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TIMBER GRIDSHELLS: DESIGN METHODS AND THEIR APPLICATION TO A TEMPORARY PAVILION

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ABSTRACT: This paper describes timber gridshell design methods and building techniques. The authors' experience with such projects is used to highlight the advantages of timber gridshells. Relevant built examples are presented and their form-finding and analysis methods are discussed. The relevance of the timber gridshell technique is illustrated by a recently built project in Cluj, Romania that builds upon previous knowledge and takes advantage of modern computational tools that are available for both architects and engineers.

KEYWORDS: Timber structure, Timber gridshell, Form finding, Structural analysis, Dynamic relaxation

1 INTRODUCTION

Timber gridshells are a solution to the growing interests of free-form architecture in the context of an ever increasing awareness of the natural limitations of our environment. The characteristics of timber gridshells - long-span, light-weight, affordable and sustainable - argue that it should be a perfect fit to some of the architectural programmes of our time. However, their use has so far been limited to experimental pavilions and a few very worthy, large-scale, permanent buildings. In this paper, we present existing gridshells that have answered the needs of architecture and discuss various methods used to design them, including physical and computational methods. We conclude by presenting a recent example that was informed directly by the construction process.

2 BACKGROUND

Shells are structures that are defined by a curved surface, often a doubly curved surface. Gridshells, also referred to as lattice shells or reticulated shells, are defined as structures "with the shape and strength of a double-curvature shell, but made of a grid instead of a solid surface" [1]. Figure 1 shows typical elements of a shell and a gridshell. The materials out of which such structures have been constructed include aluminium, steel, timber, cardboard or glass-fibre composites. As a result of the differences in the material, differences in the construction and assembly processes arise which lead to a possible classification of gridshells.
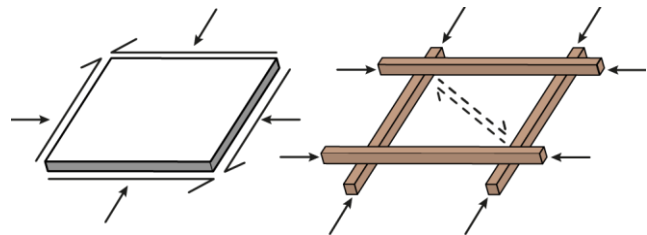

Figure 1: Left – Shell element; Right – Gridshell element

Two types become obvious: one featuring continuous grid members with long laths spanning across the whole structure overlapping each other at the nodes, and the other one featuring discrete grid members that connect at nodes (Table 1). This paper is concerned with continuous member timber gridshells only.

Table 1: Different types of gridshells

Continuous Grid Members	Examples
Timber	Mannheim Multihalle, Mannheim, Germany
Cardboard	Japan Pavilion, Hannover, Germany
Glass-Fibre Composites	Solidays music pavilion, Paris, France [13]
Discrete Grid Members	**Examples**
Timber	Pods Sports Complex, Scunthorpe, UK
Steel	British Museum Great Court Roof, London, UK

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2.1 TIMBER GRIDSHELLS

The timber gridshell technique was first developed by Professor Frei Otto and involves deforming a flat grid of identical straight timber laths into a doubly curved shape. This is made possible by the low torsional stiffness of timber and by ensuring that nodal rotations are allowed [2]. The deformation is possible in two modes, either starting flat on the ground, and pushing upwards, or assembling the grid above ground and lowering it using gravity.

Using a double-layered system, with 4 sets of laths arranged in two directions (Figure 2.1), allows such structures to achieve higher curvatures and hence, more exciting architectural expressions.
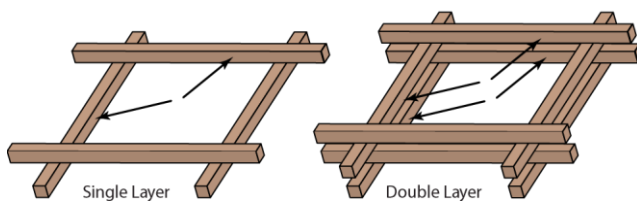

Figure 2.1: *Single layer and double layer arrangements*

Due to the two-directional arrangement of members, timber gridshells can support forces along the two directions (tension or compression) and out-of-plane bending. In order to provide in-plane shear strength and stiffness, the structures need to have diagonal bracing in the form of cross ties, rigid bracing or an active covering system.

