WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

TECTONIC DESIGN OF ELASTIC TIMBER GRIDSHELLS

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ABSTRACT: This paper aims to 'bridge the gap' between engineers and architects for a better understanding of the design process of elastic timber gridshells. The purpose is to inspire architects to develop innovative timber structural forms informed by engineering knowledge.
This paper is organised in two parts: the first part is a theoretical reflection on the concept of tectonic and on the combined application of architectural and structural knowledge; the second part is dedicated to the review and definition of the various decisions and consequences during the design and construction of elastic timber gridshells.

KEYWORDS: Timber design, Timber gridshell, Mesh design, structural approach, structural mesh.

1 INTRODUCTION

Timber gridshells are a special type of structures that combines structural efficiency with an attractive appearance. As they are highly technical systems with low-cost means, they have a very limited impact on natural resources [1]. However, the main feature is its shape. The formal freedom that it allows and its structural behaviour make the gridshells a very desirable structure in the eyes of any designer. These structures are able to cover large spans and ensure a high spatial flexibility. As such these timber structures are in vogue and its advantages for quality spatial design and the new creation potential for designers have great advantages [2].
Furthermore, timber gridshells are versatile and can be found in rehabilitated buildings as well in new buildings, roofs, as small additions in non-structural elements and even in partitions as merely an architectural object.
The origin of gridshells goes back to the 19th century (1896) and they were created by Vladimir Shukhov, a Russian engineer. However, he only addressed steel structures and not timber structures. In 1975, the first large scale timber gridshell was finished, the Multihalle, in Mannheim, designed by Frei Otto [3].
Nowadays, the construction of elastic, or post-formed timber gridshells [4] remains an issue to be taken into consideration. With this structural system, architects and engineers have moved towards a common goal the symbiosis between space and structure, the balance between aesthetics, function and proper optimization of materials. Nevertheless, due to the complexity of the design and the idealization of its construction, designers are not very keen to use it as a possible solution [5]. The main reasons for this positioning from their part may be due to the lack of information and tools that could help define this complex system, as well as some guidelines or directives [6].
Until now, gridshells have been designed on a case by case basis and have not been studied as a specific structure type that can be used in many ways and in several different situations. The starting point of a project is the architect's sketch, purely as an architectural and aesthetic ideas where the overall geometry is defined without structural considerations.
Traditionally, the structural information is only applied at the end of the design process to refine details of the conceptual sketch drawn by the architect. However, it is felt that the structural approach should be included right from the beginning [7]. There is a need to evaluate the structural performance of elastic timber gridshells during the schematic design. This could provide design rules which would facilitate discussion among designers from different areas in order to improve the tectonic characteristics of the projects.
This paper aims to understand what engineering has to offer to architecture as a methodology and support the design of the timber gridshells. Thus, the main question considered in this paper is how engineering and architectural knowledge can optimize and improve the design procedure. The methodology applied is based on a tectonic approach [8] to the design of the gridshells. It is intended that this results in a docket of notions about the design of timber gridshells, to solve problems found during the design process that can help to create structures with high spatial and structural quality. It is not the purpose to try and qualify what should or should not be

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done, what works or what does not work. Such conclusions can be applied to others areas of science, but not in architecture. Architecture is a human science which varies according to who experience it. It is also not intended to create rules or restrictions, since this is a system with yet a lot to explore.
To achieve the proposed ideas, the form-finding method will be explained and the elastic timber gridshells will be divided in three approach concepts. Also, the erection methods of timber gridshell will be analysed. Afterwards, the consequences of these decisions will be identified and proposals to address gaps in this area will be presented. With this knowledge, it is possible to minimise the use of applied forces. With fewer forces being applied to the lattice, the risk of breakages on this kind of projects will be lower than on previous gridshell projects [9].
This work is carried out from the point of view of an architect, accompanied and aided by civil engineers. It is supposed to be an integrated research as it is crucial to find new methods to design these structures, in a faster, practical and more efficient way.

