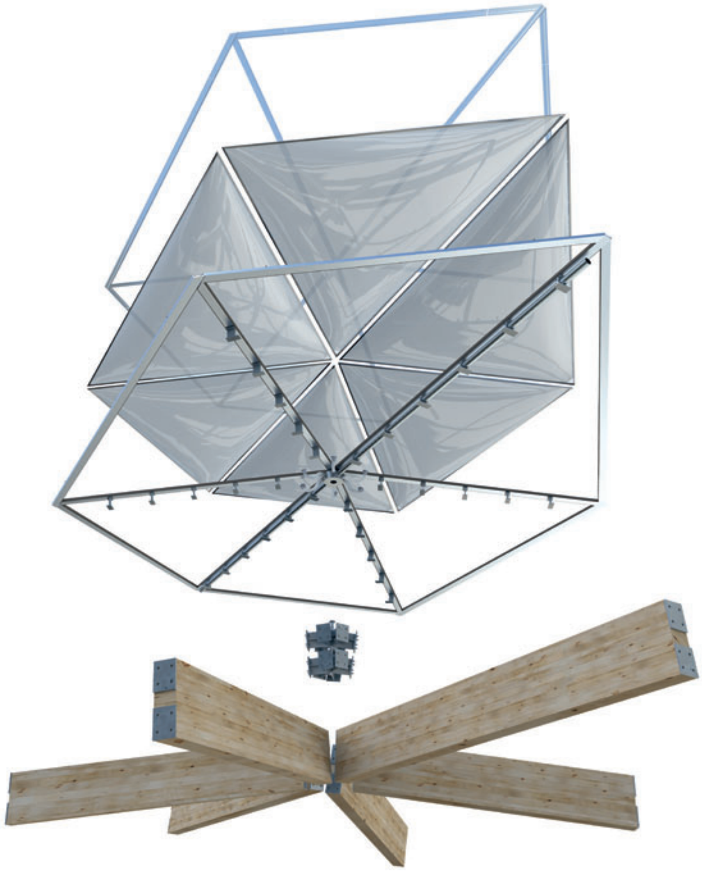
The key feature of the project was that all the nodes, beams and cushions were designed, prototyped and fabricated as one parametric family (Figures 8.5 (a) and (b)). The large amount of variation meant that an innovative systems approach was vital in ensuring that the roof could be structurally analysed, fabricated and designed for rapid, accurate assembly. For the manufacture of the ETFE cushion fixing extrusion node connections, five-axis machines were used. This included complex milling, cutting and drilling in preparation for hand welding. Assembly marks were milled into each element's surface which included an ID number which denoted their specific orientation and position in which they had to be welded together. This parametric approach and the use of scripting were also adopted by specialist timber contractors Wiehag and ETFE contractors se-austria (seele). This permitted the exchange of data sets and geometric rules facilitating the gradual refinement of the design through successive digital and physical prototypes.

Construction of the roof was carried out without scaffolding, 'by numbers' using IDs engraved on each beam and node (Figure 8.6). Along its 300 m base-span, the completed timber structure was 5 mm out at each end.

Timber components of varying number and different cross-section are accommodated at the different node joints (Figure 8.7 (a)). In the areas where the ETFE foil cladding was omitted, the timber was weather-protected with an aluminium cladding. It can be noted that the ETFE cushion inflation system is well concealed behind the timber with only inconspicuous transparent flexible tubing connecting the distribution duct to the fritted cushion (Figure 8.7 (b)).

Sadly, from the exterior the timber gridshell is really only apparent at the cantilevered ends, as it is covered almost completely by the ETFE cushion cladding (Figure 8.8). However, in the roof garden the timber grid is fully visible and complements the semi-mature trees that have been planted to create a tranquil resting place in the middle of the Canary Wharf business district (Figure 8.9).

(a)



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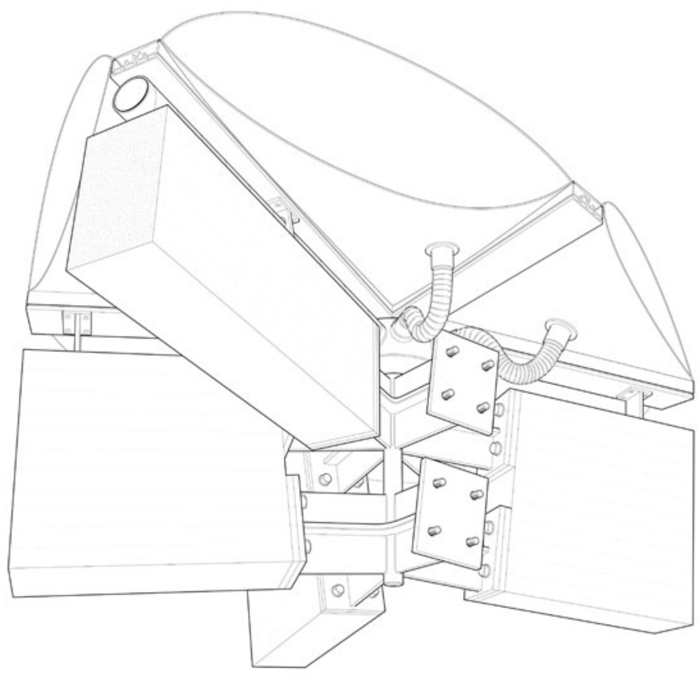


Figure 8.4 (a) Assembly of gridshell and ETFE cladding components; (b) node detail drawing
Source: © Foster + Partners.

(b)

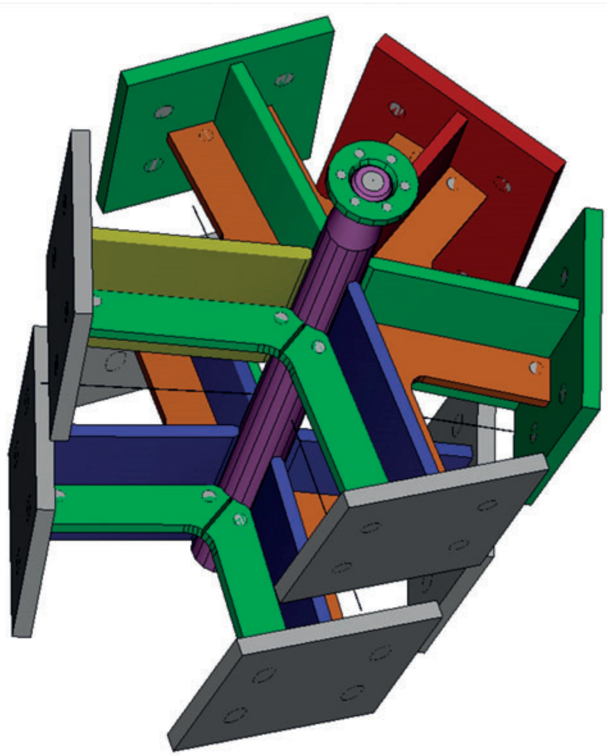


Figure 8.5 (a) An array of nodes stored on site awaiting installation. The nodes differ in geometry and variation of the number of connection arms. (b) Single node CAD drawing
Sources: (a) © Nigel Young/Foster + Partners;
(b) © Foster + Partners.

Figure 8.6 Construction in progress
Source: © Nigel Young/Foster + Partners.

Figure 8.7 (a) A typical finished node showing the different sizes of the connected timber elements, aluminium cladding to the exposed timber; (b) inconspicuous inflation system for the fritted ETFE cushions
Sources: (a) © Nigel Young/Foster + Partners; (b) © Foster + Partners.