In the case of double-layered gridshells, there is also a need to provide shear transfer between the top and bottom laths [3]. This is achieved through the nodal connnections themselves and through the use of shear blocks, inserted between the laths, leading to a "composite section that has significantly greater strength than the individual laths" [4], as shown below in Figure 2.2.
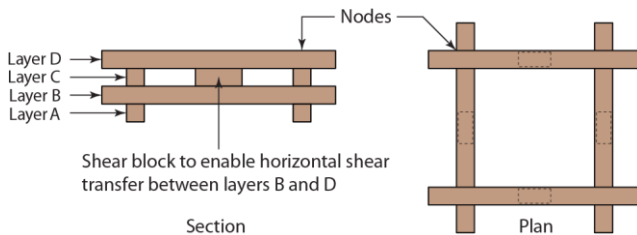

Figure 2.2: *Plan and section of double layer system showing shear blocks (adapted from [6])*

One of the advantages of the timber gridshell technique is that it allows the use of identical nodal connections, throughout the structure. However, the layered nature of the structural system, together with the fact that the post-forming process requires the layers to have freedom to slide along each other as well as rotate during construction,

create an interesting challenge for these connections. This has been resolved with two elegant solutions (Figure 2.3).

The first design, involved slotted holes in the top two layers for the bolts that would allow the necessary movement [4]. Once the final shape was obtained, the bolts would be tightened and the desired clamping force applied to the connection [3].
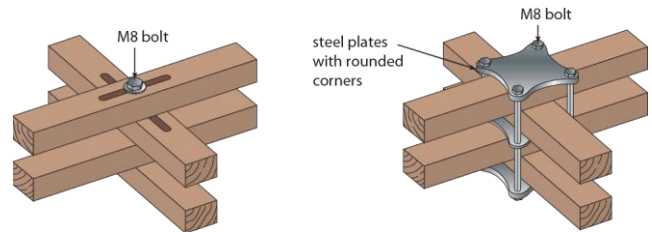

Figure 2.3: *Left – Slotted hole connection; Right – Plates and external bolts connection (adapted from [6])*

More recent timber gridshells have used a design which features steel plates between the layers with 4 bolts connecting the plates without penetrating the laths [4]. In this arrangement, "the outermost layers are effectively passengers that are free to slide relative to the central layers" [6]. Other benefits include the fact that the costly slotting of the laths is avoided. Furthermore, this allows for other features to be embedded into the design (Figure 2.4). If needed, two opposing bolts may be lengthened enabling the attachment of stiffeners [4], or as in the case of the Chiddingstone gridshell, the connection could incorporate the frameless glazing mounting [7].
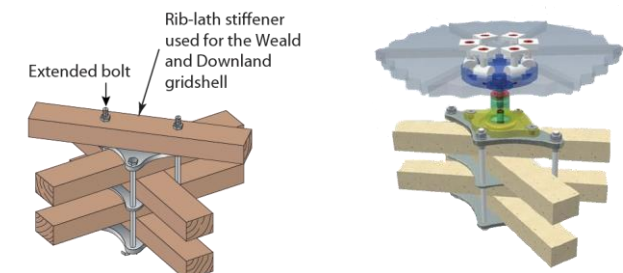

Figure 2.4: *Left – Plates connection with extended bolts and diagonal bracing (from [6]); Right – Plates connections with adaptable fixing for frameless glazing (from [7])*

2.2 EXAMPLES

2.2.1 Mannheim Multihalle

This technique was first used on a large scale for the Mannheim Multihalle in 1975 by Frei Otto together with Arup. The building, shown in Figure 2.5, featured two domes, spanning 60m and 40m respectively, as well as connecting pathways [3]. The structure was realised using 50mm x 50mm hemlock sections joined together to form the laths on a 0.5m grid layout. The system used a double layer configuration with in-plane stiffness achieved by

pairs of 6mm cables every 6th node. The details of design and construction are presented in Happold and Liddell [3] and IL13 [14].

The Multihalle was a pioneering work of design and engineering and its delivery was only made possible due to the high level of skills, knowledge and experience on the part of the people involved as well as their combined drive to innovate.

