

Elastic Timber Gridshells - Structures with an Integrated Design

Mallas elásticas de madera - Estructuras con un diseño integrado

J.G. Fernandes (*), J.M. Branco (**), J. P. Barroso (***), P.H. Kirkegaard (****)

ABSTRACT

A timber gridshell is a special type of structure that establishes a new framework for lightweight construction. It is possible to create a wide variety of shapes and geometries, therefore guaranteeing an enormous architectural freedom. However, given the variety of forms and the difficulty they can present, it is necessary to use different tools and information to support this complex process.

The present paper explores the interaction between the information and the different tools used by architects and engineers during the designing and construction process of an elastic timber gridshell, by presenting a real case study with 42m²(6,5mx6,5m) after being erected, built with the intent to explore the design and constructive process together with integrated form finding methods. In the paper, both the architect's and the engineer's optimization goals are performed on the same case study. The designing process will be presented and the construction of the elastic gridshell will be described.

Keywords: Timber gridshell, elastic gridshell, timber structures, Mesh design, structural approach, structural shell.

RESUMEN

Una malla estructural de madera es un tipo especial de estructura que establece un nuevo marco para la construcción ligera. Es posible crear una amplia variedad de formas y geometrías, garantizando así una enorme libertad arquitectónica. Sin embargo, dada la variedad de formas y la complejidad que pueden presentar es necesario utilizar diferentes herramientas e información para avalar este complejo proceso.

El presente trabajo explora la interacción entre la información y las diferentes herramientas utilizadas por arquitectos e ingenieros durante el proceso de diseño y construcción de una malla elástica de madera, presentando un caso de estudio real con 42m² (6,5mx6,5m), después de la elevación, construida con la intención de explorar el diseño y el proceso constructivo junto con métodos de integración de "form finding". En el trabajo, los objetivos de optimización tanto del arquitecto como del ingeniero se realizan sobre el mismo caso de estudio. Se presentará el proceso de diseño y se describirá la construcción de la malla elástica.

Palabras clave: Malla estructural de madera, malla estructural elástica, estructuras de madera, diseño de malla, enfoque estructural, almacén estructural.

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1. INTRODUCTION

For the last fifty decades, computers have increasingly become a larger part of the design and constructions phases of all type of structures but particularly in architectural designing. With time, computer technologies have infiltrated almost every aspect of architectural process (1). It allows to model, with great sophistication, the material capacities and proprieties of the architectural components. This new approach has inaugurated a new spirit of collaboration between architecture and engineering. Though these two areas which have often been perceived as quite separate areas of concern, new dialogues are beginning to emerge. This may lead to new hybrid information and tectonic design (2), with interdisciplinary practices that will co-exist between the two professions. One of the fields in which this hybrid information is sought, is in the relation between the form and structural properties of structural systems, leading towards an increasing interest in lightweight structures. Within these type of structural systems, shells and gridshells are a variant often chosen for their free-form and architectural expressive design (3).

1.1. Elastic timber gridshells

Elastic timber gridshells are commonly named as bending active gridshells (4) or strain gridshells (5). These structures are a spatial framework of strips and rigid joints taking advantage of the flexibility of timber. Frequently, the elements form a planar grid with rectangular gridshells and constant spacing between nodes. The strength and stiffness characteristics of the structure is obtained through its double curvature and in-plane shear properties (6). An elastic timber gridshell (7) is a solution that is based on the deformation of a flat timber grid without shear stiffness, it was first used more than forty years ago (8).

Despite the timber gridshells construction still being largely associated to the preparation of covers due to its shape, in dome, and to the fact that it is an effective model with great capacity to 'cover', these structures can have many different roles in the construction field. The versatility of the elastic timber gridshells allows them to be ephemeral and/or perennial structures, since they can be found in rehabilitation, new buildings, roofs and small interventions in non-structural elements or simply function as a mere architectural object. Everything depends on the materials and techniques used.

The design and the construction phases should be considered the dominant load case due to its complex geometry and the considerable number of factors to be considered during its different phases, as its high bending stresses, high curvatures and point loads. The complexity of the elastic timber gridshells make them a great case study. All designers interested, should be able to design it, so, it is necessary to start creating some transversal and general rules/ideas.

Examples

Although there are not many examples, it is important to present the first project carried out in 1975. By Frei Otto, the Multihalle in Mannheim (9). The structure can be seen as a true pioneering work in the timber structures area. The geometry of the structure was defined by physical form-finding while it was constructed by pushing up the flat grid of laths with aid of scaffolding towers and fork lifts.