(b)

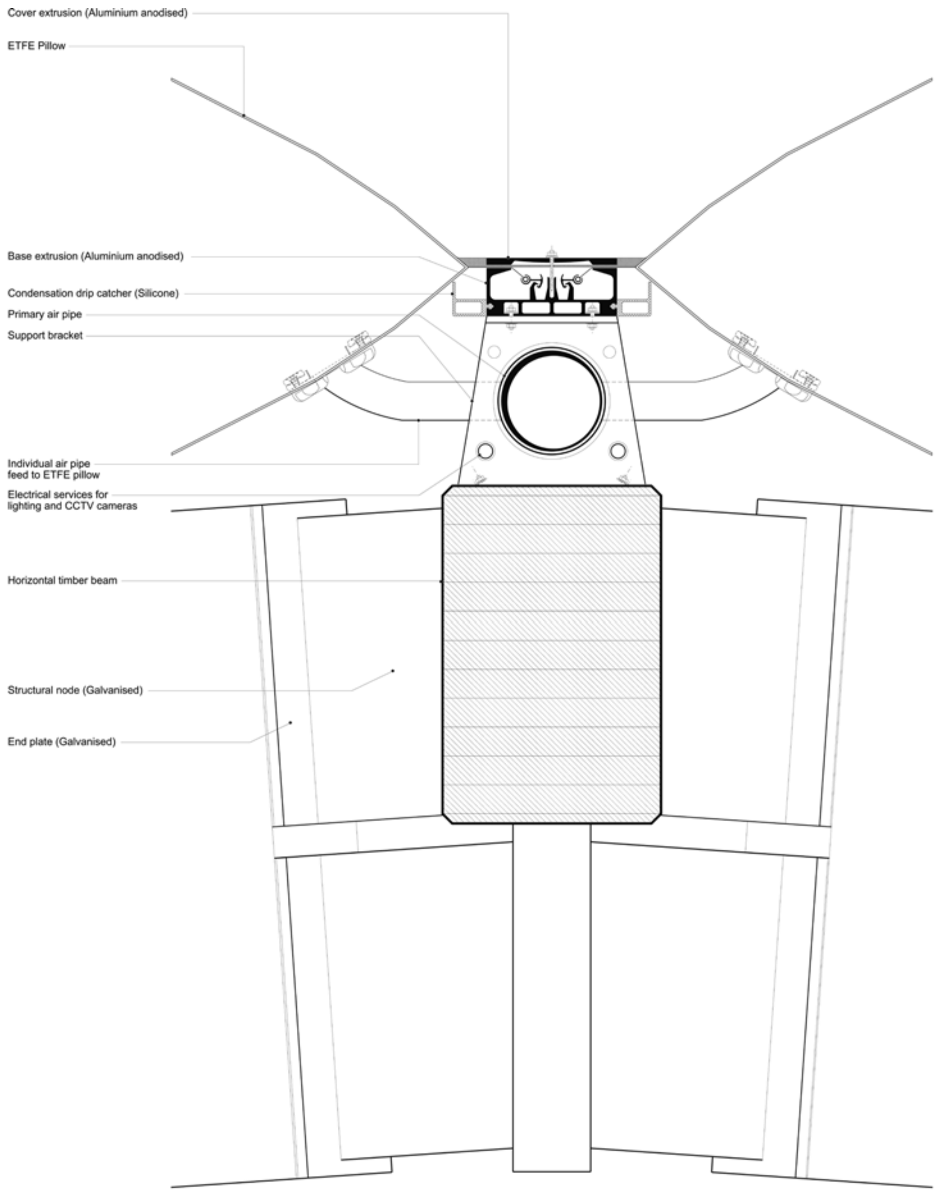


Figure 8.8 The timber gridshell is exposed in the cantilevered end of the roof
Source: © Nigel Young/Foster + Partners.

Figure 8.9 In the roof garden the timber grid is fully exposed and complements the semi-mature planting to create a tranquil resting place in the middle of the Canary Wharf business district
Source: © John Chilton.

THE MALAYSIA PAVILION, EXPO' 2015, MILAN, ITALY, 2015

SHOWING THE INCREASING popularity of timber gridshells, examples appeared at the Expo 2015 held in Milan from May to October 2015. The first, a competition-winning design by the Malaysian architect Serina Hijjas of Hijjas Architects + Planners (formerly Hijjas Kasturi Associates), was inspired by the sustainability theme of the Expo and the shape of rainforest seeds. The Malaysia Pavilion incorporated glued laminated hardwood timber in pod-shaped gridshells (Figure 8.10 (a)). Double-curved triangulated grids were made from individual elements up to 120 mm x 650 mm, connected with around 3,000 fabricated steel plates bolted to the inner and outer surface at each node (Figure 8.10 (b)). All the components were manufactured in Malaysia for transport to Milan and assembly at the Expo site. An opaque Serge Ferrari Précontraint 702 membrane suspended from grid nodes provided the weatherproof envelope (Malaysia Pavilion, 2015; TensiNews, 2015).

THE TREE OF LIFE, EXPO' 2015, MILAN, ITALY, 2015

CONTROVERSIAL, BECAUSE OF its perceived similarity to the 'Supertrees' of Wilkinson Eyre and Grant Associates at Gardens by the Bay in Singapore, the Tree of Life centrepiece of the Italian Pavilion is a 36 m-high structure with a steel core surrounded by an elaborate grid of intersecting larch timber spirals (Figure 8.11). According to the project architect Marco Balich, the pattern was inspired by Michelangelo Buonarroti's design for paving in the Piazza del Campidoglio, in Rome, projected into three dimensions. The steel cable-supported tree canopy has a maximum span of 45 m and is primarily used to support a sound and light show.

According to the timber fabricator Wood Beton S.p.a., the original proposal was for a steel lattice tower and canopy projected to weigh around 500 tonnes. Subsequently the structural concept was refined and timber was substituted as the main material for the lattice. In total, 24 spirals, each 124 m long and fabricated from 19 sections of 160 mm x 280 mm glued laminated Siberian and Swiss larch (12 left-handed and 12 right-handed), create the roots, trunk and canopy of the tree, which surrounds the steel access core. To improve site safety, the extensive canopy was assembled close to ground level.

Temporary scaffold towers provided by Marssal Srl were used to access and assemble the joints. Once completed, the full canopy was gradually hoisted into its final position at the top of the core and the remaining timber grid was assembled below (Wood Beton S.p.A., 2015).

THE FRANCE PAVILION, EXPO' 2015, MILAN, ITALY, 2015

THE COMPETITION-WINNING DESIGN for the France Pavilion at Expo 2015 in Milan, by Anouk Legendre and Nicolas Desmazières of XTU Architects, highlights the changes that have occurred in timber gridshell architecture over the last 50 years. As is the case for the earliest gridshells, it is based on a regular square grid of timber elements, it has a double curvature to develop some shell action and the timber used in its construction is (at least initially) of small cross-section. But this is where the similarities end. The small sections of timber are converted into wider and deeper glulam beams that are bent or machined to create single- or double-curved components; these are assembled directly into a more widely spaced square grid plan from a mixture of continuous and discrete prefabricated elements, which are connected with sophisticated mechanical joints; the form, which is not funicular, is required to resist bending as well as compression stresses. Additionally, it is not just supporting a roof but also heavier loads from an intermediate floor and an accessible roof terrace. This was primarily achieved through the advances in engineered timber production and jointing systems, digital structural and geometrical design, manufacture, planning and fabrication.

In harmony with the overall theme of the International Exposition 'Feed the World: Energy for Life', the France Pavilion was inspired by Les Halles de Baltard, the fresh food market in Paris (Figure 8.12).