2 ENGINEERING INFORMING ARCHITECTURE

Tectonics is a seminal concept that defines the nature of the relationship between architecture and its structural and material properties. The changing definition of the symbiotic relationship between structural engineering and architectural design can be considered as one of the formative influences on the conceptual evolution of tectonics in different historical periods [10].
Both of these areas have traditionally been characterized by the development of a sequential reasoning of shape, structure and material [11]. The sequence begins firstly with the formation of the concept by the architect which is then transmitted to engineers who develop the project structurally and materially wise, in collaboration with the first [7]. Collaborative relations developed between architects and engineers contributed to the production of some of the most iconic buildings. Although the process of structural engineering already has been developed, there is still a possibility to increase the structural knowledge and create the technical possibilities, which will result in a tendency to design structures more efficiently [12].
The importance of working as a team is not something new. As Mies Van der Rohe once said, when a type of building gained importance, in the historical period it is inserted, its structure has always been the vehicle of their spatial form, as shown in the Romanesque and Gothic styles. The renewal of architecture has to focus on the structure and not on the ornaments that are placed on it. The building and its rationale are together and the structure is the form and space [13]. Further, as Corbusier said, architecture should be the expression of the materials and methods of our times, as engineers provide the tools of their time and their technical knowledge [14]. The materiality defines the experiences and gives shape to the intentions in architecture.[15] As such, the developments in civil and structural engineering profoundly affected architecture. The use of new structural materials and new structural systems determined the tectonic qualities of modern architecture. A building should be understood as a set of systems that work as one. The group of professionals responsible for these systems are always a multidisciplinary team that must fill the gap between the analytical knowledge of the structures and the wisdom of architecture [8]. One of the fields in which this efficiency between the professionals is sought, is in the relation between the form and the structural properties of the systems. This could lead towards an increasing interest in lightweight structures. Within these type of structural systems, gridshells are a variant that can be chosen for free-form and architecturally expressive design.
Still in most cases, structural considerations only come at the end to refine the details of the previously selected shape, when it is imperative to include the structural approach from the beginning. There is a need to evaluate the structural performance of timber gridshells during the schematic design, in order to provide some design strategies to ease the discussion between the designers in different areas as to improve the tectonic characteristics of the projects [7].
It is important to realise that there are already such shortcuts/notions in architecture. Architectural design as a creative artistic act, sometimes requires defiance of the established or accepted principles in order to achieve the desired result. These elements and principles are guidelines which, when used properly, may provide a satisfying result but, they are neither flawless nor complete. At the centre of this process, there is a conflict between form and function. In the timber gridshells this distinction does not exist, the structure designs the space. So, here the skill of the architect is found in the manner by which they apply aspects of design combined with artistic sensibility, his vision and the physical characteristics of the building and the environment. This is supposed to clarify and explain some of the guidelines that can be applied as an appropriated and useful design tool for elastic timber gridshells. The most important purposes of this design tool are to define the geometry, how it can actually be built and to predict the forces that will be present in the gridshell. As far as timber gridshells are concerned, and unlike most other structures, the construction phase is the most critical stage of its life. Since the shape is closely linked to the forces that are present in timber and the support reactions, these aspects must always be known when the final geometry is achieved. Thus, the chosen structural typology will certainly have an impact in the architectural image. All the design decisions focuses on the possible choices. When the material is chosen, it has particular characteristics, there is a budget, its own laws, which limit options. As such these design approaches will help to clarify the options available when it comes to making the decision about which timber gridshell to choose. The designers must look at this as a good shortcut, as something that does not rules out creative options. Quite the contrary, it gives them time to go ahead and take on new issues.

3 DESIGN APPROACH TO THE ELASTIC TIMBER GRIDSHELLS

The following section outlines what has been done in the development of the design and erection processes of the timber gridshells. The order in which the different phases of these processes will be presented are not necessarily in a chronological order. This paper is concerned with elastic gridshells only, not just in its construction phase but also in the preparation of this moment. It is extremely important to understand which aspects are taken into account before the construction to identify from the start the existing information gaps in the process. The economic advantages that arise from using elastic timber gridshells (low material quantities, cost effective transportation, large spans and low-tech assembly of linear elements) are undermined by the cost and complexity of the labour which is necessary for their erection [5].

Although there is a shortage of works in this area, the theoretical field has developed some research material around this structures. Since the last century the evolution of elastic gridshells has significantly progressed in the fields of computational form-finding and structural analysis, generally, fuelled by academic curiosity and a few number of innovators (Frei Otto, Shigeru Ban). These are people that believe that this kind of structure offers a way to facilitate the construction of large scale, low-cost elastic timber gridshell buildings in the modern built environment such as have not been seen since the likes of the Multihalle Mannheim [16].

Academically and in the field of practice, recognition should be given to some researchers who have highlighted the important of developing the design process and construction of elastic timber gridshells. Chris Williams, Richard Harris, Alberto Pugnale and Frank Jensen, are some of the most prominent researchers in the field. In the field of erection methods, but not exactly on the timber area, it is important to mention Quinn and Gengnagel who describe the main categories for consolidated construction techniques: the “pull-up” / “push-up”, the “ease down” and a further category based on inflatable membrane technology is outlined but not consistently illustrated [16].

3.1 FORM FINDING

From the literature, it is possible to create a compendium with a logical approach path to timber gridshells, since the shape approach until the phase of analyses of the behaviour of the built buildings, starting with the previous process of form finding, term frequently used to describe the method of defining the shape of a structure [17]. This process is often influenced by factors such as the type of structure, properties of the material, boundary conditions and construction requirements, in this case timber gridshells. It also has a great potential in the optimization of the geometric, material and in reduction of the structural section.

According to the work of Richard Harris and Chris Williams [17] it is easy to summarise the following approaches to the geometric design of gridshells: *Funicular methodology*, where the 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. This has been applied by Gaudi in the *Colonia Guell* and its historical roots can be traced back to Robert Hooke’s [18] catenary experiments. This process gives the designers information about node coordinates. A different way to define a gridshell structure is *analytically*, by explicitly specifying a surface and then describing a grid of nodes and lines on that surface. There are different geometric methods that could be applied to describe a grid on a surface. For practical and economic reasons this tool has been more frequently applied. The software is constantly improved due to the amount and accuracy of information that engineers are able to introduce in these reality simulation tools. A third option is a mixture between the two methodologies and it was applied in the Weald and Downland gridshell [19]. This project confirms that there is still reason to debate the use of physical models in contemporary design as a complementary tool. Lastly, contrasting with the above-mentioned gridshells, the approach where the form-finding is based on the proposed construction process. This implies starting with a flat grid and pushing the support nodes towards a desired support configuration, while also pushing the grid upwards. It is possible to simulate the proposed construction by modelling the forces applied to a grid made of springs [20].