Another reference in the timber gridshells field was recently built, in the United Kingdom, as part of a new conservation center building and storage, Weald and Downland, to the Open-Air Museum near Chichester, in Sussex. The building has drawn international interest from architects, engineers and carpenters. Besides Downland, there is a half a dozen examples of the kind. After Mannheim was built, other good examples were designed such as: the Helsinki Zoo viewing platform, by Ville Hara, in 2003; for its image and the integration of this type of structure with a metal structure, the Savill Building, in Windsor Great Park, by Buro Happold and Glenn Howells Architects, a large four-layer timber Gridshell, in 2006; the Courtyard roofing of a rural villa, Italy, by cmmkm - architettura e design, Roberto Ruggiero, Alfonso Petta, Felice Grasso and Fabio Figlia, in 2007; the Masseria Ospitale's terrace roofing, Italy, by cmmkm - architettura e design with Bernardino D'Amico and Filomena Nigro, in 2010; the Pavilion Japan, the Haesley Nine Bridges Golf Club House, in Korea, and the Centre Pompidou-Metz, in France, 2010, by Shigeru Ban.

1.2. Objectives

This paper aims to understand the construction process of a timber gridshell and what engineering has to offer to architecture as a methodology and support design of this kind of structure (10). The method applied to design the gridshell is based on a tectonic approach (11). It is intended to develop original knowledge with the presentation and application of design and constructive methodologies in a real case study. Furthermore, it is expected that this results in a summary of notions regarding the design of timber gridshells, to solve problems found during the design process that can help create structures with high spatial and structural quality.

To achieve the proposed ideas, a real case study is presented, with 42m² (6,5mx6,5m) after being erected, built in June of 2016 and dismantled in January 2017. During the 13th and 14th of June 2016, an elastic timber gridshell was built in the garden of the Architecture School, at the Azurém Campus of the University of Minho, Portugal. The structure functioned as an experience and, also, to disseminate this type of structures. Moreover, it can be said that the greatest achievement of this work is the fact that the first elastic timber gridshell was built in Portugal (12).

This work was 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. DESIGN APPROACH PHASES

To develop such structures and to enable them to be more common, it is necessary to have an information database regarding its construction and design. To advance a useful process of design, there are several requirements that must be taken into account since the examples that are to be studied up until the exploration of geometry through drawing physical models and digital three-dimensional models. These tools have to fill the gap between the aesthetic and functional requirements determined beforehand, as well as, the shape of the grid shell that can actually be built (13).

2.1. Case study

These ideas / general rules that were presented, were followed by the process of designing the case study. Due to the little feedback and know-how available about the elastic timber gridshell construction, both in Portugal and in the rest of the world, all the tools that were available for the geometric and constructive design were used.

It should be noted that the material (wood) was made available for free of charge by a company that works with wooden structures, so the decision on the type of wood did not exist and the work it was based on what was offered (table 1).

Table 1. Number of elements.

Elements	Number of pieces	Section (m)	Length (m)
Element A	80	0.015x0.06	3,55
Element B	56	0.015x0.06	3,2
Element C	16	0.015x0.06	2,85
Element D	16	0.015x0.06	2,15
Element E	60	0.015x0.06	0,9
Element F	60	0.015x0.06	0,3
Element G	8	0.12x0.06	2,6
Element H	8	0.12x0.12	1,2

Example

Based on the research of the state of knowledge, about the subject in question, a case was found to be a good example to point out due to the proximity in size/proportion and geometry to what was intended, as well as because is well documented.

A recent example, ZA Pavilion depicted in Figure 1, 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 variety of beams criss-crossed between them requires some serious thinking (14).

This double layered structure is made from Siberian larch laths, with a section of 70mm x 20mm, reaching a height of 4m and spanned 18mx13m. For the construction of the structure, the grid was assembled from 3.5m by 3.5m modules, using a double-splice joint connection with the aid of 2 additional timbers between the laths (Figure 2).



Figure 1. ZA Pavilion [14]

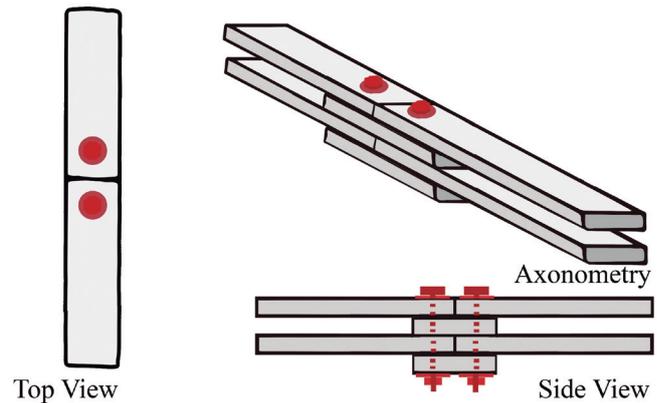


Figure 2. ZA Pavilion bolted connection

As visible in Figure 1, from the geometry of this pavilion, four arched entrances stand out as areas of highest curvature. In these areas, the structure alters from the remaining grid, being, each layer, made of 2 laths, each one with 10mm in thickness. This solution improves the bending process avoiding breakages.

