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Progressive Development of Timber Gridshell Design, Analysis and Construction

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Summary: This paper reviews significant engineered timber gridshells constructed over the last fifty years. It analyses these as a continuum to understand the significance of both the computer and the physical model especially in the design of timber gridshells. Using a series of key case studies it relates construction and manufacturing developments to the creation of such structures, charts and discusses the relevance of this reiterative process in the development of timber gridshell form, construction and understanding with a practical impact of their future development.

Keywords: *timber gridshells, design, digital design, physical model*

1. INTRODUCTION

Inevitably, the design and construction of timber gridshells, like many aspects of modern existence, is touched and shaped by the advancement in digital technology. With powerful software capable of complex structural design and component manufacture, the emphasis of such structures is shifting towards the digital spectrum. With the design of form-active structures clearly sitting within the practice of innovation, the feedback between physical models for simulation and prototyping as a checking tool remains an important process for verification and reassurance. Models were built by figureheads of shell design e.g. Torroja, and Isler to explore, understand and possibly communicate architectural/structural intentions of thin-shell construction. Important examples include the use of models in key timber gridshell construction.

2. EARLY DEPLOYABLE LATTICE GRIDSHELLS

Following Frei Otto's experimentation with steel reinforcement grids whilst visiting Berkeley in the early 1970s [1], the first examples of engineered timber gridshells were fabricated from flexible laths assembled to form regular, initially orthogonal, grids with bolted connections at all grid intersections. These exploited the inherent deployability of the assembled grid resulting from both the in-plane rotational freedom and shearing of the grid permitted by the bolted connections, and the bending flexibility of the thin laths [1] [2] [3]. All these relied on extensive physical models for form-finding and mathematical verification.

2.1. German Building Exhibition, Essen, 1962

The first opportunity to construct a sizeable grid was for a pavilion at the German Building Exhibition in Essen, in 1962. Assembled on the ground, the full 198m^2 grid was lifted by mobile crane. Partially deforming under its own weight, the draped shell form was pushed down and fixed to a predetermined base ring, anchored to the ground [1].

2.2. German Pavilion, World Exposition, Montreal, 1967

The German Pavilion at the World Exposition, Montreal, 1967, is well known for its innovative cable net roof but less well for the 365m^2 of timber gridshells incorporated as internal vestibule and film theatre roofs. Designed in 1966, by architect Rolf Gutbrod with Frei Otto and his team at the Institut für leichte Flächentragwerke (IL), Stuttgart, first a suspended model was used to determine the ideal gridshell profiles for the two irregular plans; then a 1:10 scale model was made using 2 x 3 mm timber strips. The maximum span for the 500mm x 500mm grids assembled from 42mm x 28 or 35mm hemlock was 17.5m. Engineers for the project were Leonhardt and Andrä, Stuttgart. The grids were manufactured and trial assembled in Germany. Subsequently, taking full advantage of the foldability of the regular mesh, they were compressed into long thin strips, and transported to the Expo site in Montreal as complete sections. Once there, they were winched into position using cable hoists suspended from the main roof cable net before redeployment and fixing to the reinforced concrete support structure [1].

2.3. Multihalle and Restaurant, German Federal Garden Exhibition (Bundesgartenschau), Mannheim, 1975

The best known use of the early deployable timber gridshells are those used for the Multihalle and Restaurant roofs at the German Federal Garden Exhibition (Bundesgartenschau), in Mannheim, in 1975. Although other projects had been proposed and designed (but not built) there was a gap of several years before their construction, following the Montreal Expo. Architect for the project Carlfried Mutschler has written that 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." [4]. Hence the final decision to use a timber gridshell was a giant step, it being approximately twenty times greater in area than any timber gridshell built previously, with larger spans and greater rise.