Figure 2.5: Mannheim Multihalle: exterior with two domes and connecting pathways; interior of one of the domes (from [14])

2.2.2 Weald & Downland

The Weald and Downland gridshell (Figure 2.6) was built in 2002, more than two decades after the Mannheim project. The architect was Edward Cullinan Architects with engineering by Buro Happold and carpentry by Green Oak Carpentry.

It features an uninterrupted floor space which is 48 m long and between 11 and 16 m wide, enclosed by a corrugated barrel vault shape. The double layer gridshell was built from locally sourced oak with 50mm x 35mm sections arranged on a 1.0m grid that was halved in some areas to 0.5m [4].

Figure 2.6: Weald & Downland gridshell; exterior with triple hour-glass shape; interior view (from Architect's Journal Building Library)

2.2.3 Savill Garden

The Savill Garden gridshell (Figure 2.7) was built in 2006 by Glenn Howells Architects with Engineers HRW, Buro Happold and Green Oak Carpentry [5]. It is also a corrugated barrel vault that spans over a 90 m long and, at its widest, a 25 m wide space. The gridshell roof is supported all along its perimeter on a tubular steel beam raised above ground on slanted columns.

The structure was assembled on a 1.0m grid from 80mm x 50mm larch sections arranged in a double layer system. Unlike previous projects, the two top layers (C, D in Figure 2.2) and the two bottom layers (A, B in Figure 2.2) are independently connected and joined to each other by the use of shear blocks. In this case, the shear blocks were twice the normal depth in order to provide the structure with a higher second moment of area [5].

Figure 2.7: Savill Garden gridshell; exterior with corrugated vault shape on slanted steel supports; interior view (images – Richard Harris)

2.2.4 Chiddingstone Orangery

One of the smaller and lesser known timber gridshells is the one built by Peter Hulbert Architects with Buro Happold and Green Oak Carpentry in 2004 as a roof for an old orangery which is of historic interest (Figure 2.8) [7]. Its main feature is the precision engineered integration between the double layer gridshell and the frameless glazing system. This was done by specially designed nodal connections, as detailed in Section 2.1.

Figure 2.8: Chiddingstone gridshell; interior view; detail of grid layout showing two layers, nodal connector and shear blocks (from [7])

2.3 COMPARISON

One of the advantages of timber gridshells is the relatively low cost associated with them. Figure 2.9 shows a cost comparison between the three major timber gridshell projects that have been built so far with regard to the gridshell cost only. The values are obtained from the data collected from the papers published on their design and construction and updated to 2010 GBP and can be found in Naicu [11]. Based on Harris *et al.* [4] the gridshell cost of the Savill Garden and Weald and Downland was assumed to be 28% of the entire structure. As a measure of

comparison, the cost of The Palacio de Comunicaciones[4] in Madrid, one of the more recent steel gridshells, constructed in 2009, is also shown. The comparison illustrates the financial viability of timber gridshells in relation to similar types of structures constructed from other materials and also shows that this has been the case since the first project was completed (Mannheim).
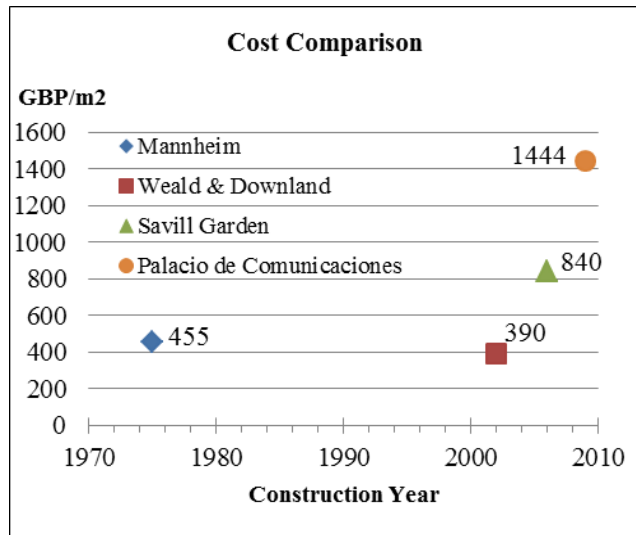