Finally, for the bracing, a third layer of ribs with the same cross-section of the grid laths was included (14).

Sketches

In the present case study, the method crossed between theory and practice went through several phases. This was not a linear process but an experimental one, based on a trial and error approach. Starting with some handmade sketches, looking for a simple geometry that was able to demonstrate different possible situations / problems, as it is possible to see in the example below (Figure 3).

The hand drawn sketches, were a very important stage because without too much effort it was possible to try different things, as different propositions, symmetries, details, etc. Also, this allowed to move forward to the next phases with a better idea about what to look for.

In this case, after some geometric experimentation this step brought some clarity about what would be the desired volumetry, as well as warned about some necessary care due to the use of two layers. Some of the care that was necessary to prevent was the necessity to allow the sliding of the pieces between the same lines of the different layers, since the outer lines would always have the greater perimeter.

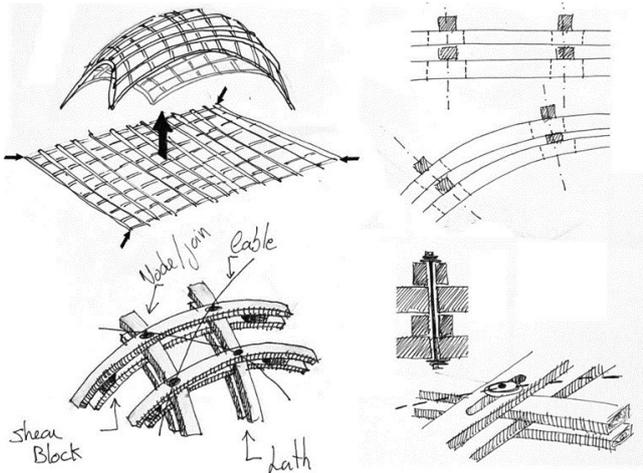


Figure 3. Sketch's examples

Physical Model

After defining the overall dimensions, height, area, grid, it was time to try the idea in a model. This model was constructed, at 1:10 scale, as per figure 4 below. This model was not an exact replica of the mesh to be constructed, but rather a mimic of the general concept (15). It was constructed with only one layer and wire-adjustable connections to allow some movement between the lines during their deformation. Its' objective was to demonstrate the behaviour of the different lines and there is no doubt about the torsion, flexion and possible breakage movements (9). The importance of the first phases was proven by the time it took to build because of the high number of connections. At this stage, it would not be possible to test all the variants studied previously in the drawing phase, due to the use of material, cost and space needed.

The construction of this model allowed to realize that the arcs of the entrances would be the most tensioned, being these the



Figure 4. Model scale 1:10

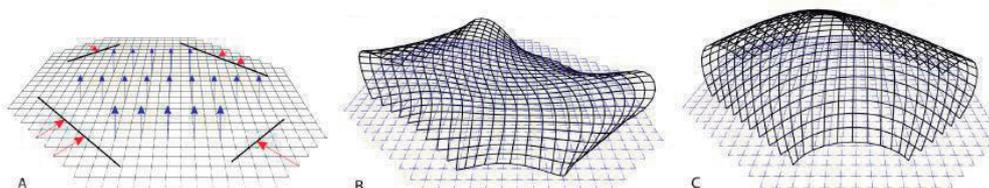


Figure 5. Sequence of obtaining the form; A: Initial flat shape with representation of the forces of deformation; B: Intermediate form; C: Final form (14)

elements that would define the maximum deformation that the material would allow. Furthermore, it was possible to understand that the elements when wet increased their elasticity considerably, facilitating the process of deformation.

Three-Dimensional Model

It is important to note that current software, has tools that allow to easily design complex structures (16). In this specific case, the software used was Rhinoceros 5 (17) and Grasshopper (18). This conjugation of software consisted in the use of the visual programming of the Grasshopper to conceive the models, and, Rhinoceros to visualize the same ones.

Before starting the modeling, it was necessary to define a strategy because the way it started would condition or facilitate the rest of the project. It was required to foresee some problems and difficulties associated with each methodology and the parameters that would be flexible during the design process.

Thanks to the previous phases, some priority characteristics were determined, that helped to define and choose the best way for the construction of the three-dimensional model. The priorities were: the defined shell-like final image; to obtain the greater number of workable parameters; the quick creation of an automatic model and parameters; give priority to the methods that make less use of drawing in Rhinoceros; and, since it was an academic scope, work in a way that somehow could bring more knowledge to the user experience.