Architects should dominate the drawing tools, scale and proportions, the full and empty volumetries and the atmosphere that they idealize, even because it is possible to understand that all the approaches presented need another (engineer) support knowledge. It is still necessary to know the properties of the material, know the buckling required to transfer forces, recognise the elements that will be more required in the structure and mediate the mismatches between the model and reality.

3.2 CONCEPTUAL APPROACH

Another way to help architects to realize what is possible or to define the options, in the mentioned design process, is to understand which key elements that could define different assemblies of timber gridshells. It is necessary to understand the structural capabilities of timber gridshells such as: the proportionality between span and height; the balanced distribution of forces in the edges and supports; the ratio and buckling necessary to unload the weight and other forces; the metric of the grid and finally the geometry. Should the elastic timber gridshells always work like a dome? What potential can be exploited? Does the design process depends on the size or the complexity of the shape? To understand the questions raised, three concepts will be analysed with the purpose of representing the general and the particular cases. The division by different approaches was made based on the gridshells geometry shape, the structural behaviour [8] and the differences in the design and construction process. It should be noted that it is a segmentation of an already particular system. These three varieties are in side of the elastic timber gridshells, which in turn are in the group of timber gridshells and these in the shells structures.

3.2.1 SET KIND

The approach concepts, as already mentioned, divides the elastic timber gridshells into three groups, two within the mesh considered regular, those that work in compression and the ones that work in tension, and one representing the irregular shells, as can be seen in Figure 1.

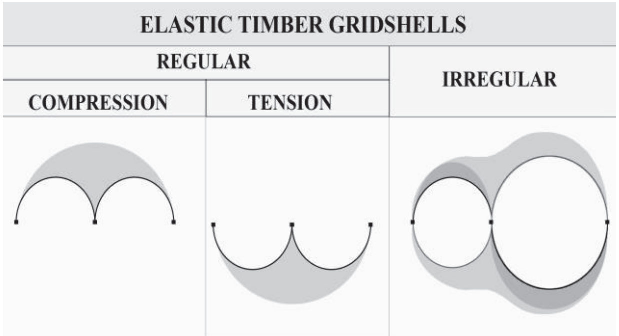

Figure 1-*Clusters Concept*

This division is complementary because it can distinguish the shell from its structural behaviour and its geometric complexity. Here the respective contribution of architects and engineers becomes clearer. The architects have some ease in handling the shape as if it was a piece of handicraft, even if it is a case of simple geometry or something more amorphous. The engineer, on the other hand almost intuitively understands the path of the forces and the areas most required in the structure. The choice of the structural concept is not just a formal decision framed in the environment in which it operates, it is also the result of an informed discussion, pro-active between the idea and its materialisation. The parts have to work as one. For it is not enough to limit the space or choose the material, the structure has to be the backbone of the architectural idea.

The *Regular in Compression* (Figure 2) represents all timber gridshells with: at least one axis of symmetry in a section and a plan; one or more lines of SF (symmetrical forces applied on opposite sides in order to apply force homogeneously); work only in compression and with a uniform discharge of forces. This kind of elastic timber gridshell takes the shape of a single shell and can represent the majority of the gridshells. It can be said that it is the simplest of them all.
That is probably why it is possible to find more examples of its application.

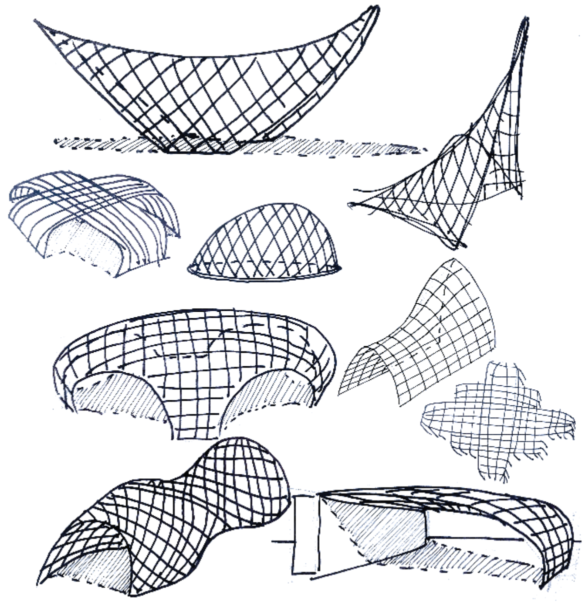

Figure 2- *Regular in Compression examples*

One of these cases is the Downland Gridshell (Figure 3). This is a well-documented and described project, a very complete constructive guide. Despite being in this category this building has a complex geometric composition and it is easy to understand the volume and read the structure.

Figure 3- *Downland Gridshell* [21]

A recent example, ZA Pavilion depicted in Figure 4, was presented as a temporary cultural venue and was designed during a student workshop in Cluj, Romania. It is a simple solution with a great result. The ZA Pavilion 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. A simple square grid is easy to imagine, but connecting multiple "trunks" with an intricate topology of beams criss-crossed between them requires some serious thinking[20].