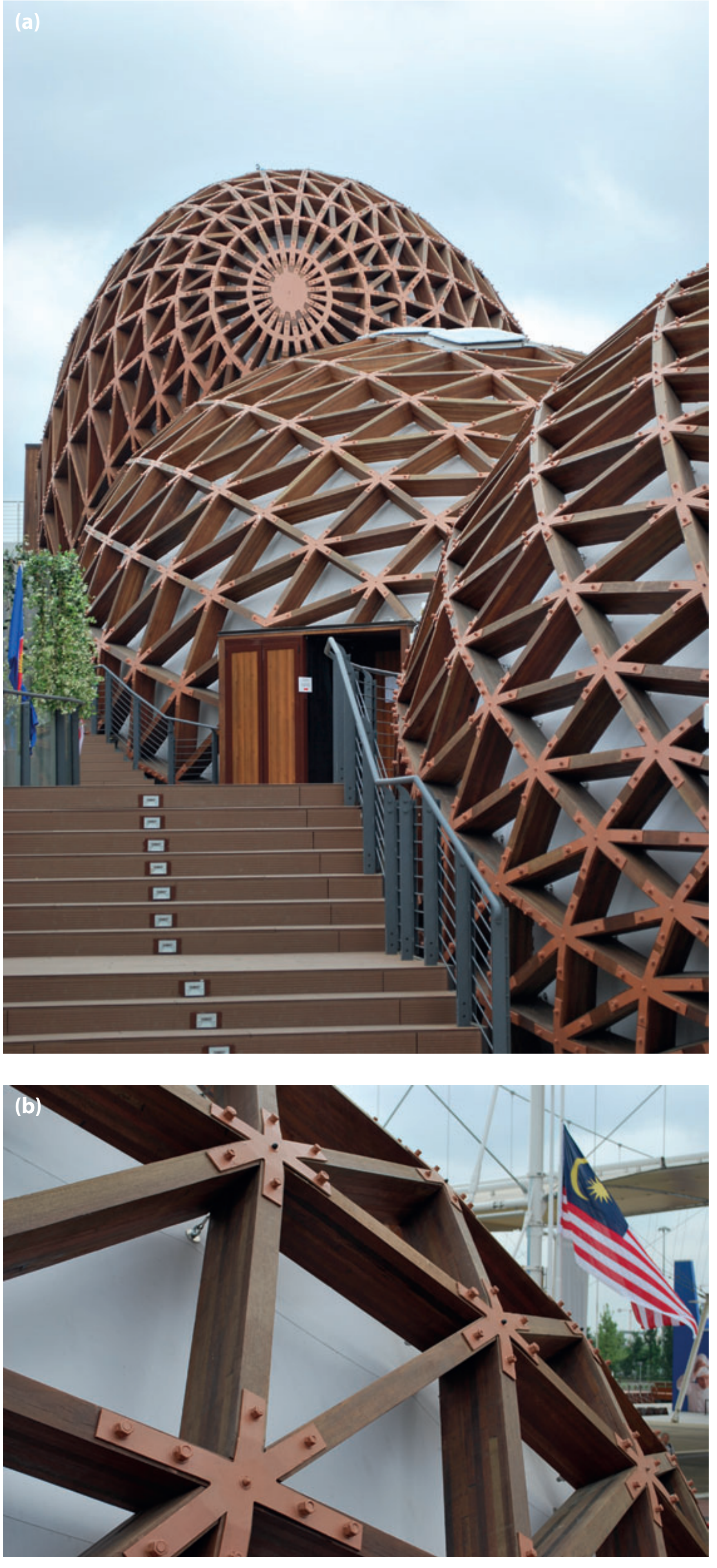


Figure 8.10 (a) The Malaysia Pavilion for Expo 2015, Milan, by Hijjas Kasturi Associates; (b) node joint detail
Source: © John Chilton.

Figure 8.11 Tree of Life, Milan: 36 m high with a canopy span of 45 m
Source: © John Chilton.

Designed to answer three key questions: (1) how to symbolise France's food-related identity; (2) how food production and consumption have changed; and (3) how to present French innovation in the field; this resulted in an 'archetypal market: freestanding spaces sheltered under one huge roof' (XTU Architects, 2015). It updates this concept creating '[a] crossroads where both production and consumption will meet, offering a new sustainable perspective' (Morewithless Design, 2015). Fabricated completely from spruce and larch sourced in France, the timber structure is designed to be easily dismantled and re-erected elsewhere.

Within the overall 35 m x 56.7 m three-storey building footprint, a key feature is a vaulted spruce glue-laminated timber gridshell of approximately 1500 m^2 in plan. Rising, in one corner, to the full 12 m height of the pavilion, the gridshell, which echoes the mountainous landscape of France (Figures 8.13(a) and (b)), drops like a cloak over the internal market hall while also supporting two upper floors. Oriented at 45° to the building façades, the undulating orthogonal grid of curved timber beams is spaced at 1.5 m centres with the horizontal upper floor structures on a 4.5 m x 4.5 m grid (Figure 8.14).

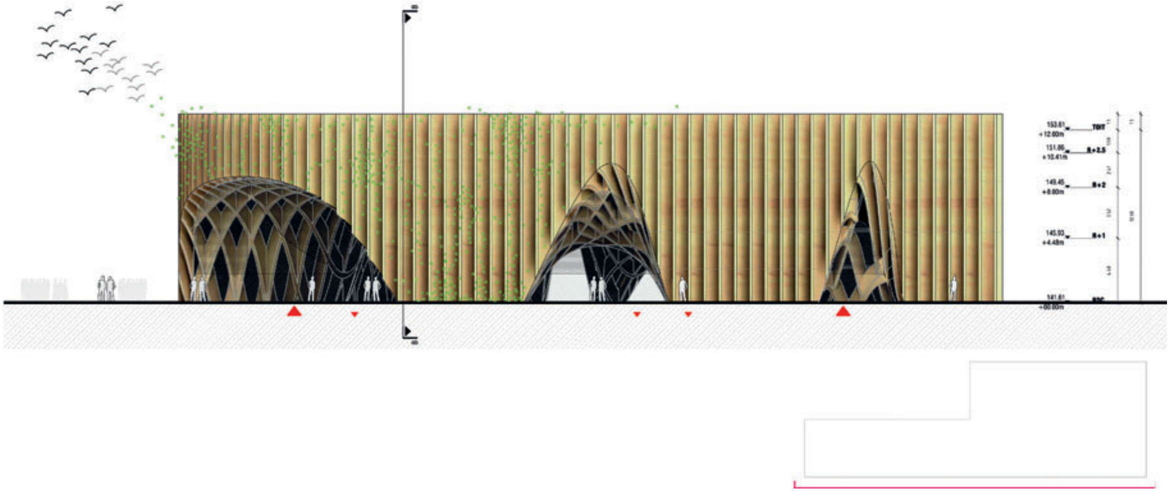
The single-curved gridshell beams are all 200 mm in width but vary between 380 mm and 960 mm deep, according to loading. They have a double-curved lower face that follows the original design surface and a horizontal upper surface. On the primary grid lines, at 4.5 m centres, beams are up to 2.4 m deep (Figure 8.15).

A key concept of the Pavilion is that it can be dismantled and re-erected at a different location, hence all joints are demountable. This was achieved using proprietary systems, KNAPP Megant™ and KNAPP Ricon™ – six types with up to 19 screw patterns, some with additional tension rods (see Figures 8.16 (a) and (b)) – and for heavily loaded joints RESIX™ connectors in conjunction with glued-in threaded rods (Figures 8.17 (a) and (b)). CNC digital fabrication to prepare the timber and accommodate the variable geometry permits the use of standard steel joint components. These are capped to provide the required fire protection (Scheurer *et al*., 2015).

As noted by Fabian Scheurer of designtoproduction GmbH and Loïc Simonin of timber contractor SIMONIN, it would have been impossible to design and build the timber gridshell vault without digital tools. At the design stage, as a member of the design competition team SIMONIN worked with XTU Architects to generate a parametric 3D CAD model using Rhinoceros/Grasshopper. Subsequently, this model was used in the structural design with Acord-BAT, for determination of timber quantities and estimation of production time. It also assisted the architects in the production of the competition-winning renders (Scheurer *et al*., 2015).

