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ELASTIC TIMBER GRIDSHELLS. FROM THE FINDING FORM PROCESS TO THE ERECTION OF EFFICIENT LIGHTWEIGHT STRUCTURES.

MÁRIO JORGE GONÇALVES FERNANDES

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Doctoral Thesis
International Doctoral Programme in Sustainable Built Environment

Supervisor
Professor Doctor Jorge M. Branco
Co-supervisor
Professor Doctor Poul H. Kirkegaard

May, 2019

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

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Supports

Abstract

Elastic timber gridshells emerged in the last century, essentially related to ephemeral buildings, setting a ‘new’ benchmark for lightweight, cost-effective, sustainable and temporary constructions. Timber gridshells are adaptable and can be used in rehabilitated buildings as well as, new buildings, new systems like roofs, or as small additions in non-structural elements and act as a simple partition. However, the main feature is not its use, but its shape and how it allows some freedom in its design; an attractive characteristic for designers due to its structural behaviour.

Based on the advantages of the structural system, it should be expected that timber gridshells have a wider presence in contemporary architecture. However, this is not the case, there are very few examples being built. One reason why this happens, is because of the difficulty to reach the desired design since there is a lack of information about the tools that can help to define such complex systems.

Until today, the design and construction of elastic, or post-formed timber gridshells, have only been based on a case to case basis and have not been studied or used as a type of structure that can be repeated in several different applications.

The aim of this thesis is to contribute to answer this difficulty, i.e. working on overcoming the lack of design guidelines, by presenting a state of the knowledge on elastic timber gridshells and by case studies analysing the process involved in building this kind of a structures.

The thesis is addressing elastic timber gridshells, from the design phase to the construction phase. The results obtained show that this type of structure can be very interesting at a functional level with numerous tectonics characteristics that make elastic timber gridshells attractive as a structural solution in contemporary architecture.

Keywords: Elastic timber gridshell, Timber structure, Design process, Form-finding, construction.

Resumo

As malhas elásticas de madeira surgiram no século passado, essencialmente relacionadas com construções temporárias, estabelecendo uma "nova" referência para construções leves, econômicas, sustentáveis e efêmeras. As malhas de madeira são adaptáveis e podem ser usadas em edifícios a reabilitar, bem como, novos edifícios, coberturas, ou em pequenas modificações como elementos não estruturais. No entanto, a principal característica não é seu uso, mas sua geometria e como isso permite uma enorme liberdade formal torna-se uma característica atraente para todos os projetistas.

Com base nas vantagens deste sistema estrutural, é de esperar que as malhas elásticas de madeira tivessem uma presença mais ampla na arquitetura contemporânea. Contudo, não é o caso, existem poucos exemplos construídos. Um motivo para isso acontecer é a dificuldade em projetar as formas desejadas, pois existe uma lacuna de informação sobre as ferramentas que podem ajudar a definir estas geometrias complexas. Por exemplo, as ferramentas baseadas em softwares computacionais têm um grande potencial para o processo de projeção das malhas de madeira nas fases de projeto e construção, onde a localização da malha e a otimização ocorrem, seguidas por um processo de produção industrial. Até hoje, o projeto e a construção destas estruturas, foram estudados apenas de caso a caso e não foram estudados ou usados como um tipo de solução que pode ser repetida em várias aplicações diferentes.

O objetivo desta dissertação é contribuir para a resolução desse problema, ou seja, trabalhar na superação da falta de diretrizes de projeto, apresentando um estado do conhecimento sobre as malhas elásticas de madeira e analisando e explicando o processo envolvido na construção deste tipo de estruturas.

Esta tese aborda as malhas elásticas de madeira, desde a fase de projeto até à fase de construção. Os resultados obtidos mostram que este tipo de estrutura pode ser muito interessante a um nível funcional, com numerosas características com valor tectônico que tornam as malhas elásticas de madeira atrativas como uma solução estrutural na arquitetura contemporânea.

Palavras-Chave: Malhas Elásticas de Madeira, Estruturas de Madeira, Processo de construção, Form-finding.

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1 Introduction

Considering all the technological and civilizational advances that have occurred in the last two millennia, buildings can have the most varied functions. Nevertheless, the main objective of a building has not changed, i.e. protect the interior space from external actions. The structural system chosen for a building is based on the geometry sought for both the interior space and the applied loadings. The most common structural system is the one that includes both horizontal and vertical elements like a column and a beam scheme, for example a portal frame. The horizontal loads are collected by the façades and the vertical ones by the slabs. Both loadings are transferred through the slabs and the beams to the columns which then carry them down to the ground through the foundations. This building solution is the one most commonly used in buildings. Nevertheless, there are also other structural systems like gridshells that do not separate horizontal elements from vertical elements.