Figure 2.9: *Timber gridshell cost comparison; using £2010 adjusted values per m²*
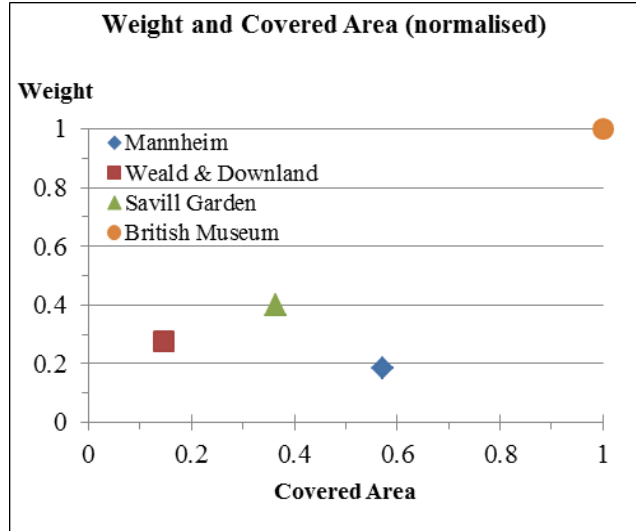

Figure 2.10: *Normalised weight and covered area comparison; British Museum Great Court Roof used as nominal value*

Furthermore, timber gridshells are very efficient ways to span large distances. Figure 2.10 shows a comparison of their self-weight against the covered area [11]. In order to better compare these structures, the values were normalised against the reference values for the British

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[4] Communications Palace Courtyard Roof by Schlaich Bergermann und Partner

Museum Roof. The area was chosen as representative because of the different shapes that they cover and choosing a single span would penalise some in reference to the others.

The result of this is that timber gridshells compare very well with steel ones. For example, the Savill Garden Building weight and covered area are both around 40% of that of the British Museum, whereas the Mannheim Multihalle weighs only 20% while covering 60% of the British Museum area. This was however intended to be a temporary building.

2.4 PAVILION ZA

More recently, a double-layered timber gridshell was designed during a student workshop in Cluj, Romania with the widely used digital physics modelling package Kangaroo Live Physics.

Figure 2.11: *Pavilion ZA (image – Dragos Naicu)*

The gridshell, shown in Figure 2.11, functioned as a temporary cultural venue in Cluj-Napoca, Romania. It spanned 18 m x 13 m with a height of 4.0m by using a structure with laths made from Siberian larch, 70mm x 20mm in section. The grid was assembled from 3.5m by 3.5m modules, connected on site using a double-splice joint (Figure 3.1). In-plane bracing was achieved by a third layer of locally sourced spruce ribs with the same cross-section.
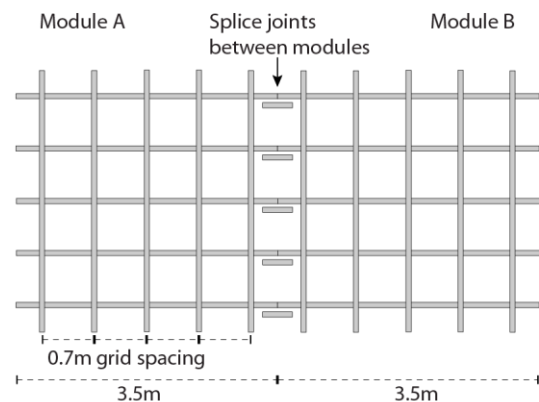

Figure 2.12: *Typical gridshell modules (plan view)*

The pavilion featured four arched entrances where areas of highest curvature were present. In these areas, 2 laths, each one 10mm in thickness, were used for each layer so that bending the gridshell into shape would be possible without breakages (Figure 2.13).

Figure 2.13*: Pavilion ZA: typical connection showing thinner laths used for higher curvature areas at entrances, slotted hole and steel bracket for bracing attachment (image – AStA Cluj)*

The pavilion was designed and built by local architecture students, with funding acquired through sponsorship from local commercial institutions, including the timber supplier. The first author was involved in all stages of this project.

3 MATERIALS

Different architectural and structural solutions create varying requirements for the materials they employ and there is no timber choice applicable for all. Table 2 below summarises the reasons for the materials used.