At the execution stage, with designtoproduction GmbH as 3-D planning consultant, a fabrication quality parametric model was scripted with Rhino–Python using Rhinoceros 5. Following the assimilation of results from the structural analysis into SIMONIN's initial 3-D model, data was exchanged via Excel tables and finally integrated into the fabrication model. Timber is an anisotropic material and its strength reduces dramatically when its fibres are cut, which occurs during the CNC milling of curved components. Here, a limit of ±5° was set as the angle between the cut and the fibre direction. For 730 beam segments, three types of blanks were specified: straight, arched or curved for components with very low, constant or high curvature respectively. The size and shape of the blanks were optimised to facilitate production and provide an economic solution. SIMONIN used a Grasshopper model to extract production data to inform the lamination process, (Figure 8.18) (ibid.).

Figure 8.12 (on facing page) East (top), South (middle) and West (bottom) elevations of the France Pavilion, Expo 2015, Milan
Source: © XTU Architects.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+12.00m
151.86 R+2.5
+10.41m
149.45 R+2
+8.00m
145.93 R+1
+4.48m
141.61 RDC
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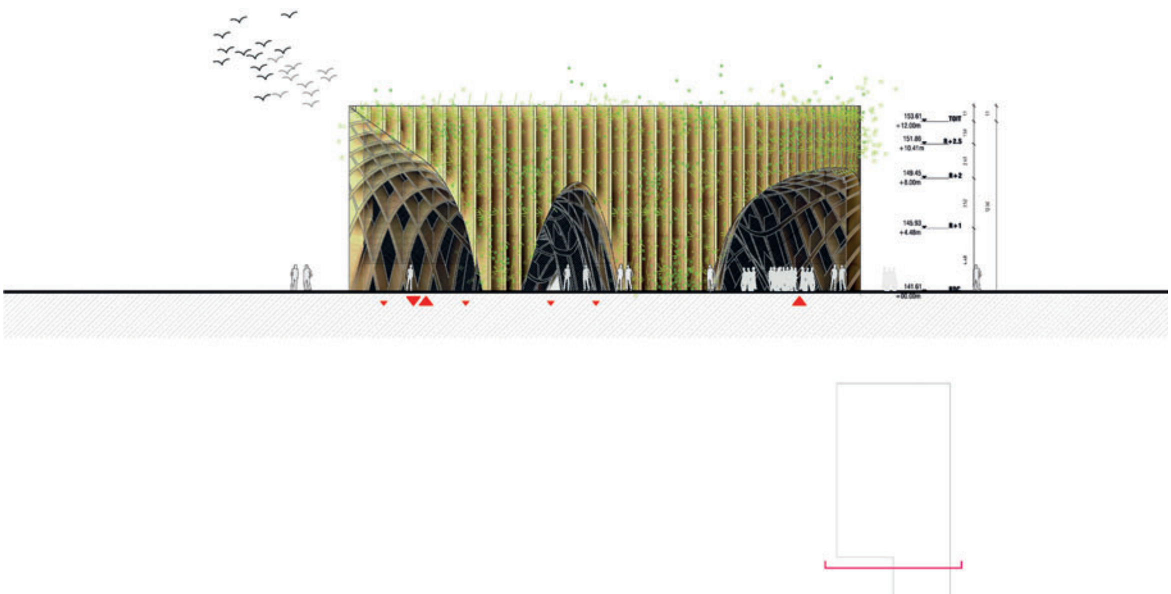
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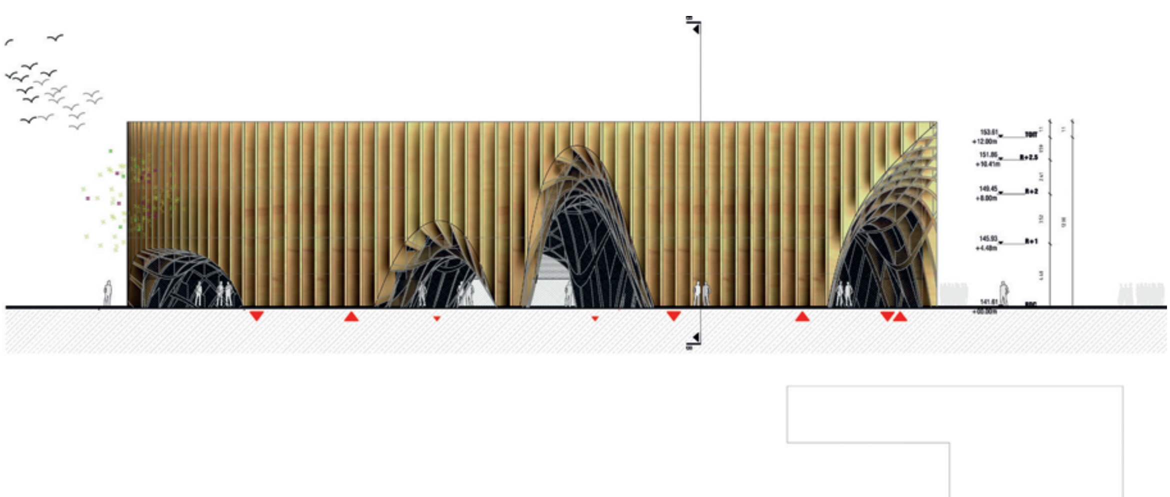
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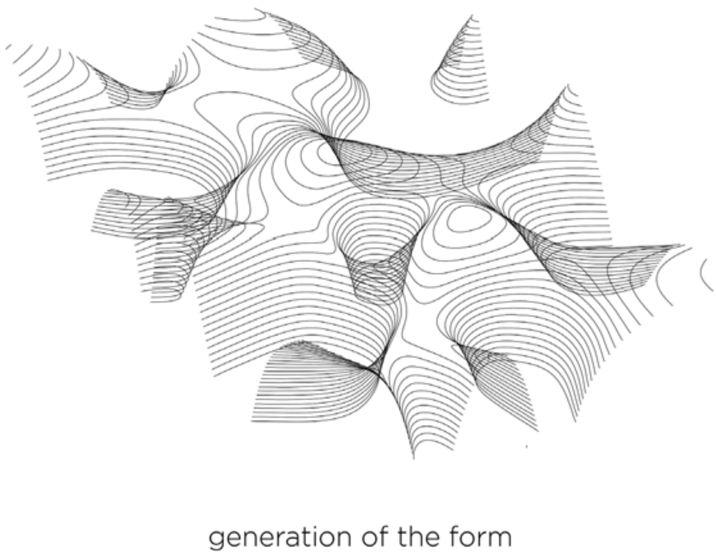

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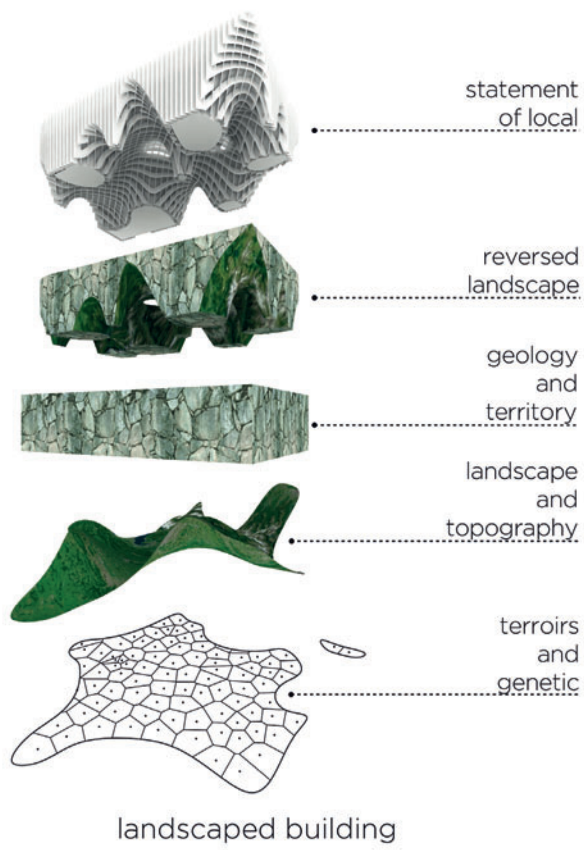

Figure 8.13 (a) Generation of the shell form; (b) landscaped building
Source: ©XTU Architects.