1.1 Elastic timber gridshells

Timber gridshells are constructive systems that, although they are not new, they deserve to be explored. It is a type of structure that enchants due to its peculiarities, such as its lightness, behavioural efficiency, optimization of the structural section and the assembly process constructed. They are highly technical systems with low-cost means and a very limited impact on natural resources (Paoli, 2007). They can be constructed in a relatively short time and allow organic forms and complex geometries, impossible to obtain with standard structural systems.

Between the different possibilities of gridshells types, presented further in this thesis, it was defined to address in this work the elastic timber gridshells (see Figure 1.1). First, this typology represents a very particular system, with unique specificities regarding its conceptual process, construction/erection, details and service-life. Despite their great potential, it is obvious the lack of knowledgement about the system to support designers interested in exploring elastic timber gridshells. More than forty-five years after the construction of the first elastic timber gridshell, computers can now be an important utensil in the development of timber gridshells. Complex forms can be shaped with relative ease in a computer contributing to solve different kind of difficulties and problems starting from the designing phase until the final construction (R. Harris & Kelly, 2002).

Figure 1.1- Example of an elastic timber gridshell (Pone, n.d.)

Elastic timber gridshells are commonly named as bending active gridshells (Tayeb, Lefevre, Baverel, & Peloux, 2015) or strain gridshells (Michalatos & Kaijima, 2014). Those gridshells have the unique advantage of using timber elasticity while defining a spatial framework of strips and rigid joints, after reaching the final geometry. Frequently, 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 (Chilton & Tang, 2017). Elastic timber gridshells are based on the deformation of a flat timber grid without shear stiffness (Verde & Truco, 2009).

These structures are comparable to a shell system with large openings, in such a manner that it allows for the strips or grids to behave, in terms of structure, as a shell. A gridshell is a very effective way of addressing the various structural and architectural demands, such as openings, by concentrating the shell into linear strips. Likewise, the out-of-plane stiffness, and the buckling capacity can be adjusted by modifying the depth of the strips. Hence, making it possible to pre-fabricate by producing discrete sized strips. Therefore, applying a numerical form finding process, based on the actual potential of computers in simulation, it is possible to have the engineer and architect working together in developing a pleasing shape that is efficient (Hurol, 2016).

The assembly stage, in particular, the deformation of the timber elements (Lienhard, Alpermann, Gengnagel, & Knippers, 2013), is the most important step of the entire process out of, the conception, calculation and construction (Fernandes & Branco, 2015). There are several ways to assembly them, such as those mentioned in Quinn and Gengnagel , 2014 who described some methods that will be addressed further on. Their advantages, regarding the common structures, are transversal to all the methods of assembly: the minimum use of material and modularity due to a minimal cross-section, the small size of individual elements and repetition of the constructive details, its structural efficiency obtained by its structural resistance due to its shell-like geometry and the distribution of forces through continuous lines, as well as the safety due to its redundancy when some elements fail. Nevertheless, several constraints may be found such as a significant number of small imperfections (Bulenda & Knippers, 2001)(Malek, 2012), the geometric complexity and the need for a large amount of labour (Douthe & Baverel, 2009). These are probably the main reasons that prevent a more generalized implementation of these structures. Their complex geometry creates knowledge gaps in relation to its design, construction and behaviour. As referred in Fernandes et al. (Fernandes, Kirkegaard, & Branco, 2016), it is believed that this has prevented the use of these structures for more than 40 years.

Due to the complexity already mentioned, the development of these structures must involve the work of a multidisciplinary team. Architects and engineers should be involved in the various stages of development of elastic timber gridshell. When it comes to these structures, when an architect draws a curved line, the engineer must already be involved in the decision-making process, as this line will arise from the deformation of a straight element. Thus, this curved line in addition to be being an architectural element is also a feature of engineering.

The gridshells have a structural system described by a three-dimensional curved surface. External loads are transferred to the supports, predominantly through forces acting in the plane of the shell surface, which are called membrane stresses that can be in compression, tension or under a combination of both. A ‘thin’ shell must be sufficiently ‘thick’ to carry these compressive stresses without buckling. Elastic timber gridshells can be built as a continuous surface or from discrete elements following that surface.