Table 2*: Timber species choice and reason for use*

Project	Reasons
Mannheim	**Western hemlock** [1] Available in long lengths, normally straight grained, due to the tree growing up to 60 m with a straight bole
Weald & Downland	**Oak** [4] Durable, available from sustainable sources in the UK and with a better performance that the other species on the shortlist
Savill Garden	**Larch** [5] Available at the client's commercially managed and certified woodland; of "exceptional quality"
Pavilion ZA	**Siberian Larch** Based on the use of larch for Savill Garden; available from supplier; aesthetic quality and durability

In addition, timber gridshells require the use of very long straight laths. In order to achieve this, joining shorter timbers is necessary and it also provides the means to control the timber quality.

For both the Weald & Downland and Savill Garden gridshells the same process was used. The timber was "sawn, finger-jointed and planed off-site" [2] producing 6.0m lengths. Using a workshop on-site, the higher grade material was scarf joined into the specified lath lengths. Lower grade material was used for shear blocks and auxiliary pieces [2].
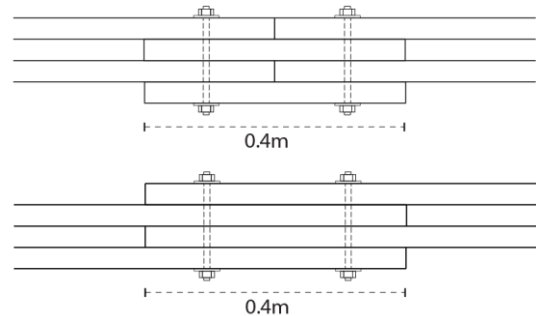

Figure 3.1*: Section view: Top – splice joint used for Pavilion ZA (includes two additional timbers between the laths); Bottom – alternative splice joint (overlap of layers means no additional layers are needed)*

The method described above involves specialised carpentry skills in order to produce a quality product, in addition to special working conditions on and off site. More recently, an alternative method of joining the timbers was devised and used in a few cases that involved the assembly of grid modules from the timber lengths available, followed by the splice-joining of the modules.

Figure 3.2*: Pavilion ZA interior (image – AStA Cluj)*

The authors have first become aware of this method through its use by a team of architects and engineers in Naples, Italy [9]. Pavilion ZA was designed and built using this approach due to the fact that the Siberian larch lengths available were 4.0m. Figure 3.1 shows the connection used for Pavilion ZA (top) together with an alternative option

(bottom). The use of a modular system can lead to the visibility of kinks in the deformed grid when there is not enough lateral resistance from the connections (Figure 3.2). The alternative connection would be a better choice in this case.

4 FORM FINDING

The term *form-finding* is often used to describe the process of defining the shape of a structure which features a complex geometry. Under this category, one would include shells and gridshells as well as cable nets, fabric structures or pneumatic structures. This process is often influenced by factors such as structure type, material properties, boundary conditions and construction requirements.

4.1 FUNICULAR APPROACH

Funicular gridshells are produced by inverting the shape of a hanging chain model, which is under pure tension, thus obtaining a pure compression structure under its own weight. Most famously, this has been applied by Gaudi for the Colonia Guell and it has its historical roots in Robert Hooke's catenary experiments.

Professor Otto developed the prototype for timber gridshells by taking advantage of the fact that "the shape of a quadrangular chain net can be recreated in the initial shape by a flexurally semi-rigid lattice of steel or wooden rods in a uniform mesh provided that the lattice is rotatable at the inter-section points" [3].

As a consequence, the Mannheim Multihalle had its shape determined by a hanging chain physical model which was translated into a compression structure using photogrammetry [3].
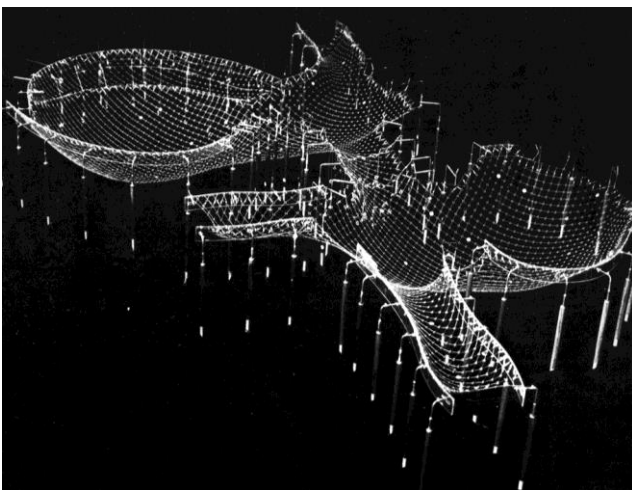