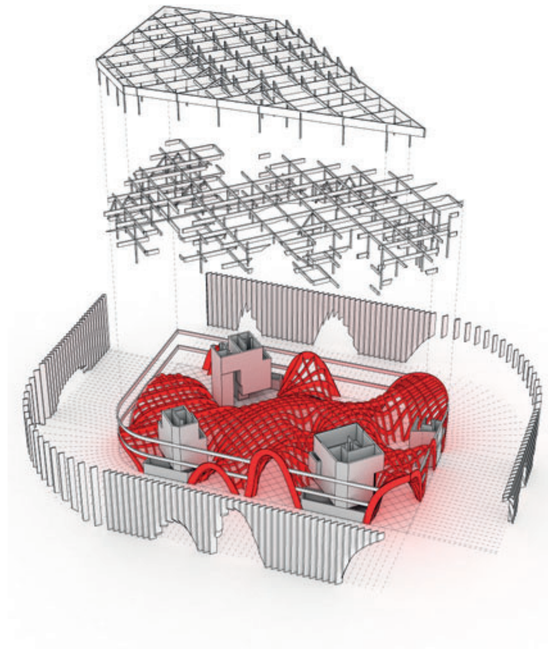

Figure 8.14 Layout of timber structure of the France Pavilion. The gridshell is shown in red.
Source: © designtoproduction GmbH.

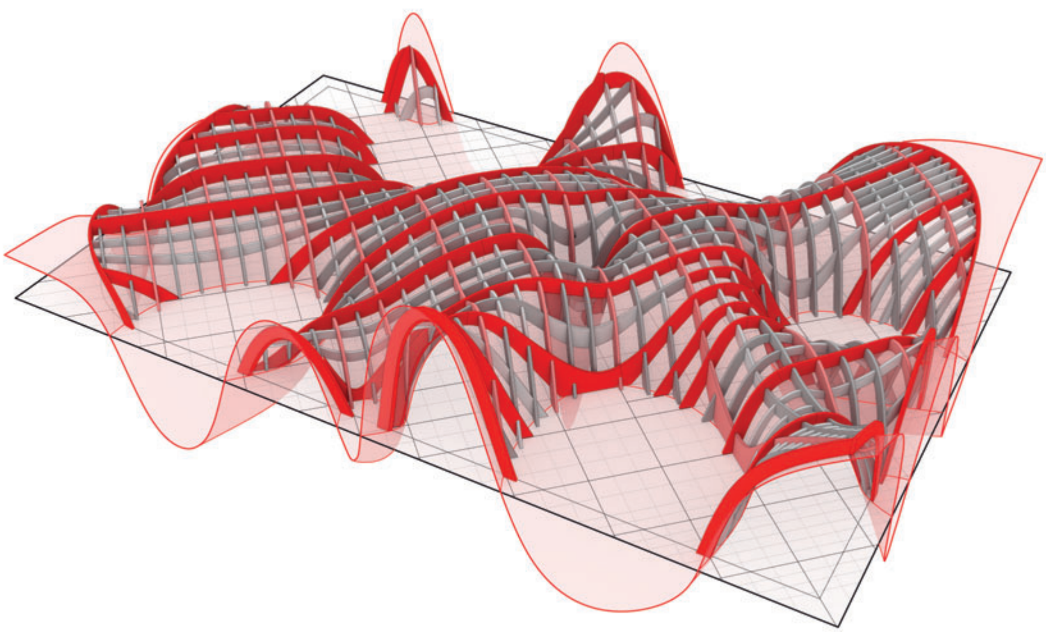

Figure 8.15 Gridshell showing primary beam locations and how this relates to XTU Architect's original reference surface
Source: © designtoproduction GmbH.

(a)

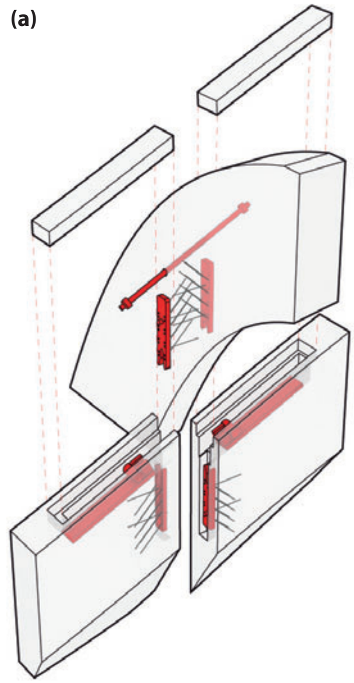

Figure 8.16 (a) Detail of typical KNAPP™ connection; (b) typical joint being prepared in the workshop
Sources: (a) (© designtoproduction GmbH; (b) (© Simonin SAS.

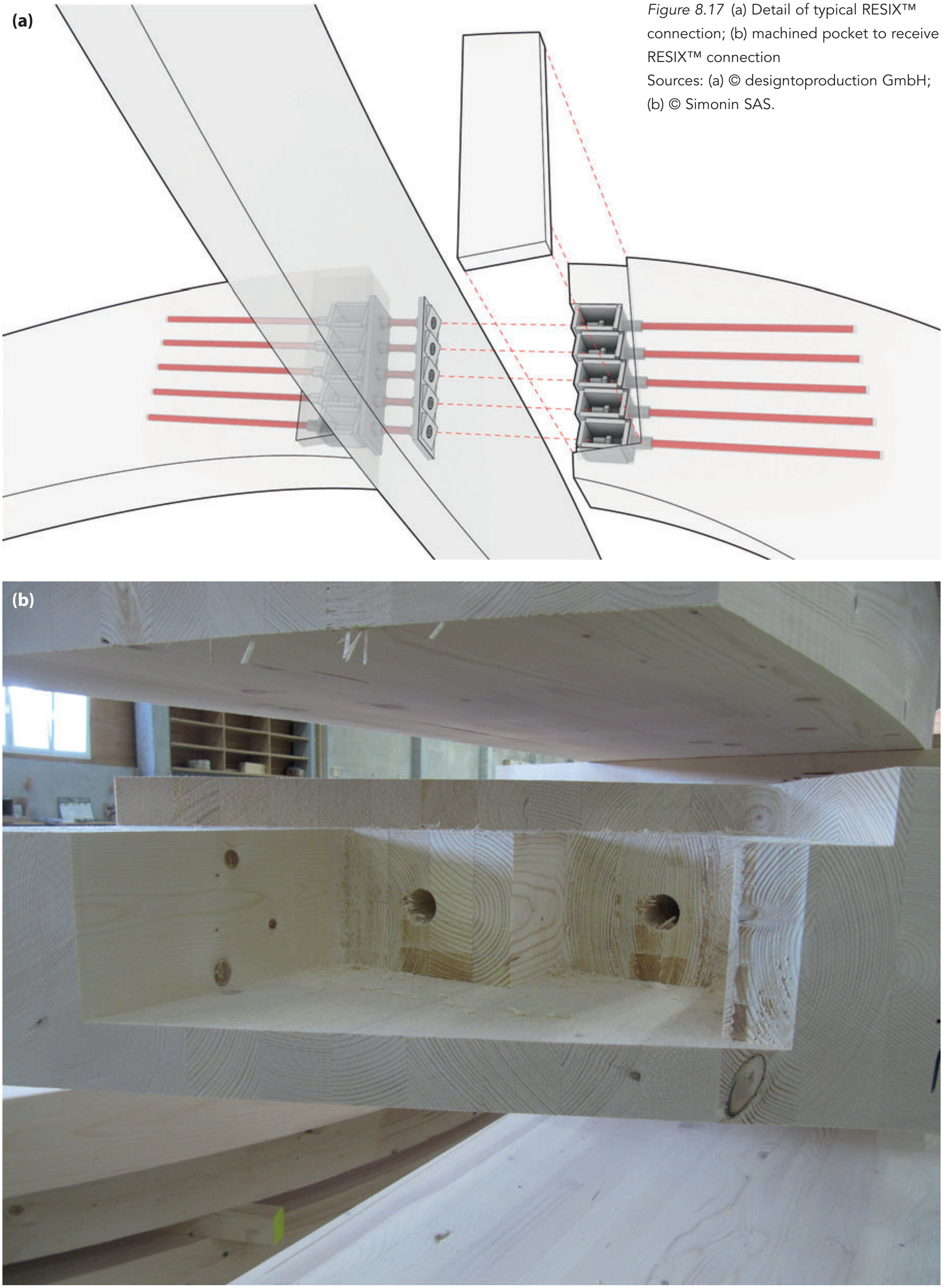

Figure 8.17 (a) Detail of typical RESIX™ connection; (b) machined pocket to receive RESIX™ connection
Sources: (a) © designtoproduction GmbH; (b) © Simonin SAS.