Figure 4-*ZA Pavilion* [20]

The second, *Regular in Tension* (Figure 5) shows; also at least one axis of symmetry in a section and in a plan; a support or several supports grabbing the mesh in order to create a homogeneous structural behaviour; working only

in tension. It is obtainable from the vertical mirror of a regular mesh and can be suspended or hung. This typology presents a facet of timber gridshells that despite not yet having been explored in a real context, is presented as an optimum system to be applied in various situations. It is a lightweight system with a reduced section and with a great structural and geometric flexibility that would certainly be an ideal solution for new constructions and for intervention on built heritage.
As mentioned, there are no records of construction of this kind of shell.

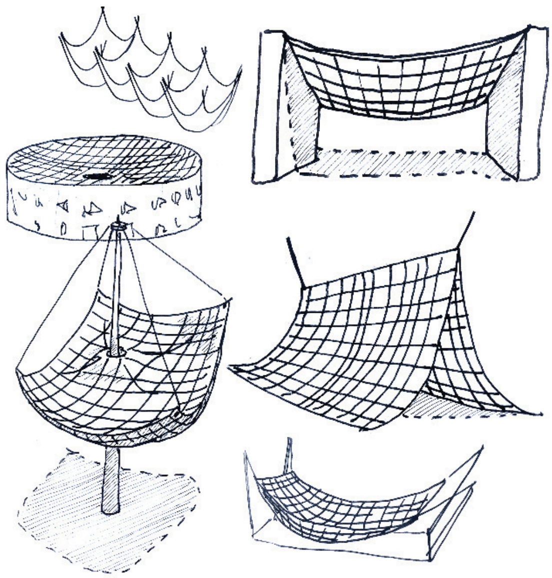

Figure 5- *Regular in Tension*

However, Heinz Isler, the Swiss artist-designer-engineer known for his concepts and methods for free form shell structures, directed his efforts away from the mathematics of engineering and focused on the physical model, as can be seen in Figure 6. This study into physical modelling placed emphasis on form and stability. The goal was to create structures of high efficiency with the lowest possible environmental impact. As has been argued in this paper Heinz Isler also believes that architecture and engineering are just two aspects of one thing [22]. Isler left a lot of work done in this area due to models which were used to find the most suitable form for shells.

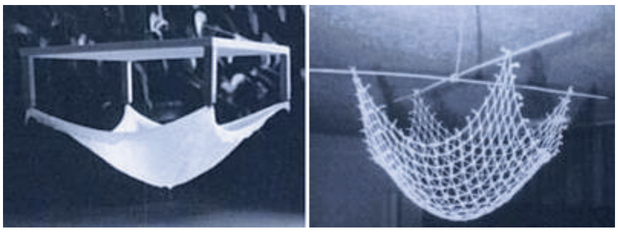

Figure 6- *Heinz Isler hanging Models*[7]

Also Gaudi cannot go unmentioned in this area of tensioned models, He was the major driver of this methodology. In Figure 7, one can see the inverted model in tension of the *Sagrada Familia*.

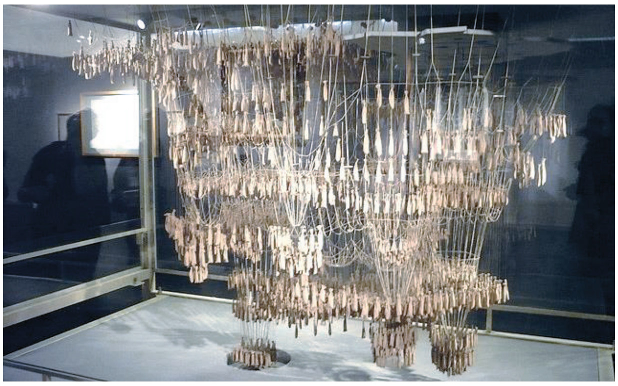

Figure 7- *Sagrada familia Model, from Gaudi*[8]

Finally, the *Irregular group* (Figure 8): more complex, it is a structure with a very difficult geometry; it can work in tension, compression or both; in general it is not built from a homogeneous application of forces (SF); often presents no axis of symmetry; the geometry presents a more complex and amorphous aspect than the first two groups. Here it is possible to identify the most famous example of a timber gridshell, the Pavilion of Manheim Multihalle (Figure 9).

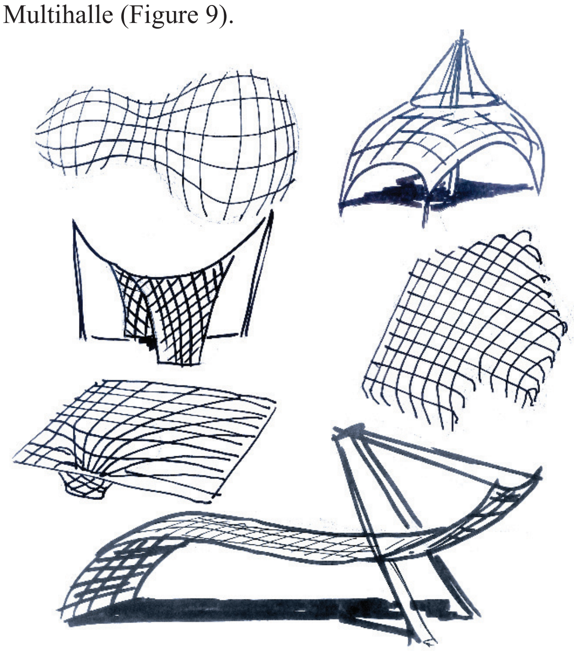

Figure 8- *Irregular*

This work of Frei Otto is today an icon of timber gridshell. It has a strong and easily recognizable image as shown by Figure 9. The geometry of the structure was determined by physical form finding and it was constructed by pushing up the flat mat of laths by aid of scaffolding towers and fork lifts. Its idealization and construction were difficult [23] but it was not only because it was the first. Its complexity and its scale brought great challenges to all project interveners, made possible only by the cooperation of all areas. However, as is visible even today, timber gridshells with a more complex and irregular structure have a good performance and excellent results as regards the creation of striking atmospheres.