However, Grasshopper did not have the ability to simulate the constructive process of the mesh, creating the necessity of making use of the Kangaroo Live Physics plug-in (19). This computational tool is based on a method called "Dynamic Relaxation" (method that allows to obtain a geometry in which all the forces are in balance) (20). It started with the definition of a base geometry (flat mesh), to which elements were associated with the properties of the material to be used. Then the boundary conditions were imposed and the forces of deformation of the mesh were defined. A simulation was then carried out until the mesh reached equilibrium, thus obtaining the new geometry. The described process, that can be seen in Figure 5, was repeated, changing the applied forces and following three factors that were taken as the most basic level components of the designing tool: material model; approximation of the target shape; equilibrium form finding procedure (13). It was finished when the desired geometry was reached, based on previously imposed requirements: geometry of the final shape; internal forces; support reactions; forces needed to bend the grid into shape; geometry of the grid before it is bent into shape; information on the accuracy of the results; maximum buckling of the elements, etc.

It is important to note that this model was used only as a geometric exploration tool, because it did not reproduce the actual characteristics of the material and the conditions of the constructed gridshell.

Despite the good final result of the model obtained from Kangaroo Live Physics, another model was developed using another Grasshopper's plug-in, named Karamba. Using the same procedure as per the development of the previous model, the new one gave the opportunity to introduce more variables to the model, obtaining a more realistic final form.

Final description

The result of the previous phases was the project of an Elastic timber gridshell with a flat grid with about 80m² open. This flat grid would be tensioned, making it deform until it gained a new shape, as shown in figure 6.

A flat shell with a regular square grid in the two-dimensional planes with the corners cut, using double layer and with two axes of symmetry. There was a line spacing of 0.7m, with 9m lines composed of 3 wooden elements each. This would result in a tri-dimensional structure with bolted connections in 6cm tears holes, so it could move during its construction, as can be seen in Figure 7. With variable heights of 2.1m and 3.4m in the span arches and the centre of the mesh respectively.

To keep the cost controlled and since the wood was offered, the locks were designed with wooden elements that are placed diagonally to the grid (Figure 8).

3. CONSTRUCTION

For everything to be prepared and built during the two-day workshop, it was necessary to take into account some preparation work beforehand. At the design stage, the size of the items to be transported was still to be considered and to be handled on the day of construction. For this reason, all the lines were divided into 3 pieces each (6 pieces with the two layers) and the connection between the parts of the same line will be screwed using a double-splice joint, as is possible to see in the Figure 9.

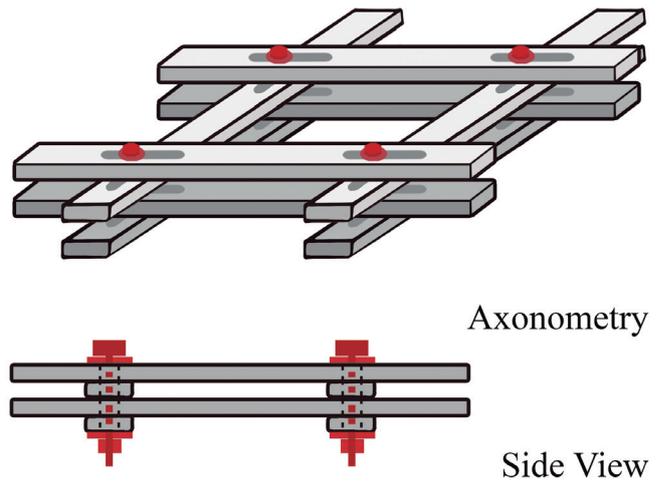


Figure 7. Double layer bolted connections

Therefore, the structure was divided into 9 quadrants, 1 central, 4 lateral and 4 at the corners. Each type of quadrant consisted of different types of elements as the Figure 10 shows.

For the construction of this structural mesh it was necessary to design an inventory with the different types of pieces. So, it was designed 8 different types of elements, presented in the table below. Finally, in addition to the dimension of the pieces, the idea of receiving only the pieces cutting and making all the tears on the same day, made impossible to construct within two days as programmed. Therefore, the design of all the type pieces were sent to the wood company with the location and dimension of all the tears so that they could come ready to use.

For security and for clarification of some doubts, two arcs were tested until the breaking point, as it is possible to see in Figure 11 a, b. These experiments aimed to perceive the reaction of the wood when folded quickly. Thus, a line was tested that would simulate the most tense arc of the case study, ensuring that this was the worst case scenario (21).