Fig. 1. Mannheim Multihalle (Photo: Gabriel Tang)

The Multihalle project is a classic example of physical models being used for both architectural and structural design. Initially, a 1:500 scale wire mesh model was made at Frei Otto's studio, Atelier Warmbronn, to determine the preliminary architectural/spatial form of the gridshell. To determine the size of net required to make a larger scale model, approximate dimensions of the of the curved mesh model were obtained by measuring the length of fine threads stretched across the surface at regular intervals [4]. These measurements were then used to establish the pattern for the chain net of a suspended model, constructed at 1:98.9 scale [2]. 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. 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 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. Lath layers are connected at the nodes by 8mm bolts with spring washers. The shell has a surface area of 9500m^2 and plan area of 7400m^2 [1].

As engineers for the gridshell, Ove Arup employed physical wire mesh models to simulate lifting of the grid by cranes. Their tests indicated that expensive 200-tonne capacity equipment would be required. Excessive cost, therefore, led to the adoption of the actual erection method - lifting of scaffolding towers with fork-lift trucks [2]. Several laths required repair due to breakage during the raising of the grid, see Fig. 2.

Fig. 2. Repaired breakage of lath – Mannheim Multihalle (Photo: Gabriel Tang)

3. SECOND GENERATION DEPLOYABLE LATTICE GRIDSHELLS

More recent examples are the Weald and Downland gridshell, 2001, (Edward Cullinan Architects) [5] and the Savill Building gridshell, 2005, (Glenn Howells Architects) [6]. These are the most widely known examples of timber gridshells initially assembled flat at height and subsequently formed predominantly by the action of gravity.

3.1. Weald and Downland Gridshell, Singleton, 2001

The Downland Gridshell was the first double layer timber gridshell in the UK and was designed and built in early 2000 by the architectural studios of Edward Cullinan Architects. The project, located within the South Downs in Singleton, Chichester in England forms part of the Weald and Downland Open Air Museum which houses and exhibits historic timber framed buildings and traditional timber construction techniques. The 50 acre museum preserved, conserved, repaired and reconstructed 45 timber buildings from the 14th and 15th century. The gridshell was built to accommodate a conservation centre, storage as well as archive facilities where classes and exhibition were held, a move that improved and centralized research facilities to improve the off-site arrangement of these amenities before.

Through competitive tender, the design and construction team evolved. The design team consisted of Glenn Howells Architects, Buro Happold as structural engineers and Green Oak Carpentry Company as carpenters for this project. A complex build, this construction fostered and benefitted from a close collaborative relationship between the consortium of experts. The Downland gridshell was widely described as having a triple bulb hour-glass shape open on both ends. On plan, the building measured 50 metres in length and 16m at the widest point narrowing down to 12.5m at the waists. It measured 7.35m in the lowest points and at the central bulb, the tallest point measured 9.5m [5].

Fig.3. Weald and Downland Gridshell (Photo: Gabriel Tang)

Downland gridshell lies across a sloping site with the timber gridshell sitting atop a masonry box which houses the archive stores. Requiring an ambient temperature, this artefact store is earth banked into the slope on one side. The timber gridshell has a floating floor that sat over this masonry plinth to appear as a single story building on one side.

The structure was latticed from timber laths 50mm wide by 35mm deep arranged in a double layer configuration. To brace and stabilize the structure after the gridshell was formed, further laths 50mm by 35mm were used to triangulate the structure. These laths also provided cladding support for the cedar cladding and higher polycarbonate roof.

A innovative development from its Mannheim predecessor was the use of a new patented system of node connection clamps that locked the timber lattice in place. This was an improvement from the drilling through of the timber laths of Mannheim Multihalle which caused numerous breakages that required repairing.

Being form-active structures, the stiffness of gridshells are very much determined by geometry. Building form and shell curvature was important to achieve structural stiffness. Formfinding for this project was conducted and determined by both physical and computer modelling. Physical models were imperative to determine the final geometry. The formfinding process was reiterative and employed both the physical model and computer software written by Dr Chris Williams from Bath University.

A prototype measuring 5m by 2.5m was constructed as part of an undergraduate project of Frank Jensen supervised by Dr Chris Williams at Bath University. The prototype study showed that in using this system, a shell of double curvature measuring a double radius of 5m was achievable. For the prototype, 120 linear metres of improved green oak were used. They were finger-jointed with 225 finger joints, seven of which failed in this investigative study. With a 3% failure rate, this was applied in the actual construction of the structure.