[7] http://blog.buildllc.com/2009/04/heinz-isler-a-few-important-things/

[8] http://dataphys.org/list/gaudis-hanging-chain-models/

Figure 9- *Manheim Multihalle* [24]

A more recent and geometrically simple example can be observed in the Figure 10, the Sutd Library Pavilion, built in 2013 in Singapore. The idea was a part of a competition where its potential was realized and the project completed. A low-cost gridshell made from 3000 unique plywood panels creates a vaulted form with no internal walls or columns and is clad in 600 hexagonal steel tiles. This emphasizes the ephemeral aspect of such solutions, an important feature in a period in which it requires flexibility and elasticity in the space created by architects [25].

Figure 10- *Sutd Library Pavilion* [9]

With these three groups, it is intended to explain the different approach concepts. Each one will aim to demonstrate different levels of structural and formal complexity and outlining results regarding structural behaviour, dimensions, and joints.

3.3 ERECTION PROCESS

Timber gridshell construction shows limits already at small scale. When the scale is larger, a lack of a standardised, cost-effective erection method implies that techniques have to be reinvented every time and gridshells become affordable only for exceptional projects, such as the Downland Museum or the Multihalle in Mannheim [24] leaving the costs and time to vary depending on the context.

As mentioned before, it is fair to say that the erection phase is usually a major, if not dominant, load case for an elastic timber gridshell due to high bending stresses induced by tight curvatures and point loads in the laths. This effect depend on the method of erection as well as on the shape and size of the shell. The main reasons for minimizing bending-induced stresses are to prevent ruptures of the beams during erection and to ensure that sufficient stress reserves are available in the beams under external load cases. While every major gridshell project has experienced breakages during erection, the number of ruptures has progressively reduced. During the erection of the project Essen, due to inherent stresses, several grid rods directly next to the joints were broken [26]. At Manheim quite a number of finger links broke on site during the erection process [23]. In the Downland gridshell with 10000 connexions in the structure, there were around 145 ruptures during construction. Practically all were failures of the finger joints [21]. Finally, in the Savill Garden gridshell [27], which had extremely low curvatures and a fully scaffolding-supported erection there was only a couple of failures during the construction process. While this progressive reduction of ruptures is very positive, it comes at the cost of increasingly slow and costly erection [16].

Despite this, Quinn and Gengnagel, in their "*review of elastic grid shells, their erection methods and the potential use of pneumatic formwork*", the authors acknowledge five main viable means of elastic gridshell erection which can be used combined, if necessary: "pull up", "push up", "ease down", "inflate" and "by constrain".

3.3.1 PULL UP

The first known example of a timber elastic gridshell is the experimental prototype built in Essen, in 1962, by Frei Otto. This 15m grid shell was erected by means of a single mobile crane but also by wooden stilts used to support the perimeter. This erection method, in Figure 11, has the benefit of speed. However there are several disadvantages. Cables, even when branched off into clusters of fixing points, introduce large point loads and subsequent stress concentrations into the structure. While clusters of wires will better distribute the applied vertical loads (out-of-plane), they introduce compressive membrane forces (in-plane) which will increase buckling risk for the laths. Furthermore, the crane erection method can only apply force in the vertical direction and is not restrained in the horizontal direction. The lack of horizontal restraint from the cables is beneficial due to the necessary grid distortion during erection. However global horizontal restraint of the gridshell itself or at least its edge must be provided by separate means. Typically crane erection requires very calm weather and is only practical for small shells [16].

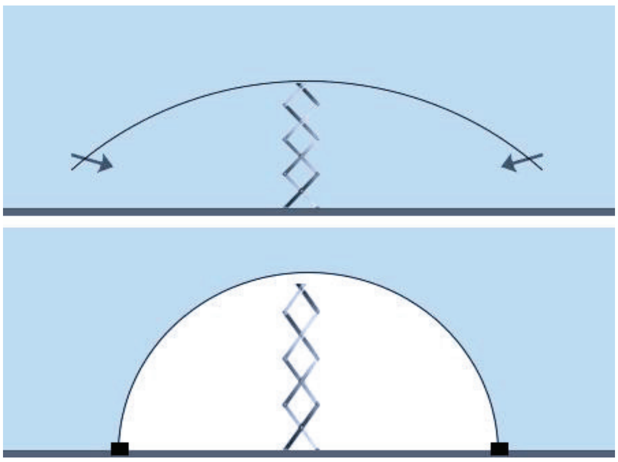

Figure 11-*Erection process scheme*

[9] http://www.jebiga.com/sutd-library-pavilion-city-form-lab/

3.3.2 PUSH UP

Originally, the Multihalle Mannheim was planned to be erected using four 200t cranes but finally a system of jacking towers was devised by the contractors and engineers in order to cut costs. 3.5m by 2.5m H-shaped spreader beams were connected via ball joints to the 1m square scaffolding towers which were up to 17m tall. These towers were jacked up vertically using fork lift trucks which were able to accommodate the necessary lateral translations of the lifting points. A key feature of the erection process (Figure 12) was that "the lattice was anchored with cables, at certain key points, to prevent collapse". The spacing between the towers was 9m and the laths deflected by 200mm under bending from self-weight. This deflection had to be gradually reduced to around 50mm by progressive stiffening of "strips" along the grid shell followed by the height adjustment of grid zones [16].