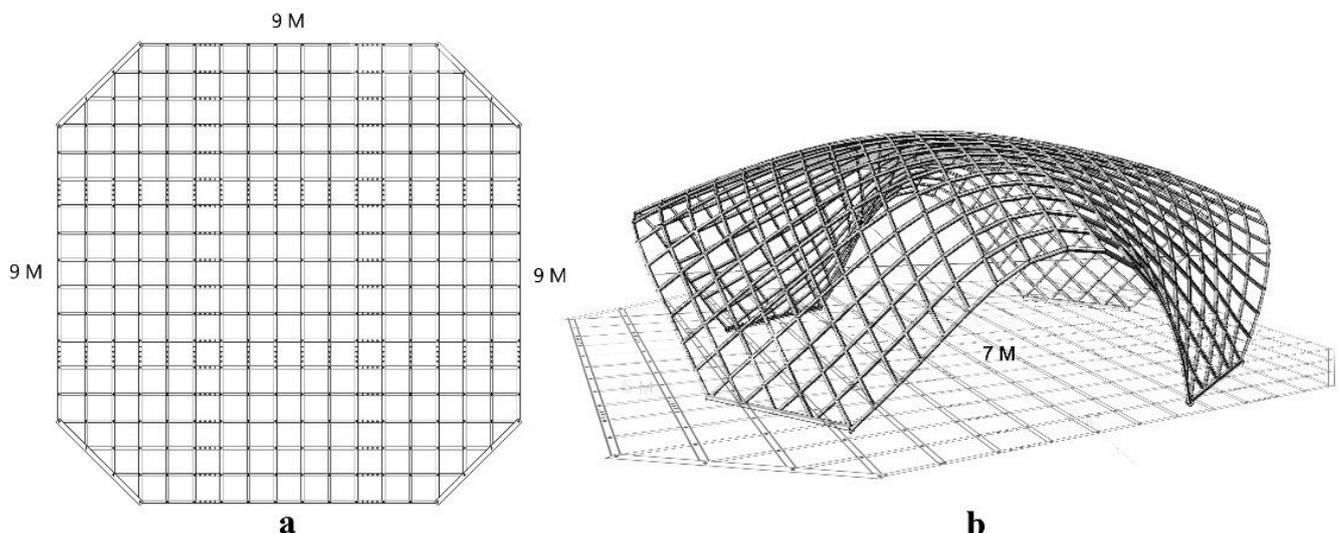


Figure 6. Study case Final form (21)