Fig. 4. Patented clamping system used in Weald and Downland Gridshell (Photo: Gabriel Tang)

Another innovation/improvement from the Mannheim Multihalle construction is the way the gridshell was constructed. By forming the gridmat at a higher level on a working platform, this allowed the timber to work with gravity by being dropped into their designed position.

Timber were finger-jointed to remove knot defects and to form laths of 36 m lengths that formed oak timber felled from Normandy France as the timber specification was very high.

Following the construction of the masonry box, gridlines were marked on the floor deck. To create a level working platform, scaffolding was extended over the adjacent terraces. The four layers of timber were laid on top of this scaffolding to form a lattice with metre long edge lengths. The eventual mat measured 47m long by 25m wide [5]. To complete the 50m width, the mat was stretched in the longitudinal direction. This lattice was jacked above this scaffolding for working on as jacking towers were brought onto site. Manoeuvring this complicated matrix of timber and scaffolding and jacking towers required seamless coordination. A sophisticated method of colour coding the lattice mat was used to locate the different areas on the mat easily. To ensure that movement was purely vertical, the central node of each dome was identified and checked to ensure that movement is vertical.

Safety was of paramount importance and progress from the dangerous pushing up procedures of Mannheim Multihalle construction in the 1970's discussed in the earlier section 2.3, saw the use of safety scaffold towers put up to prevent personnel casualties should there be structural failure. The first part of the gridshell to be formed was the central dome. Upon this taking shape, the timber gridmat was restrained at the boundaries. The other two domes were then formed by installing straps to form the waists of the triple hourglass shape gridshell. It was noted that this formation sequence was in fact different from the original idea/ plan of erection / forming.

The departure from previous construction of gridshells saw the construction being executed on an elevated level and allowing gravity to lower and form the domes. The use of PERI scaffolding towers was learnt from the works at Hannover Expo of 2000 for the Japan Pavilion made from recycled paper tubes. This modular system, with supplementary patented components, as well as the firm expertise made their use appropriate and indispensable.

3.2 Savill Garden Gridshell, Windsor, 2005

Following on from the Downland gridshell which generated worldwide interest in timber gridshells, construction design of this typology were further investigated as possible solutions. Completed in 2005, The Savill Building was designed by Glenn Howells Architects as an entry pavilion to the grounds of Windsor Great Park. The Savill building is canopied by a shallow double layered timber gridshell. On plan, the building, takes the shape of a leaf (Fig. 5) measuring 90m long and 20 metres wide. The underside of the dramatic gridshell, displays a complex build up of timber and has been described by the architect Glenn Howells as "like a duvet being fluffed up"[7]. The shallow gridshell undulates to reflect the rolling hills of the Royal Landscape.