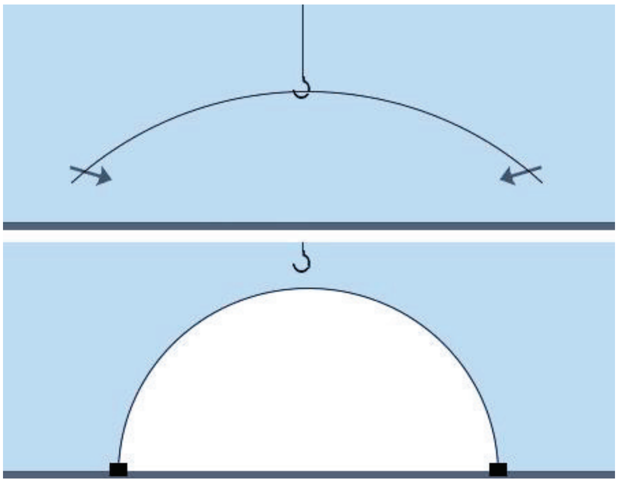

Figure 12-*Erection process scheme*

3.3.3 EASE DOWN

The three most recent timber elastic gridshells built by Buro Happold (Japan Pavilion, Weald and Downland Centre, Savill Garden), were erected by means of scaffolding support underneath the entire grid shell area coupled with incremental and controlled displacement of the laths. The unique aspects of this method, seen in Figure 13, are the high layout level for the flat grid, from which gravity is harnessed and the laths that are gradually displaced downwards (allowing also for lateral movements). Scaled physical models played a crucial role in planning, predicting and checking of the erection process. Detailed labelling and measuring of the structures during deformation was carried out to monitor and control the process. Additional straps and ratchets were required to initiate further "scissoring" in order to successfully form the crowns and valleys of the Weald and Downland Centre [16].

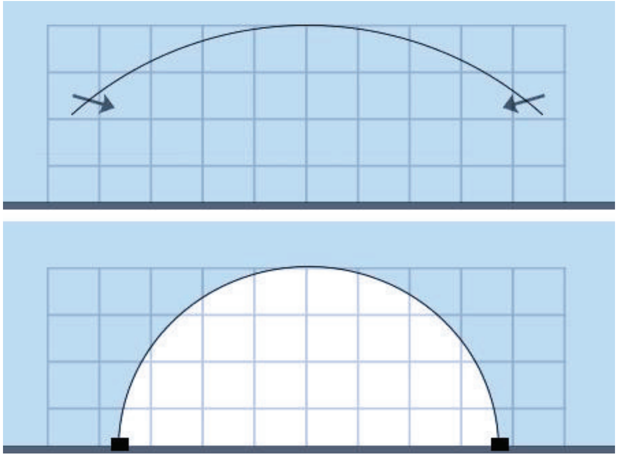

Figure 13-*Erection process scheme*

3.3.4 PNEUMATIC FORMWORK

This method has not yet been applied to Timber gridshells. Therefore, it is only possible to conjecture some conclusions from its application to other systems/materials and from the empiric knowledge notions. It is possible to understand that the flatter zones of a pneumatic cushion are better able to resist vertical external loading with low static pressures than "steep" surfaces and small horizontal contact areas. And yet, small curvatures while beneficial for erection are undesirable for the final shell geometry due to the resultant low shell stiffness. Therefore, the shape of the pneumatic formwork and the final grid shell must be developed in unison. The most critical challenges for the erection of elastic gridshells, by means of pneumatic formwork are concerned with the following major issues: stability and restraint of the grid shell mechanism during erection and ensuring that the target surface geometry is achieved despite sagging of the cushion. It is proposed that regardless the cushion type, the gridshell should be raised to a height higher than its final destination such that the beam ends can be lowered to their supports via deflation in a controlled manner [16].

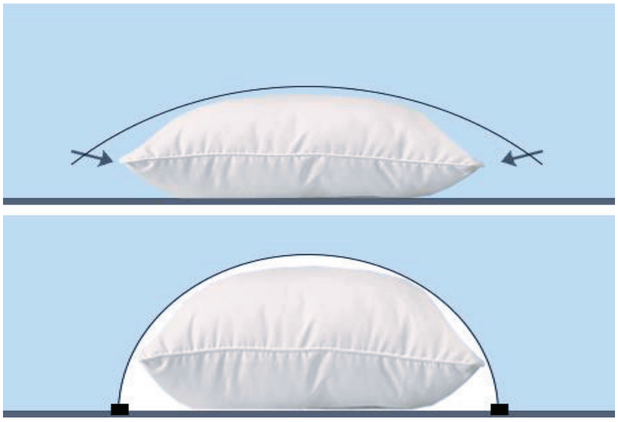

Figure 14-*Erection process scheme*

3.3.5 BY RECESSING / CONSTRAINING

About this method, for the moment, there are no built records. It is presented as another theoretical possibility to explore. Starting from the constraining of the two sides of the gridshell, if it is a regular grid with two lines of SF, can be easy applied the shape deforms to start modelling.