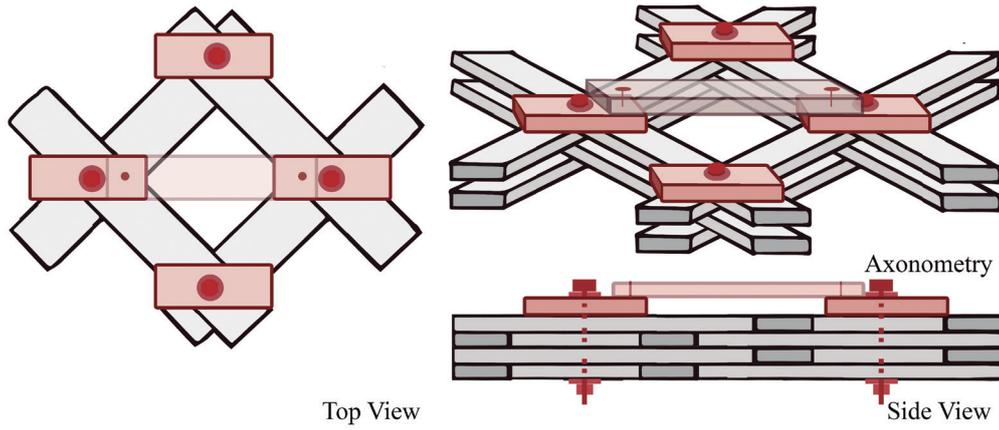


Figure 8. Diagonal locks with timber elements

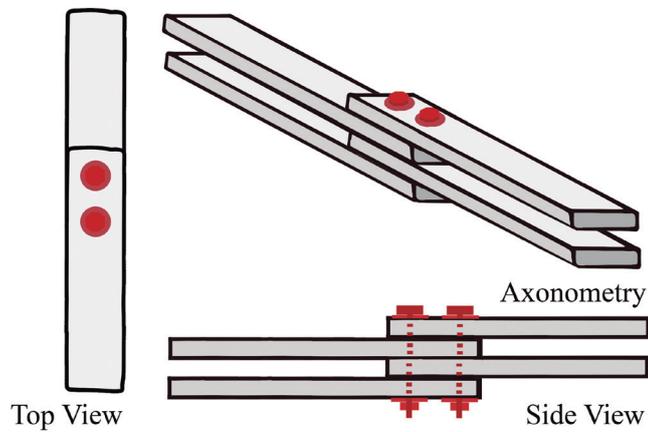


Figure 9. Bolted connections in the same line

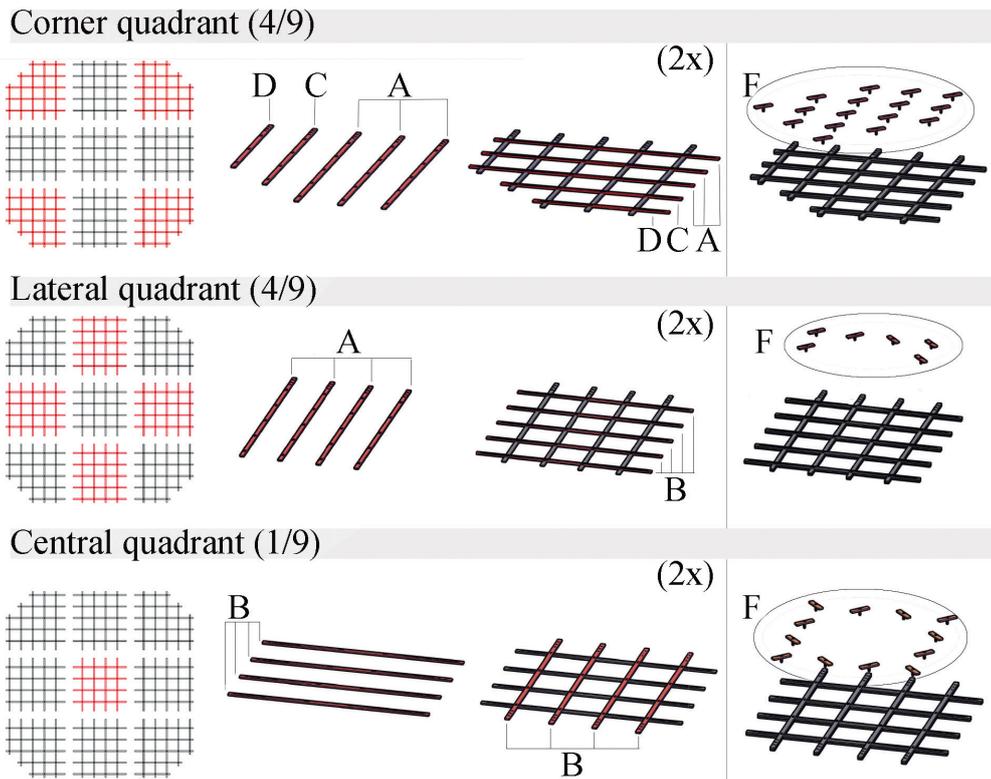


Figure 10. Quadrant typology

After the tests, it was easy to see that there were two main problems. The (many) nodes present in the wood and some connections were too rigid and did not allow for the movement of the elements of the mesh during the deformation. Firstly, it was defined that during the construction of the mesh, its' elements would be constantly watered to increase the moisture content of the wood, which would ease its deformation, avoiding breakage. Another possible process would be to soak the elements in water for some time prior to construction, but there was not enough equipment capable in terms of size. In addition, a visual check of the elements was done to leave out those with larger nodes. In relation to the stiffness of the connections, long screws were chosen that allowed to hold the elements but also to keep them loose to the point where they allow movement of the mesh elements during the deformation of the same.

3.1. Assembly process

June 13th

To begin construction, the pieces were separated and organized by quadrants (see Figure 12a) and then the respective quadrants were assembled, as previously mentioned, at the construction site. The constituent elements of the quadrants were joined by simple connections with M8 screws, measuring 8 and 10 centimetres in length.

Several pieces of aid were placed in the quadrants to the subsequent application of locks, as shown in Figure 12b. It was necessary to place these pieces in this first phase joined to the structure through the existing connections in the quadrants.

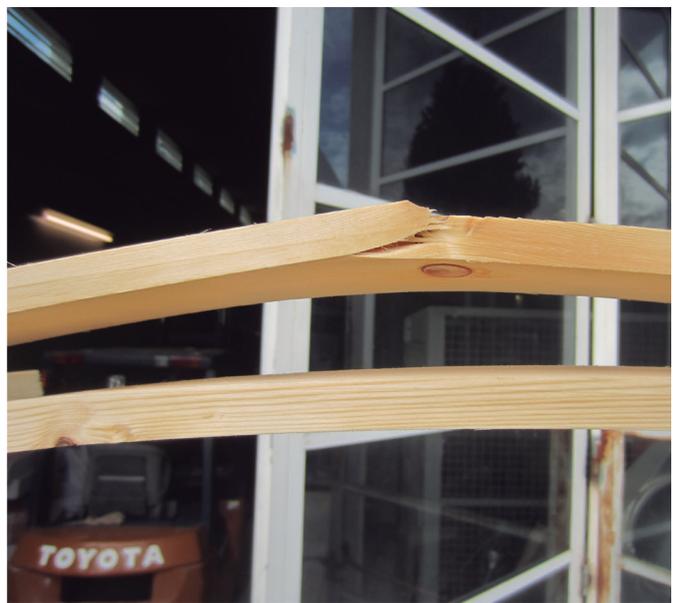


Figure 11 a, b. Arch test



Figure 12 a, b. Gridshell Construction

To allow the support system designed for the structure, it was necessary to place two elements that “embraced” the elements in the area of future supports. These elements, like the previous ones, are joined to the remaining structure through the existing connections.