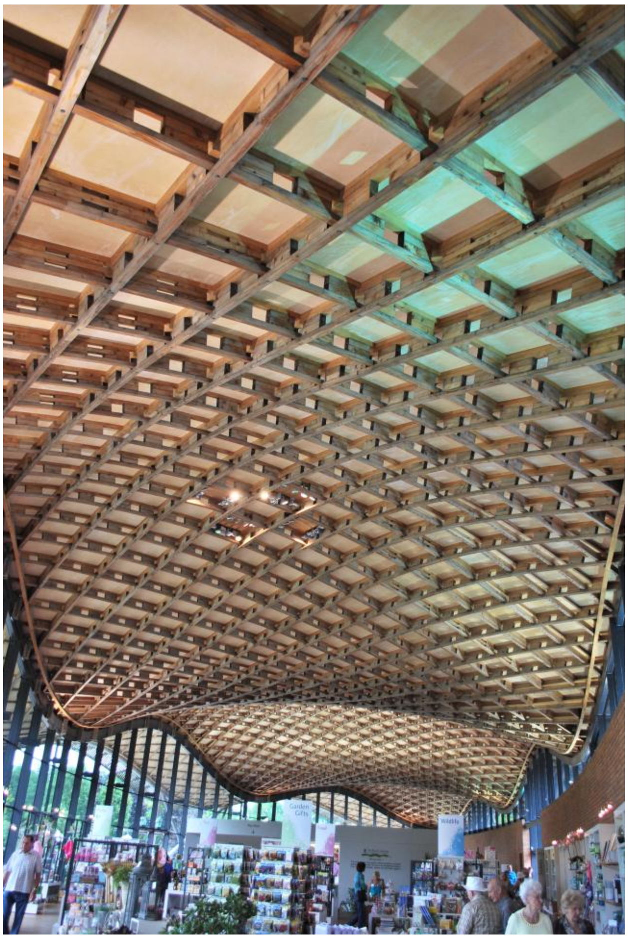

Fig. 5. The gridshell roof at The Savill Garden Gridshell seen from the inside (Photo: John Chilton)

One of the clients' requirements was that the timber used should come from the park wherever possible. The oak outer rainscreen and finishing, as well as structural larch laths and their blocking pieces were all sourced and lumbered from the royal forests.

On plan, the geometry of the building perimeter was generated by the intersection of two arcs. The insulated gridshell roof was constructed from larch laths 80mm x 50mm with a 160mm thick insulation over plywood covering [6]. Formfinding was investigated with the help of computer scripting of Dr Chris Williams at Bath University. The analysis of structure was also achieved digitally. Three dimensional digital models proved very useful as it formed the basis on which details and geometry of building components were developed. To transfer and collect the roof forces, a tubular ring beam was introduced. This ring beam was supported by quadrupled legs that transferred roof loads onto the ground.

The connection of laths to the metal ring beam was solved by using lvl (laminated veneer lumber) that transferred load.

This gridshell bracing method at The Savill was different from predecessors. Unlike the roof of the Mannheim Multihalle which was braced with steel cables, and unlike the Downland gridshell which was braced with timber laths, the gridhell roof of the Savill building achieved in-place stiffness by birch plywood which also supported the raised seam metal roof. This solution eradicated the use of visually obtrusive structural elements to clarify the structural reading and expression of construction and timber build up. Over this insulated metal roof sits a rainscreen of oak also lumbered from the Royal forest.

The advancement of digital technology has impacted on the different processes of putting the building components together and realising a design. 3D digital printing enabled sophisticated physical models with geometrical precision are now possible. These computer generated physical models were useful for geometry study and effective as a communication tool of design and analysis discussion.

Technology also had a positive impact on the simplification of component and manufacturing process. Once timber was felled, they were graded visually and marked with a fluorescent crayon. The timber then passed through a machine that read these defect markings, cutting out the defects and sorted the timber into various grades.

These shorter pieces of wood which measured an average of 0.6m were joined together using a finger-jointing machine to form lengths of 6m. These pieces were further joined together into longer laths. This was achieved under a poly tunnel on site by carpenters scarf-jointing at 1:7 slope by hand. This was observed as an interesting juxtoposition of 21st digital century jointing technology sitting hand in hand with a traditional method used for centuries [6].

Again, like Downland gridshell, The Savill Gridshell was constructed on a higher level and lowered into position over time. However, unlike the Downland gridshell which wrapped around the space to form both walls and roof, the Savill gridshell only functioned as a roof.

The double layer gridshell was constructed in 2 stages however. The construction principles differed as well. To form the required geometry, the first stage comprised a single layer lattice mat was lowered into shape. Horizontal blocking pieces were screwed onto this. Shear blocks were then screwed onto the first 2 lath latticed layers which formed the undulated roof form. The next double layer was built atop this and screwed into position. This effectively produces a structure with the properties of a deep section with greater out-of-plane strength and stiffness. The lower grade pieces were used for shear blocks and packing pieces. This differed from the Downland gridshell construction where all four layers were bent together.