Figure 4.1: *Hanging chain model used for Mannheim Multihalle (from [14])*

This model is shown in Figure 4.1. This process gives the designers information about node coordinates. Scale model testing was also used, firstly for an early prototype

gridshell in Essen, and then for a larger scale Mannheim model [3].

4.2 ANALYTIC APPROACH

Another way to define a grid structure is by explicitly specifying a surface and then describing a grid of nodes and lines on that surface. This method was used for the Savill Garden project, which departed entirely from the use of physical modelling.

Instead, form-finding was achieved entirely using computers and the surface was defined mathematically by a damped sine wave for the centre line and varying size parabolas for the cross-sections [5]. A regular grid was then imposed on the surface generated using the Chebyshev net method. There are an infinite number of Chebyshev nets that can be applied to a surface, and its orientation is one of the main design parameters available at this stage. In addition, there are other geometric methods that could be applied to describing a grid on a surface.
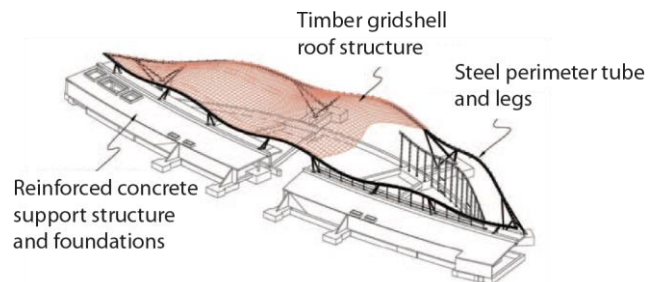

Figure 4.2: *Savill Garden roof structure (from [5])*

4.3 COMBINED APPROACH

A mixed mode between the two approaches is also possible and was used for the Weald and Downland gridshell. In this case, the gridshell was developed from the architectural concept using physical models.
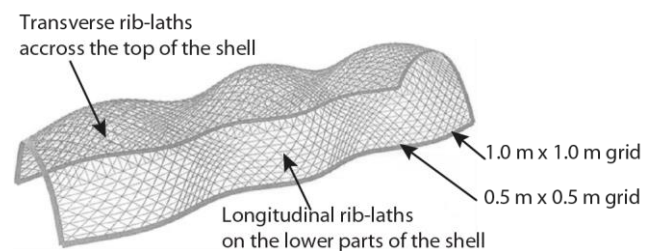

Figure 4.3: *Weald & Downland structure (from [4])*

In the initial stage, these informed a computational process that led to a non-funicular, corrugated form. Since the self-weight of the building was relatively small, this form was better suited to resisting lateral wind loads [4].

The design process loop involved architect's drawings providing information about the shape, which was then used in the development of physical models and these

subsequently helped derive a computer model of the shape" [4], based on a Dynamic Relaxation software, specifically written by Dr Chris Williams of the University of Bath. Dynamic Relaxation uses particles (nodes) that are linked by elements and is used to solve static problems by converting them to dynamic systems using virtual masses and damping at the nodes [10].

This project, situated between Mannheim and Savill from a chronological perspective, shows that there is still a case to be argued for the use of physical models in contemporary design as an adjacent tool to digital ones, as is also argued by Azagra and Hay [8].

4.4 CONSTRUCTION BASED APPROACH

Unlike the aforementioned gridshells, the form-finding of the Pavilion ZA gridshell was based on the proposed construction process. This involved starting with a flat grid and pushing the support nodes towards a desired support configuration, while also pushing the grid upwards. This proposed construction method was in turn, influenced by the methods available to the construction team.