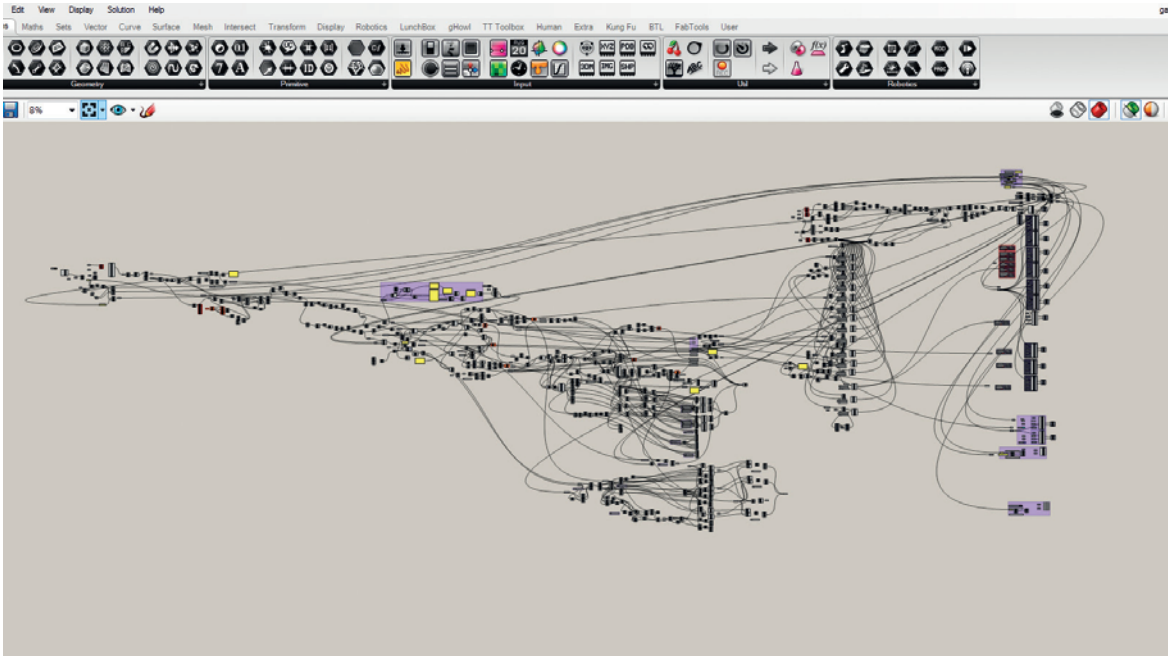

Figure 8.18 Grasshopper model used by SIMONIN to extract production data and to inform the lamination process
Source: © Simonin SAS.

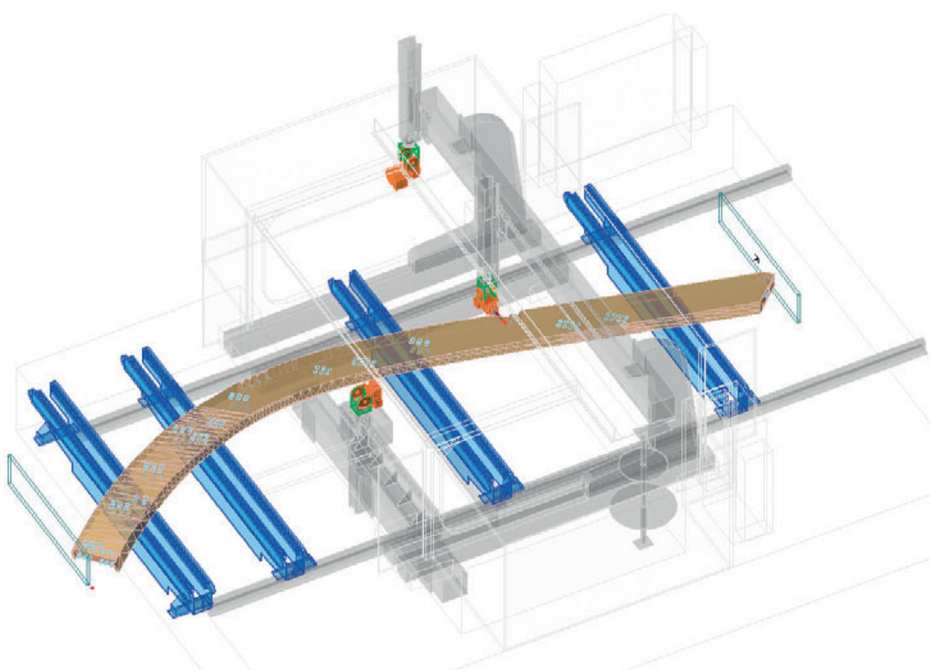

Figure 8.19 CAD models were used to check the digital fabrication process
Source: © Simonin SAS.

Details of all required cuts, drillings, machined pockets and slots for connectors were generated with the parametric model, including checking that all fastenings screws would not protrude from the timber sections (Figure 8.19). Exploiting their specific capabilities, AlphaCAM software controlled the five-axis milling of beam faces and LignoCAM was used for machining connection details. Fabian Scheurer and Loïc Simonin clearly stated that it would have been impossible to realise the timber structure of the French Pavilion economically and within the time available without using digital fabrication (Figures 8.20 (a) and (b)). Simonin's Technowood TW-Mill required approximately 1750 hours to produce 1450 timber components (ibid.).

This had to be a fast track project. It took five months from the inception of the fabrication model before the full digital fabrication data was available. This was at the end of November 2014, just over five months before the opening date of the Expo – 1st May 2015! However, fabrication had already commenced and was running in parallel. In fact, the first components (Figure 8.21) had already been erected in Milan a few days earlier and assembly progressed rapidly (Figure 8.22) (ibid.).

Completed in time for the Expo's official opening to the public, the France Pavilion clearly demonstrated the benefits of digital design and fabrication. It fulfilled XTU Architects' design intention of luring the visitor to begin an exploration of the building by entering the cave-like portal (Figure 8.23). Once inside, they are immersed within an inverted landscape defined by the form of the gridshell. Spaces within the grid are populated with 'vaults of plenty' displaying 'regional specialities, delicacy tastings, scientific and biotechnological research, agro-ecology, new agri-food technologies, genetic discoveries, life chemistry and beneficial flora' (Figure 8.24) (XTU Architects, 2015). The prefabricated timber structure which includes the gridshell is an exemplar of low-carbon construction. In addition, the France Pavilion is reusable.