For this gridshell, more than 20 km of timber of 80mm x 50mm larch timber was used to form a roof that weighed 30 tonnes. Should the same roof be constructed from concrete, it would have been much heavier. The timber gridshell therefore reduced much of the loads that the quadrupled legs and foundation [6]. (Harris and Roynon 2008)

4. RIBBED LATTICE GRIDSHELLS

Ribbed lattice gridshells are not deployable. They are assembled directly to the double-curved shape, generally using wider but thinner timber boards that are more flexible. This practically eliminates the tendency for lath breakage encountered in more traditional gridshells. Alternate boards cross in a grid pattern, determined by the local curvature. Generally the spaces between parallel boards are filled with short timber pieces so that a full lattice of intersecting ribs is formed.

4.1. Expodach Pavilion, Hanover World Expo 2000

This method was used for the Expodach Pavilion by Herzog and Natterer at the Hanover World Expo 2000 [8]. Modular roof segments 19m x 19m were assembled from both continuous and discrete elements and constructed directly on formwork in their final double-curved form, with all geometry digitally predetermined. 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 380mm centres, on the principal diagonal, relaxing to 1600mm centres in the more lightly stressed areas adjacent to the ends of the cantilever truss supports [8] [9].

5. PREFABRICATED LATTICE GRIDSHELLS

Difficulties in manipulation of large flexible deployable timber lattice grids, both ‘push-up’ and ‘pull; down’ has led some designers to propose various prefabrication techniques, for instance, lath preforming and assembly from smaller modular sections. These have been used successfully in the following projects.

5.1. Nara Silk Road Exposition, Japan, 1988

Surprisingly the first extensive use of prefabricated lattice timber gridshells, for the Nara Silk Road Exposition, Japan, in 1988, appears to have almost disappeared from the collective memory, perhaps because they survived for only a few years after the exposition. Three gridshells were constructed, each of different form and size: the 1531 m^2 Nara Pavilion, 62.5 m in length and up to 32 m wide; the 2123m^2 Theme Pavilion, 104.5 m long and up to 30 m wide; and the smaller Information Office, 39.5 m long, Like the Mannheim shells, these were doubler-layer grids with 70 mm x 40 mm deep laths, on a 500 mm grid and with single bolted node connections. In contrast to the push-up erection technique used for the, initially flat, Mannheim deployable lattices, the Nara shells - engineered by Takenaka Corporation with structural advice from Gengo Matsui - were assembled from pre-bent timber prefabricated into 4 m wide sections. These were connected together ‘in-the-air’ with steel plates and bolts [10] [11] [12]. Pre-bending of the timber laths practically eliminates the possibility of breakage during assembly – a common problem in the early deployable lattices - whilst the relatively small modular sections assembled to a predefined geometry simplify the erection process for the three-dimensionally curved surfaces.

5.2. Centre Pompidou-Metz

Centre Pompidou-Metz [13] by Shigeru Ban, in 2010 [14], exemplified the extent of digital advancement in form-finding and manufacturing terms. Here initially oversized glue-laminated components were fashioned to the required form using CNC milling equipment.

Having a hexagonal plan with side length 52m, the roof, of approximately 7000m^2 in plan, has a maximum width of 104m; however, the roof structure spans a maximum of around 50m. Although the initial design concept envisaged a reciprocal/lamella grillage system of discontinuous, mutually-supporting elements with simple connections [13], the final solution, reminiscent of the 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 1.57m (derived by subdivision of each roof edge by 33) resulting in a three-way grid having beams spaced at about 2.7m centres. 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 36m, and boundary rings where the main building core punctuates the envelope [13] [15].

5.3. Yeoju Golf Club, Korea

Perhaps less-widely known than the high-profile 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, again of laminated timber members on a 36 x 72m hexagonal-triangular grid, is held aloft by 21 tree-like columns, in three rows of seven. Like a wooden puzzle the geometry has to accommodate three layers of continuous timber elements. The surface generated is composed of around 3500 individual pieces and requires almost 15000 lap joints [15].