The availability of modern software tools and computational power allow complex structures like timber gridshells to be designed more easily. Kangaroo Live Physics (used together with Rhino3D and Grasshopper) is a computational tool developed by Daniel Piker based on the Dynamic Relaxation technique [10] and was used for Pavilion ZA.
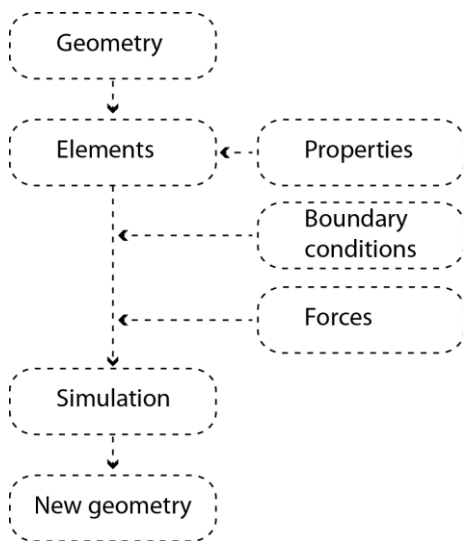

Figure 4.4: Computational design loop

The process of form-finding used is illustrated in Figure 4.4. Starting from an initial geometry, in this case a flat grid, spring elements are generated and are assigned certain properties. This is followed by the assignment of boundary conditions and various deforming forces. The dynamic simulation is then performed and, when equilibrium is achieved, a new geometry is obtained. The process can be repeated and various parameters can be adjusted in order to fine tune the geometry according to criteria such as overall dimensions, maximum curvature, etc.
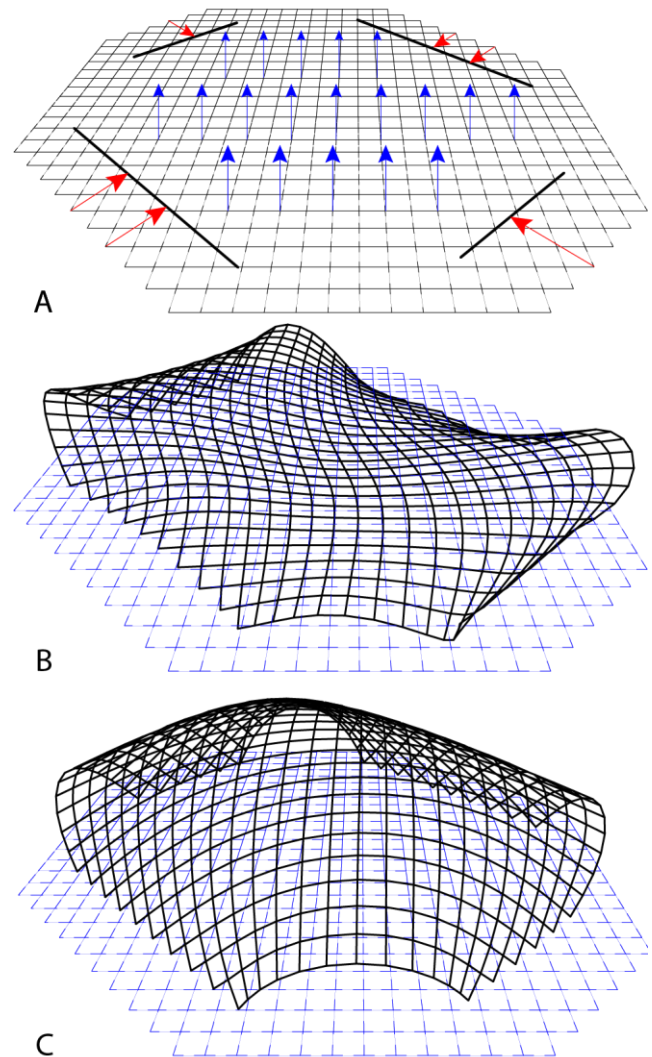

Figure 4.5: Form-finding sequence
A) Initial grid laid flat (support and grid forces illustrated)
B) Intermediate shape
C) Final deformed grid

It was possible to simulate the proposed construction by modelling the following forces applied to a grid made of springs:

- Pulling force applied to the support nodes aimed at moving them to the desired support configuration

- Upward pushing force on all the grid nodes aimed at lifting the grid

- Bending resistant force applied to the grid aimed at simulating the actual bending of the laths

- Spring restoring forces aimed at maintaining the node-to-node distances

The simulation requires certain values for spring and bending stiffness as well as the forces being applied. In this case, "dummy" values were used, not representative of actual properties. Figure 4.5 shows the initial geometry together with the applied deforming forces, an intermediary shape and the final deformed grid. Following a process of material tests (or by using reliable information about material properties), it would be possible to replace the "dummy" values with actual ones.