An extremely important detail was that the attachment bolts were not tightened properly, thus allowing the structure to move without becoming too rigid during the erection process (see Figure 13a).

In order to finish the first day of the Workshop, the different quadrants were connected as it is visible in Figure 13b, through similar connections to the previous ones. Some pieces were placed all over the grid, with the nail gun, making shims between the two layers, creating more points of contact between them.

June 14th

Two hours before the beginning of the deformation of the shell, the pieces began to be irrigated the pieces in order to ease their deformation (see Figure 14a). At the same time, several pieces were built with wooden elements to serve as anchors and assist during the process of erecting the mesh. Moments before beginning this process, the grate was transported to the place where its final position would be (see Figure 14b).

The centre of the shell was erected manually, and the struts constructed were placed in the inner zone of the grid, as can be seen in Figure 15a. The next phase was to mount the tension application system on the flat mesh. The system used was a set of 6mm steel cables that would come to be pulled with the aid of two lever winches, one in each direction.



Figure 13 a, b. Gridshell Construction



Figure 14 a, b. Gridshell Construction

During the application of tension, the supports could move horizontally, the grid was lifted and placed on elements of wood, thus allowing the movement of the supports, presented in Figure 15b.

The application of tension was started through the winch lever; safety cables were placed parallel to the tensioning cables (see Figure 16a). After a first application of tension, sometime was given to the wood so that it could adapt to the imposed deformation.

During this waiting time, the cables were adjusted and the winches lever for a second application of tension. The weights were also repositioned, which were the definitive support of the structure. During the interval in between the application of tension, hammers and pliers were used to adjust the connections and help the structure to accommodate itself to its new shape, as is visible in Figure 16b.

With all these processes completed, a new phase of tension application began. The processes described above were re-

peated until reaching the desired form for the structure (see Figure 17a).

Once attained the desired geometry (see Figure 17b), it was time to fix the structure. For this, the locks were placed in the previously placed parts, all the connections were tightened, the concrete blocks were placed properly to serve as support and prevent the horizontal displacement of the structure and the lever winches and tensioning cables were removed.

3.2. Issues

During the application of tension, there were some problems. In the central zone of two of the most requested arcs, there were ruptures in the elements of the two layers due to the existence of knots, as it can be seen in Figures 18 a and b. As a solution, two pieces of one of the arches were replaced and the second arch was reinforced in its upper zone with a new piece. Furthermore, to prevent similar new problems, some elements that showed a risk of rupture were reinforced.



Figure 15 a, b. Gridshell Construction

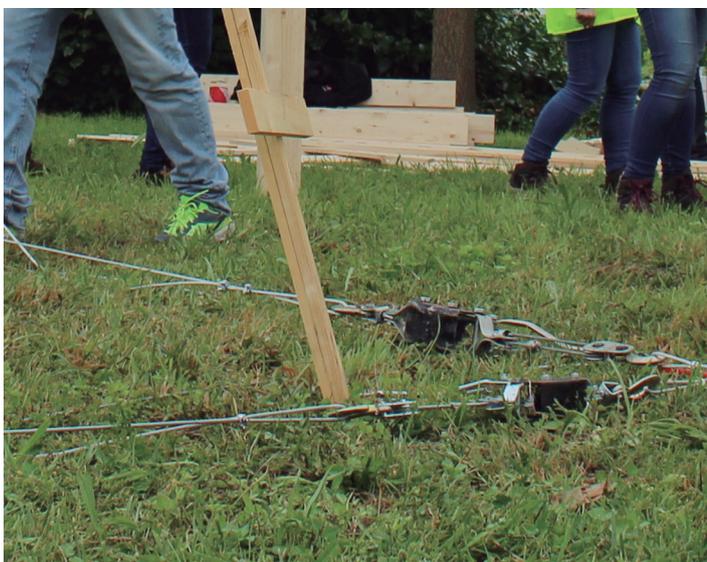


Figure 16 a, b. Gridshell Construction



Figure 17 a, b. Gridshell Construction



Figure 18 a, b. Element break

Another problem arose with the application of the locks. The locks were placed in a vertical position, perpendicular to the ground, which forces them to be nailed in curved positions, and they are constituted by rectilinear elements. This situation was corrected by changing the direction of the locking elements.

Finally, after a few weeks, a new problem arose, which was predicted: due to the loss of tension and its own weight, the structure began to suffer from a displacement in its central zone, more concretely in quadrant number 5 (see Figure 19). Due to the self-weight load being too low and the stiffness of the structure too high, its central elements did not deform. As such, their central zone is completely flat. In order to prevent this problem, the central zone of the mesh should have been considered, creating a curved upper zone. The force in this zone would have to be maintained over time so that the problem would not arise again, that is, the solution could go through the collusion of a brace.