ÎLE SEGUIN 'CITÉ MUSICALE', BOULOGNE-BILLANCOURT, PARIS, FRANCE, UNDER CONSTRUCTION, EXPECTED 2016

A COMMON THEME in the development of timber gridshells was the involvement of Frei Otto who worked with different architects and engineers. For the gridshells described in Chapter 2, a common thread is the involvement of engineers Buro Happold. Building on the experience gained by founders of the practice in the realisation of the Mannheim Multihalle, the company has worked with a number of prominent architects, Shigeru Ban, Edward (Ted) Cullinan and Glenn Howells. However, in recent years, the baton appears to have passed to Shigeru Ban Architects as the champions of large-scale timber gridshell architecture with a portfolio of built and unbuilt projects. The timber and cardboard tube Japan pavilion for the Hanover Expo 2000 was followed by the Centre Pompidou-Metz (2010) and Haesley Nine Bridges Golf Resort (2010) and is now being demonstrated in the Cité Musicale in Paris (under construction at the time of publication in 2016) and an extensive new headquarters building and production building for Swatch/Omega in Biel (Bienne) in Switzerland, where completion is expected in autumn 2016. Unbuilt competition entries include, for example, the Zagreb Airport New Terminal, Croatia, 2008, where his timber gridshell design won second prize, an Environmental Sciences Museum, in Mexico, 2010. Current proposals include double-layer grids for the Oita Indoor Sports Center and a single-layer woven grid for the Oita Prefectural College of Arts and Culture, Japan, 2015.

The Cité Musicale, Boulogne-Billancourt, designed by Shigeru Ban Architects Europe with Jean de Gastines Architectes, is a multi-purpose and concert hall complex located in the western outskirts of Paris on the Île Seguin (Figure 8.25) (Shigeru Ban Architects, 2015a; Jean de Gastines Architectes, 2015). Ovoid and nest-like, the building's façade is structured using a free-standing hexagonal-triangular gridded glulam timber gridshell (Figure 8.26).

Figure 8.20 (a) and (b) Production of gridshell components using a five-axis Technowood TW-Mill
Source: © Simonin SAS.

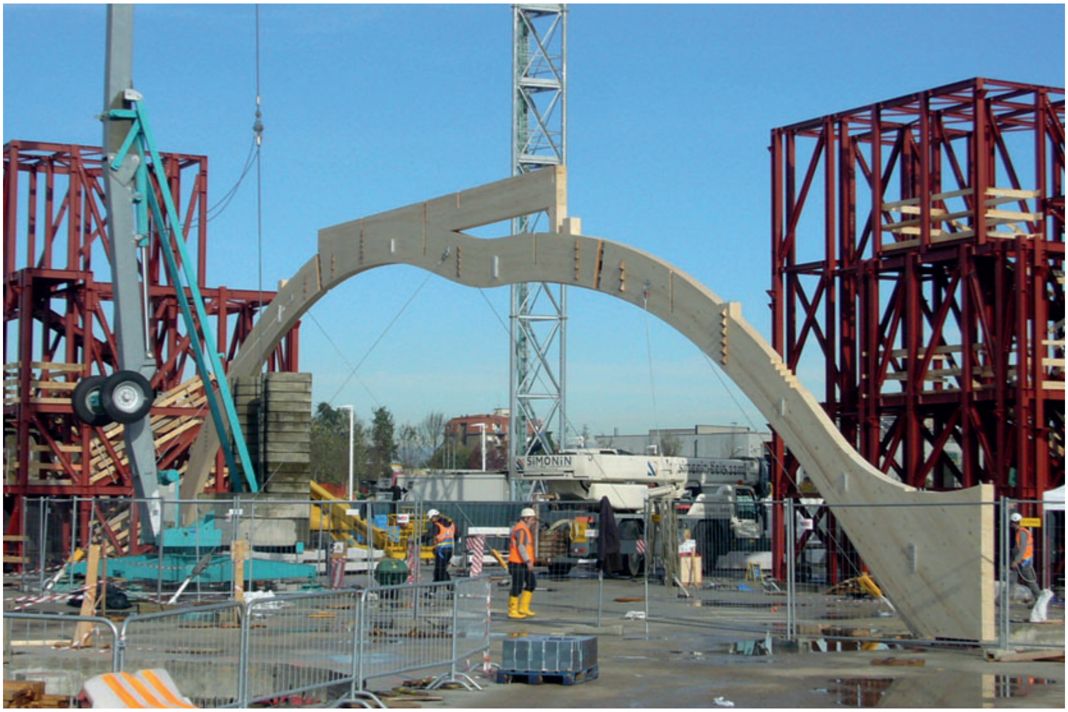

Figure 8.21 Erection of first components at the site in Milan, 18 November 2014
Source: © Simonin SAS.

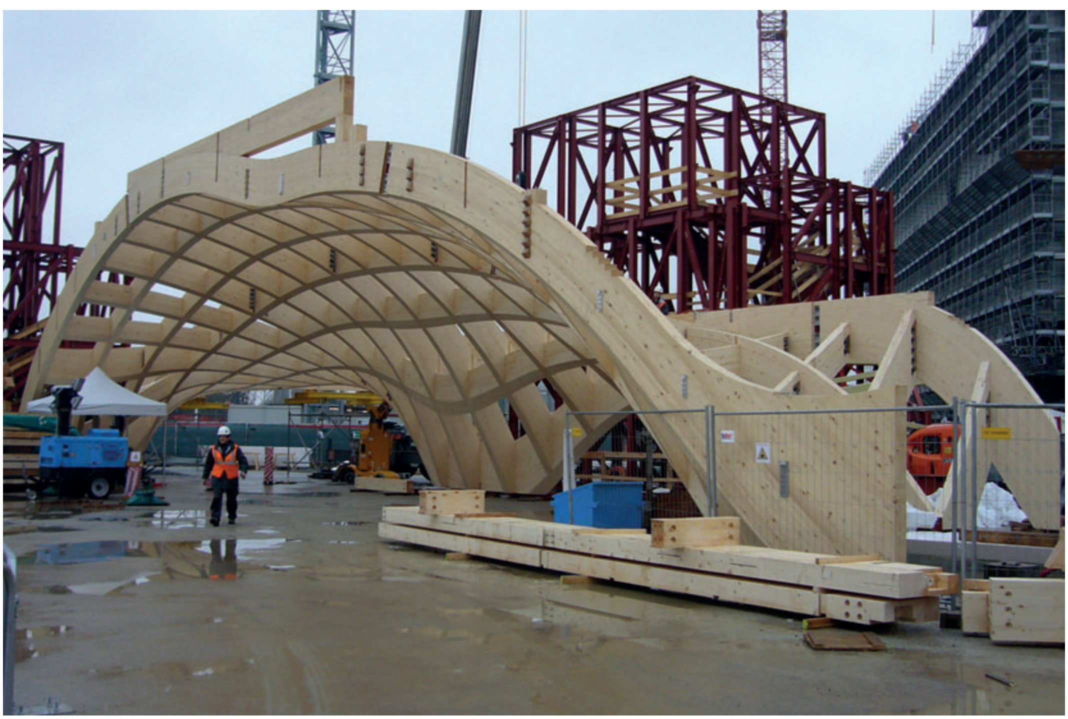

Figure 8.22 Assembled components of the gridshell, 2 December 2014
Source: © Simonin SAS.

Figure 8.23 Exterior of the completed France Pavilion at the Expo 2015 in Milan
Source: © XTU/Studio A.Rispal/Cyrille Dubreuil.

Figure 8.24 Interior of the completed France Pavilion at the Expo 2015 in Milan
Source: © XTU/Studio A.Rispal/Cyrille Dubreuil.

Figure 8.25 Cité Musicale on the Île Seguin, Boulogne-Billancourt, Paris. The ovoid gridshell façade of the auditorium stands out from the general silhouette of the island
Source: © Shigeru Ban Architects Europe – Jean de Gastines Architects – Perspective Morph_Passerelle.