In addition, the simulation applies all the forces simultaneously, whereas the proposed construction process (and the actual one) involves a sequence of deformations applied to local areas of the grid, usually an overall lift followed by inward pulling of the supports followed by more lifting and so on.

As resources and manpower were limited on site, there was no way to monitor the build in order to provide a quantitative comparison between the simulation and the gridshell. However, from a qualitative point of view, there were close similarities, especially regarding the shapes of the grid in the intermediary positions.

Furthermore, there were only 3 member breakages recorded in total during construction (out of 2760), indicating the curvature analysis and section design was correct.

5 ANALYSIS

The form-finding process described in Section 4 has to be followed by a structural design phase that involves sizing members, detailed connection design and structural calculations for the appropriate load scenarios. This sequence is often an iterative one, where optimisation for various criteria takes place.

Firstly, the shape of the gridshell is directly linked to the size of timber members to be used, as well as to the number of layers. Either one of them can have the dominant influence. The projects built so far feature a single or double layer configuration but there is no reason not to extend that further, leading to bigger spans. Thinner members achieve higher curvatures but have lower compressive and bending resistance.

Secondly, as for any compression dependant structure, the analysis of timber gridshells requires a non-linear study to evaluate buckling behaviour. Gridshell buckling is a vast topic in itself. Malek [12] provides a good understanding of the mechanics of gridshells, and sensibilities of the performance in relation to grid density, grid size and corrugations in the shape.

In addition, material properties have to be carefully considered to allow for accurate representations. For the projects described here custom computer programs were used, as well as commercial software packages and material testing programmes were used to determine the properties of the timber and connections to be used [3], [4].
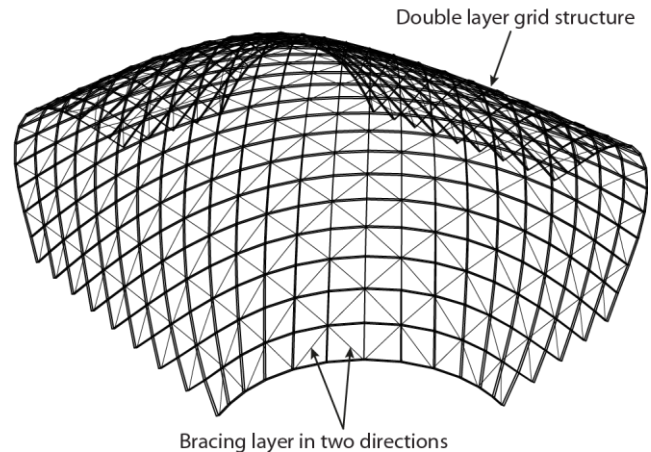

Figure 5.1: Structural model

For such problems, explicit or implicit methods can be used. Implicit methods involve some form of matrix calculations and are usually performed by commercial software. Autodesk Robot Structural Analysis was used to evaluate the performance of Pavilion ZA based on a structural model developed by the authors and presented in Naicu [11].

Additionally, explicit methods can be used and Dynamic Relaxation is one example of such methods. Senatore and Piker provide a good account of this [10].

6 CONCLUSIONS

Timber gridshells offer the attractive possibility of creating complex surfaces and spaces using a set of straight elements that are bent into shape. This makes them affordable and relatively easy to build. Their design and analysis methods are diversified and have evolved over time. Computational possibilities are no longer a limiting factor in the design of timber gridshells. A recent example, Pavilion ZA, was presented which was designed using open-source software by students. Form-finding for Pavilion ZA was based on the construction process and it is now possible to find the shape of a timber gridshell by simulating its real construction process. It would also be possible to simulate and monitor a construction sequence. Even though specialised carpentry skills are usually necessary to achieve the long laths typically used, an alternative modular method was presented that has been used for Pavilion ZA. The convergence of sustainability concerns and computational abilities makes the timber gridshell technique relevant now.

ACKNOWLEDGEMENT

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