5.4. Hermès, Paris, 2010

Similar techniques facilitated the installation of interior timber gridshells for the French fashion house Hermès, in Paris, in 2010. Their Rive Gauche store includes three free-form timber gridshell pavilions or “bulles” designed by Rena Dumas Architecture Interieure (RDAI). At up to 12m in width and varying in height from 8 to 9m, the intricate organic shell forms, engineered by Ingenieurbüro Bollinger + Grohmann, Frankfurt, dominate the sales space. 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. After consideration of several alternative methods, the final construction is of site-assembled, 60 x 40mm, pre-bent laminated battens which were fabricated using CNC cutting, bending and gluing. Sections of each gridshell were preassembled and glued before trial mounting on the installation rig at the workshop. Subsequently the “bulles” were dismantled and re-erected on site [16].

5.5. Waitomo Glow-worm Caves Visitor Centre, Otorohanga, Waikato, New Zealand, 2010

Fig. 6. Waitomo Glow-worm Caves Visitor Centre, gridshell of prebent laminated LVL laths on a 4.25 x. 4.25m grid (Photo: Kirsten Gibb and Jason Hall)

The Waitomo Glow-worm Caves Visitor Centre, in Otorohanga, New Zealand, demonstrates the synergetic use of lightweight cladding, inflated ethylene tetra-flouro-ethylene (ETFE) foil cushions, with lightweight structure, a widely-spaced (approximately 4.25 x 4.25m) lattice timber grid, Fig. 6. Here, laths were prefabricated from laminated veneer lumber (LVL) manufactured from Radiata pine and connected at the nodes using a single 20mm diameter bolt. Twenty-eight to 34 metre long double ribs, 324 mm deep overall with top and bottom layers connected by intermediate glue laminated block spacers, were fabricated in three sections joined on site with mechanical splices. Each 160 x 108mm lath was composed of three layers of 160 x 36mm (ex 170 x 39mm LVL) glulaminated to predetermined curve and twist to suit the toroidal geometry of the gridshell [17].

6. CURRENT PROJECTS AND FUTURE DEVELOPMENTS

The recent developments of computerised software have considerably influenced the current design approach towards grid shell structures. They can be effectively used in combination with physical models to improve the overall design process achieving architectural, structural and manufacturing results barely achievable through the only use of physical models. The key advantages of digital models are the higher level of accuracy and their relatively cheap costs in terms of materials and time required. They can be divided in two main categories: design tools based on geometrical properties, such as the equal distance between the mesh nodes in a quadrangle grid [18], and the design tools based on Finite Element Analyses which consider the material’s mechanical properties, the types of joints and the imposed loads and displacements. Their use is generally combined in an iterative design process alternating geometrical and structural software packages process in order to gradually improve the initial geometry. The recent trends in this fields aim to the progressive integration of geometrical and structural aspects into a unique designing tool able to offer an interactive design environment and in real-time feedbacks in terms of curvature, stress, strain, reaction forces and displacement.

6.1. The Toledo Gridshell, Faculty of Architecture, Università degli Studi di Napoli Federico II, Naples

The Toledo Gridshell designed, manufactured and assembled by a team coordinated by Sergio Pone [19] represents a good example of the contemporary approach to the design of timber gridshells. The structure has been designed for the courtyard of the Faculty of Architecture, Università degli Studi di Napoli Federico II in Naples. It is the last example of a set of gridshell structures designed and realised by the same team in the last five years and the arrival point of a design approach started with simple physical models and now supported by a refined digital tool compatible with the main 3D architectural and structural software.

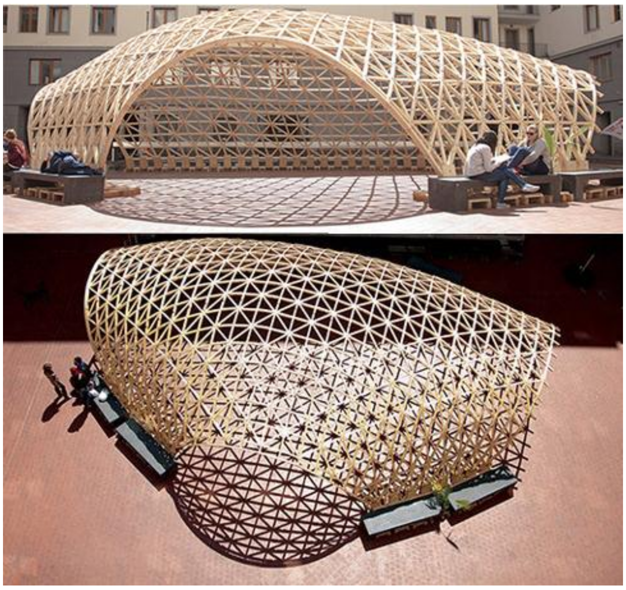

Fig.7. The Toledo Gridshell, Faculty of Architecture, Università degli Studi di Napoli Federico II, Naples (Photo: Gianluca Jodice)[19].