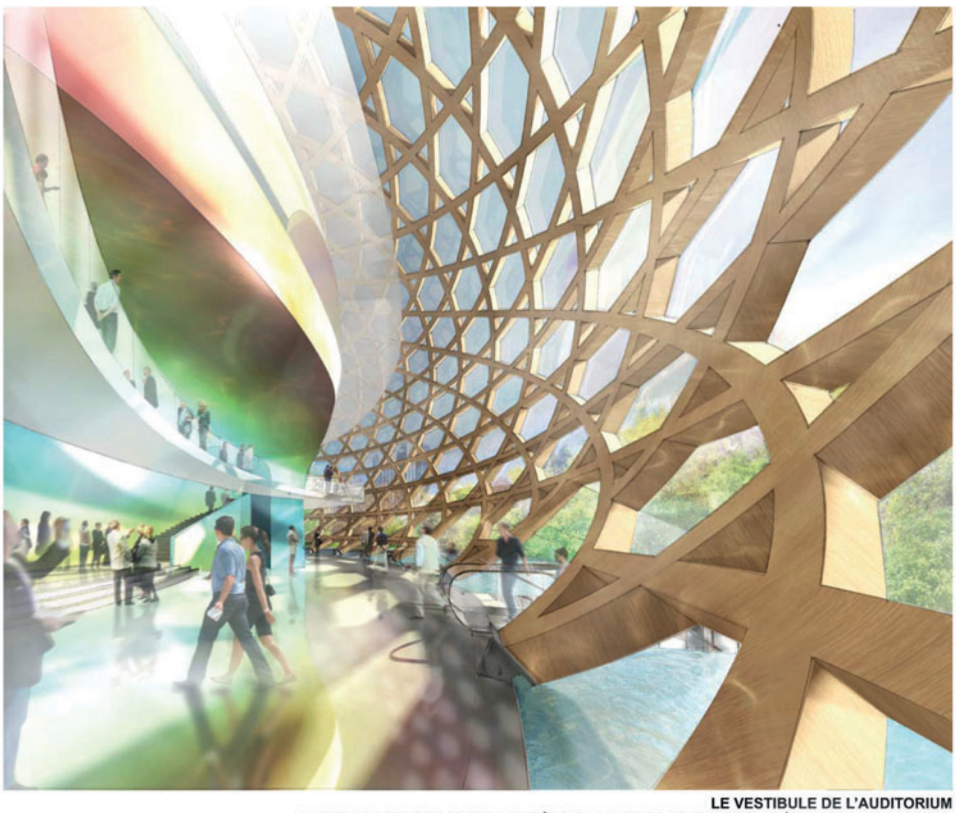

Figure 8.26 Auditorium vestibule: the impression of space is amplified by the continuous reading of the timber gridshell rising to the sky
Source: © Shigeru Ban Architects Europe – Jean de Gastines Architects – Perspective D Ghislain_Vestibule.

Fabricated by HESS TIMBER GmbH & Co. KG, the 5660 m² timber gridshell façade is constructed from double-curved glued laminated spruce timber beams (Figure 8.27). The beams vary in size from 300 mm x 300 mm to 300 mm x 420 mm (HESS, 2015). Connections in the structure are designed to minimise the use of metal components. Erected using a tower crane located on the central core of the building, the partially completed grid is shown under construction in Figure 8.28.

NEW HEADQUARTERS FOR SWATCH/OMEGA, BIEL (BIENNE), SWITZERLAND, UNDER CONSTRUCTION IN 2016

FOLLOWING AN ARCHITECTURAL competition in 2010, the design of Shigeru Ban Architects Europe was selected to create a new headquarters building for Swatch and production building for Omega, in Biel (Bienne), Switzerland (Swatch Group, 2015). A dominant feature of the winning design is an extensive sweeping curved timber gridshell (Figure 8.29).

Intended as the new headquarters for Swatch, the gridshell is located in the watch manufacturing area. Its flowing organic form (Figure 8.30) will house showrooms and administration offices, spanning Gottstattstrasse, to link the delivery and collection entrance on Rue Jakob Stämpfli with the recently completed timber-framed Swatch/Omega central building (Shigeru Ban Architects, 2015b) (Figure 8.31).

At the time of writing, mock-ups have been constructed to demonstrate how the proposed ETFE foil cushion façade will interface with the digitally fabricated timber gridshell (LEICHT GmbH, 2015).

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Figure 8.27 Curved glued laminated timber gridshell façade components being prepared in the workshops of fabricator HESS TIMBER GmbH & Co. KG
Source: © Rensteph Thompson/HESS TIMBER GmbH & Co.KG.

Figure 8.28 The partially completed grid under construction
Source: © HESS TIMBER GmbH & Co. KG.

Figure 8.29 Model of the proposed new headquarters building for Swatch in Biel (Bienne), Switzerland
Source: © Shigeru Ban Architects Europe.

Figure 8.30 Rendering of the atrium interior for new headquarters building for Swatch in Biel (Bienne), Switzerland
Source: © Shigeru Ban Architects Europe.

Figure 8.31 The flowing timber gridshell roof crosses Gottstattstrasse where it connects to the Swatch/Omega facilities
Source: © Shigeru Ban Architects Europe – Perspective D Ghislain.

POSTSCRIPT

From the selected case studies we have presented, it is clear that timber gridshells result from collaborative team working and synergetic integration of architecture, structure and craft, themes strongly ingrained in their realisation. Furthermore, the recent advances in engineered timber and fabrication technology have emerged as strong thematic threads. Although not solely restricted to timber applications, digital design and fabrication have changed the way architects, engineers and fabricators approach timber as a construction material and gridshells as a structural solution.

In the early years, form-finding depended largely on physical model-making. The 'proximity' and direct intervention of the designer in the form-finding process resulted in gridshells that are pure in structural and formal expression – the use of timber appears very intuitive. Harnessing the flexibility of thin timber laths resulted in gridshells with an impressively small thickness-to-span ratio. These early years were a period of fervent experimental exploration. The uniform orthogonal grid mesh maintained a uniformity and resulted in the deformable nature of the early examples, highly expressive of the construction process.

The charm and the thinking process of the artisan are highly expressed and omnipresent in early timber gridshells. Mannheim Multihalle gridshell was heavily marked by chalk and pencil during construction. The Weald and Downland gridshell has an equally crafted sensibility – the care, attention and skills of the carpenter can be seen by the way the structure was crafted, likened to an intricate piece of furniture crafted by the human hand.

By contrast, advances in engineered timber production have reduced the effect of defects in the raw timber. For thin laths, techniques for detection and removal of defects and weak sections and efficient and strong jointing of the resulting short sections have enabled the creation of a stronger and more uniform engineered product. The ability to use smaller sections of timber, previously regarded as having little or no economic value, has had a major impact on the sustainability of timber gridshells in a resource-conscious environment.

The Centre Pompidou-Metz, completed in 2010, saw a significant departure from previous practice with the abandonment of the initially orthogonal flat grid. Instead a more widely spaced three-way mesh was adopted, forming a pattern of triangles and hexagons, which, unlike the classic gridshell, is not deployable. Using sophisticated form-finding and parametric geometric design software managed by designtoproduction GmbH and CNC manufacture, Holzbau Amann GmbH was able to achieve precise curved glulam timber components that were assembled *in situ* to complete the finished double-curved gridshell form – a definite triumph of the machine in realising the conceptions of the human imagination. With prefabrication possibilities, the construction of a timber gridshell structure has become more accurate, and other ways of constructing timber gridshells have become possible. The SUTD gridshell in Singapore and the KREOD pavilion in London clearly illustrate this. Although the resulting gridshell is a precise piece of engineering with a predetermined geometry, the assembly process often involves relatively unskilled labour. Freed from the need to deform a flat orthogonal mat, the grid pattern has subsequently developed into one with irregular units of varying size no longer limiting the aesthetic expression of the gridshell. Hence, timber gridshells are achieving an increasing level of visual complexity. With new computational advancements, the gridshell is now liberated, free (-formed) and can now truly become a 'shell with holes'.

With bated breath, the future development of timber gridshells is eagerly anticipated …

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