3.3. Final Geometry

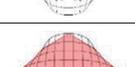
The constructed gridshell presented very positive results, with a few number of issues, described before. Comparing the constructed gridshell with the computational model developed, could be concluded that the geometric differences between them were very small. On Table 2, the main dimensions of the three-dimensional model and the constructed gridshell are compared.

Regarding the structural behaviour, the gridshell presented very good results. Despite the displacement that occurred in the centre of the structure, turning this central area into a flat grid, this event was predicted in the structural analysis developed in the three-dimensional model before the construction. A possible solution for this issue was already mentioned before.



Figure 19. Central displacement

Table 2. Comparison between Three-dimensional Model and Constructed Gridshell dimensions (22)

	Three-dimensional Model	Constructed Gridshell	Figure
Centre height [m]	3,14	3,10	
Entrances height [m]	2,10	2,10	
Diagonal length [m]	7,08	7,12	
Covered area [m ²]	51,30	51,84	

3.4. Disassembly

The gridshell was designed to remain in place for 6 months. After this time, the shell would be dismantled, proving its ephemerality, and in a way that does not endanger the safety of its users. Considering that the wood used was treated, that gave a few guarantees of its structural capacity and also the fact that Guimarães is a city with a thermal amplitude of maximum and minimum around 40° Celsius (23) which accelerated the process of aging of the wood. So, in January 2017, 7 months later, the mesh was cracked and broken, with the central quadrant already visibly felled and the parts of the quadrants of the supports with a curvature much higher than expected. Some of the elements are not reusable. However, a large part can be reapplied and perhaps the mesh rises again.

The dismantling process was relatively fast, unlike its construction. At this stage, only two people were working, and the process lasted for about 5 hours.

4. CONCLUSIONS

The focus of this paper was to understand the several phases in the design and construction of an elastic timber gridshell and how engineering information could help these phases. Accordingly, it was possible to recognize, mainly in chapter 3, that the construction of these gridshells require the full accompaniment of these professionals. Whenever an element is folded, whenever a connection is tightened, or a lock is placed it is important to realise the need for these phases to be done correctly and at the right time. With these structures when an architect draws a curved line, the engineer must be, already, included in the discussion, because this line will arise from the deformation of a straight element, thus this curve line in addition to an architectural element it is also a feature of engineer.

As presented in the paper, other case of timber gridshells with similar geometry to the case of study exposed was studied. From these, the ZA Pavilion is a good example of an elastic gridshell to be compared with the one developed, not just for the similarity in size and shape but too for being developed in a similar context.

Both gridshells were successfully built, however some issues have been raised and the solutions can be compared. On the ZA Pavilion design, the behaviour of the structure at the four arched entrances was taken in account, being these the areas of highest curvature. For these areas, a solution of 2 laths of 10mm in thickness, per layer, was used to substitute the 20mm lath present on the most part of the structure. This solution allowed the absence of breakages during the bending process of the structure [14]. On the case study, for the same areas some ruptures occurred on the elements during the bending process, what could be avoided if a similar solution to the ZA Pavilion were used. On the contrary, in the ZA Pavilion design, the connection method used to join the various modules of the grid, consists on the use of 2 additional timbers between the laths, what was not the most efficient solution. The use of this type of joint enabled kinks after the grid be deformed, due to a lack of lateral resistance from the connections [14]. On the case study, an alternative connec-

tion was used, consisting in overlap the layers of the modules, avoiding additional layers and reducing the possibility of kinks at these areas.

4.1. Outcome

From a pragmatic and critical reflection, some topics were created with more ideas and information failures to continue this work of sharing theoretical and practical information in the elastic timber gridshells field:

- The tension gives stability to the structure. The more tensioned, the less influence the outer forces have on the geometry;
- Locking with wooden elements should be avoided as they add an extra load;
- The locking mechanism does not function as an isolated element and its presence is only effective in the assembly;
- The position of the braces depends on the geometry, dimension, grid etc... But their placement will always be necessary in the long run;
- A mesh with two layers must be optimized and can change the metric of the grid. Or, use only one layer in the areas where less load is desired;
- The elastic gridshell coating material should provide rigidity to the structure or must have the capacity to adapt to its deformation;
- The geometric assessment and monitoring of these structures, during the entire design and constructive processes,

considering the starting position adopted, is of the utmost importance for the design process;

- The software lacks the “time” factor where the adaptation of the wood to the deformation and consequently loss of tension must be considered;
- The design process lacks rules of geometry and effective proportions as a complement to the structural analysis.

For further developments, it is still necessary to reflect on the ability of architects and engineers to control the process, instead of letting be the tool controlling the project. It seems that, in many situations, architects get carried away by the easy use of software forgetting the reality / context. It has transformed their buildings into craft works.

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