This method has the advantage that it is only necessary to apply forces on two sides. However, it also implies a great dependence of the place where it can be built, as it always need to be fixed in two directions. It will also require greater care with regard to the fixed points and the points where the force will be applied so that the energy reaches the wooden elements in a homogeneous way without load peaks in individual elements. This method wins by speed and because it can be applied in media with low resources so as to be low-tech.

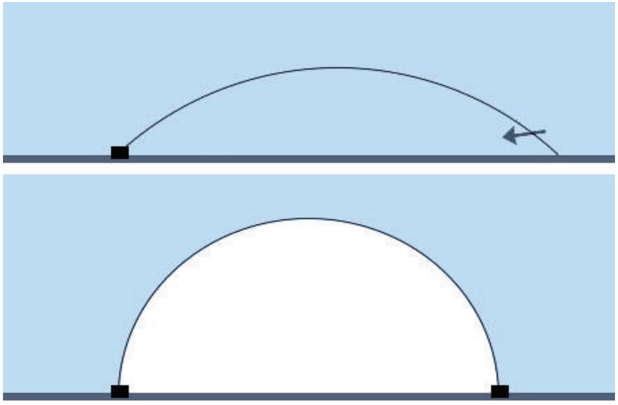

Figure 15-*Erection process scheme*

3.3.6 CONSTRUCTIVE DETAIL

It must be clear that all the engineering decisions made during the design process have a result in the architectural image, from the form-finding to the approach concept and the erection process. To use in full the tectonic properties of this structural system the architect has to add to his list of tools the engineering support. The architect should try to facilitate the construction and engineers should make clear the physical and material limits for each method.

Starting with the material (timber adaptation and its formal flexibility know no limits), adaptation to the environment, and the huge variety of textures, shapes and colours. It has to be understood as a material with different physical properties depending on the species and the application. The species of timber and it section are 'small' choices with major repercussions in all other decisions as well as in the final image. It is necessary to know the characterization of its properties, its ability to flex, bend, buckling, ductility and its elastic capacity to return to the original form (Figure 16).

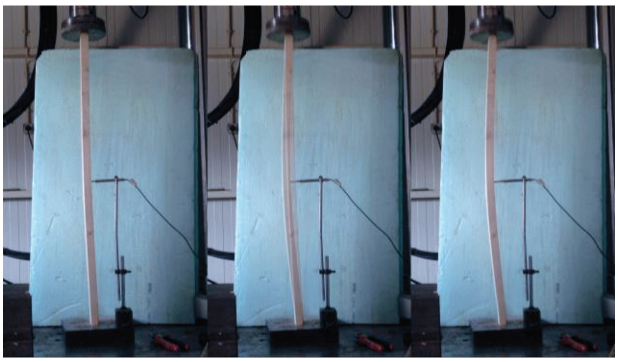

Figure 16-*Timber characterization (1m x 6mmx2.5mm)*

The decision about node detail and the end-to-end connection will have some consequences as well. At the outset, it has to be taken into account how the gridshell will be raised, as it will influence the locking structure and what will be the skin of the building. The choice of linker can facilitate the construction or it can hamper it. For example, in the process of erection 'by constraining', the use of grooves should be considered which will allow some slippage between the elements or the use of plates. Otherwise, the application of force commandeered on some elements may be excessive and generate some rupture.

Using the example of the ZA Pavilion, the choice of the structure of the lock, had a direct impact on the bonds and the architectural image gridshell. It is not intended to judge the architectural or structural quality of the building, just a pragmatic analysis. A system with two layers with screwed connection and a slot allowing the slip has been used, as can be seen in Figure 17. The locking is done with timber elements placed at the end of each diagonal raster, preventing the displacement. This replication of the lines created a visual duplication of the grid and consequently it became more closed. This decision had consequences in the metric reading of the building, the interior relationship with the outside, the light input and the construction process. On the other hand, it allows to always keep using the same material to avoid mixing other materials with a different visual impact.

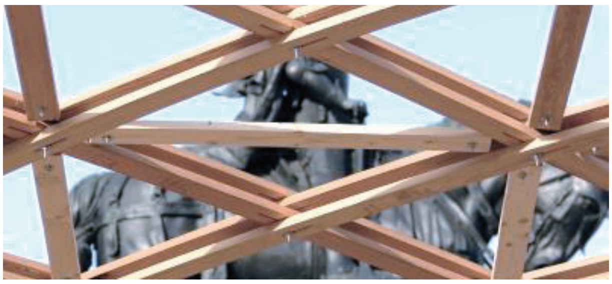

Figure 17- *Locking detail of the ZA Pavilion* [10]

It is possible to see that there are many options with regard to this decision as it is possible to check in Figure 18.It can be seen in the work of Quinn and Gengnagel [16] that a variety of solutions can be used in real cases. There is no rule, but there are solutions that are more appropriated than others and also in these details it is expected engineering to inform architecture.

As a result, the architectural design is the consequence of solutions carried out through this design process to solve the individual issues while at the same time resolving the global issue of the building. It is an intense and complex mix that involves all sections of this analysis using the design concepts defined herein and the presented methodologies to fulfil the purpose of the tectonic design. The apparent success of good design will be evident in the continued facility and freedom found by this combination of knowledge.