The 3-D modeling tool has been developed in order to integrate and, if necessary, replace the traditional form finding process originally based on physical models able to reproduce specific structural properties or assembling procedures. The first benefit of a digital approach is to avoid the survey of the physical models, sometimes realised by means of expensive and time consuming 3D scanners, which is generally necessary to obtain the 3D geometry required by the FEM structural software. In addition, due to relative lightness of timber gridshells compared with concrete or masonry shell structures, the vertical load (at the base of the inverted hanging models) is not necessary the main driver in the form finding process which has to consider the incidence of asymmetrical loads. Thus, it could be strategic to set the form finding process in order to meet other requirements such as the maximum curvature of the slender elements or the 3D configuration which allows the use of initial flat timber grids.

The design tool [20] is based on the well know Rhinoceros 3-D modeling software, developed by Robert McNeel & Associates, which can be integrated with several plugins such as Grasshopper™ (graphical algorithm editor), Kangaroo (a live physics engine for interactive simulation, optimization and form-finding directly within Grasshopper™), Galapagos (a generic platform for the application of Evolutionary Algorithms) and Karamba (an interactive structural analysis program). The plugins can be combined in a design tool which provides a real-time feedback about the behaviour of the design solution allowing an iterative improvement of the initial geometry.

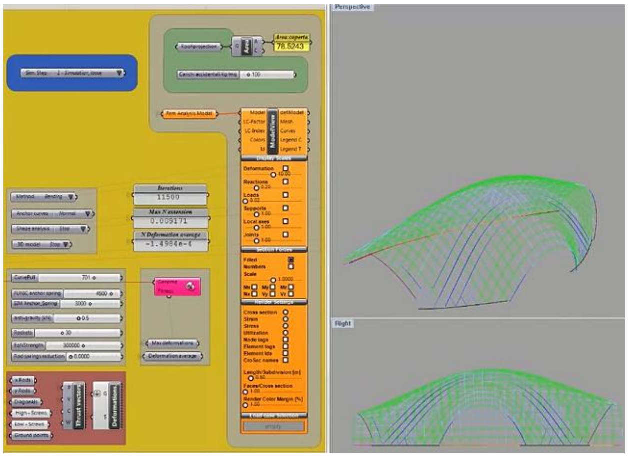

Fig. 8. The design tool implemented in Rhinoceros (Photo: Daniele Lancia).

Once the geometry satisfies the initial geometrical and structural requirements, the structural behavior is analysed through commercial FEA software, in this specific case ABAQUS FEA, which considers the geometrical non-linearity, the complex material response and the large deformations occurring during the analysis. The results obtained through the structural analysis provided the data for the final validation of the structure but offered also useful information about the forces required to obtain a specific configuration (used to choose the assembling equipment) and the expected stress state and curvature of the components during the assembling phase (to avoid any damage due to an incorrect erection procedure).

Finally, the manufacturing of the components was based on the geometrical data obtained from the digital models. More refined tools based on Grasshopper™ can further improve the fabrication process in order to meets the requirements of an industrial manufacturing of the components.

7. CONCLUSIONS

In summary, this paper aims to present and discuss the progress of timber gridshells over the last 50 years, using case studies to discuss the situation of the present processes and also speculate on the progress of technologies, especially the impact of computers on the future application of such form-active structures in the architecture vocabulary. As technology progresses into an increasingly digital age, the computer has a bigger role to play in the development of grid shell structures. It has seen changes in the last 50 years, how the construction method and material thinking in the design of gridshells has evolved.

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