[10] http://www.grasshopper3d.com/photo/za-pavilion-2013?context=user

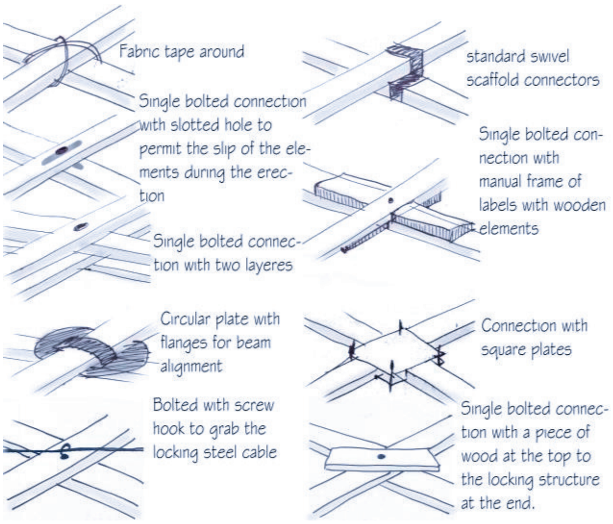

Figure 18- *Timber gridshells node details*

4 CONCLUSIONS

The goal of this paper has been to outline what engineering has to offer to architecture as a design methodology, as well as to know how the engineering and architectural knowledge can optimize and improve the design procedure of elastic timber gridshells. Thus, in this work, the concept of tectonic and the advantages of combining the architectural and engineering knowledge were discussed. Moreover, it has been presented a review of the form-finding process, the structural approach concepts and the erection methods. Also comments were addressed with benefits and caveats of the consequences of all the decisions made during the entire project. Finally, some results will be presented in a docket of notions about the design of elastic timber gridshells.

Since the lack of design notions was previously identified, now it is necessary to make clear that engineering has to offer an integrated approach. A methodology that should not be complicated but rather complex, as it is possible to see in Figure 19. Neither the architect nor the engineer can do this alone, it takes both to create delicated and informed gridshells.

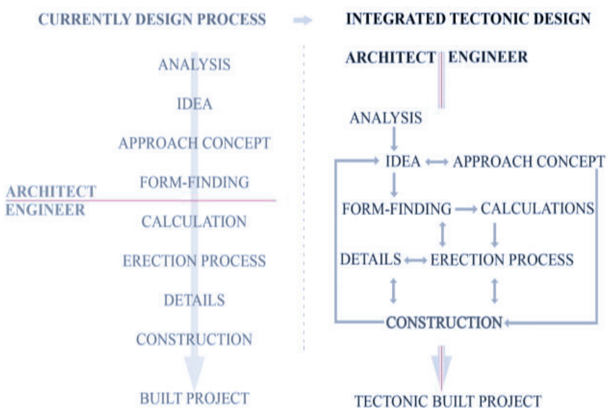

Figure 19- *Design Process for elastic timber gridshells*

The more skilful and informed the architect is the bolder and innovative may the result be and engineers should be pro-active in all phases of the project. This way engineering and architectural knowledge can optimize and improve the design procedure featuring the structural system and determining guidelines, giving some ideas and comments that can be stated for the elastic timber gridshells:

FORM FINDING:

- The shell shape should be defined geometrically or digitally for the purpose of making their construction possible;
- The architect has at her/his disposal tools that allow her/his to control the volumes even if they are irregular and amorphous;
- The architect must be able to master the mesh geometry as well as to be able to explain it to engineers;
- If the first design approach is the work of the architect the structural approach should be introduced at the same time by the hand of engineers;
- If the best optimal form is used the thickness of the structure can have a substantial reduction;

APPROACH CONCEPT:

- The span must be proportional to the height;
- A gridshell can work in tension or compression or both depending on the approach concept;
- Curvature and height of the timber gridshell should be sufficient to work as a compression or tension structure;
- Horizontal forces at the edges and supports should be balanced
- Buckling of the surface should be avoided
- The fact that there are no beams and pillars give it always unique tectonic characteristics;
- Each work must be understood as a single case but the Approach Concept should be perceived as a tool applicable to various circumstances.

ERECTION PROCESS:

- The surface should be bendable;
- Must be avoided the application of localized forces;
- Besides the obligatory projects, an erection project should always be prepared;
- Costs and work time will always be directly related to the adequacy of several decisions in relation to the context and available means;
- The irregular mesh can be mounted with more than one erection process combined;

CONSTRUCTIVE DETAIL:

- Can be thin or thick. This will have an impact on the resistance of the mesh but also in its ability to flex and on its weight;
- The erection should be based in view of the timber adapting properties;
- Joins and the locking elements should allow rotation of members before fixing.
- The links should be chosen taking into account the erection process, the behaviour after that and the Architectural image;

- Architect must be skilful in handling all the phases of this process;

Further step will be deepen and evaluate these notions in a construction of a one scale case, a regular model in compression with 7mx7m. This will happen in the context of a workshop where these ideas will be presented and discussed among architects and engineers.

ACKNOWLEDGEMENT

This work is financed by FEDER funds through the Competitively Factors Operational Programme - COMPETE and by national funds through FCT – Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633.
The support of the Foundation for Science and Technology (FCT) through doctoral fellowship SFRH/BD/104677/2014 is grateful.
The support of the Aarhus University through the financial support for participation in this conference.

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