Based on the selection of material, a large variety and combinations of structural systems can be generated by means of its elastic deformation. Considering the material’s behaviour, these structures become a distinct structural type, whose geometry it is predefined based on an analytical analysis of the behaviour which is based on the moment curvature relation, or experimental form-finding methods. Form finding of shells started out by using the inversion or hanging-chain method. The designer searches for a shape, which carries applied loads in axial compression without any bending forces, or as minimal forces as possible.

1.2 Research Questions

The development of a design methodology based on what engineering have to offer to the architecture can harness their potential to a better learning process about elastic timber gridshells. With respect to that methodology, this thesis looks at the work process between architects and engineers with the aim of identifying the best moments of convergence. Therefore, the research begins with the contributions that have been given to field, and how the design of gridshells has been influenced by information from different areas. Next, the presentation of converged information is given demonstrating the difficulty of separating the two areas, arriving at the tectonic value of elastic timber gridshells.

These structures have inaugurated a new spirit of collaboration between architecture and engineering. New dialogues are beginning to emerge between these two professions, which have often been perceived as quite separate areas of concern. Architecture and engineering are coming together within a culture of mutual respect. This may lead to new hybrid information, interdisciplinary practices that exist within the space between the two professions, i.e. the emergence of a kind of architect-engineer of the digital age (N. M. Larsen, 2012).

Furthermore, it is understood that as the above-mentioned areas do not overlap also the methods should not do so. Thus, can be created a methodology that accommodates empirical practices and knowledge about the material and ways of obtaining the geometry that may be complementary and that are an added value for the process, instead of being abolished in detriment of digital tools.

Even because from the moment when computers first made a significant impact on architectural design, a critical counterculture began to emerge. This counterculture championed the tectonic and claimed that those who were producing seductive computer imagery failed to understand the intrinsic nature of architectural production. It was argued that architecture was not born from the algorithmic potential of computer programs, but of the tectonic capacities of materials. With time, however, computer technologies have been absorbed by almost every aspect of architectural production and are now being used to offer insights even in the realm of tectonic.

For the development of this thesis, there are five research questions, which have been defined in order to structure and develop systematically the research work.

- **No. 1:** What defines an elastic timber gridshell as a structure and an architectural element? How can these structures be classified structurally and geometrically?

Consideration of this question will lead to initially investigate an overview of their history and techniques around them. In chapter 2, it will also be presented some examples as well as remarkable persons considered relevant in its development;

- **No. 2:** What should be taken into consideration and which are the main advantages of using digital tools during the design of a Gridshell?

It is necessary to understand if there are a replacement of the analogue tools or if the digital software's are a supplement, and at what stage of the creative process they should be included. The design process is not easy and without any knowledge on the subject this becomes an enormous problem. Recently new digital technologies for designing and manufacturing have inspired architects to take advantage of these new possibilities in their architecture projects. New digital technologies have generated the development of new use of materials, innovative production technologies and the understanding of the transfer of knowledge to the design and production.

Thus, to answer question no. 2 the digital design and manufacturing technologies will be explored, in chapter 3, and outline the way they are facilitating the computational process, generating a relationship between structure, material and form based upon the logic of the manufacturing technologies - a process defined by R. Oxman as the material-based-design (Oxman, 2012);

- **No. 3:** Which is the better way to go from a bi-dimensional to a three-dimensional shape in the construction of an elastic timber gridshell and what is the impact of the details in the final image?

Trying to focus the research interest in the specific point of timber gridshells design process, the relevance of the assembly method becomes evident. Furthermore, the constructive details are keys points for timber structures in general, but in this case the process make the connections gains of even greater importance. It is therefore relevant to know different kinds of connections that can be used in construction and clearly understand their behaviour in global. In order to clarify question no.3 about the methods of the elevation process and elucidation about the constructive details, several to studysolutions will be presented in Chapter 3. Subsequently, in Chapters 4 and 5, some of these solutions will be discussed in more detail;

- **No. 4:** What data is needed and how can be merged the information and characteristics of the material with the digital models?

During construction, the gridshell lattice is bent and warped, resembling the desired shape. The geometry of the shape is dependent on the bending behaviour of the material. To be capable to calculate the structural behaviour of the gridshell, the design model should be a precise approximation of the outcome of the construction. To answer question no.4, a cooperative process which includes the collection of the characteristics of the material and its compatibility with the digital models will be presented in chapter 4; and,

- **No.5:** How can engineering support architecture decisions?

The final question seeks to explore, 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, creating and implementing a method that would work as a conceptual design tool. To verify the results of this tool, an experiment is shown in chapter 4 and 5 with the presentations of the results in final chapter 6. This investigation will explore the potential of the approach of research question 5 for the design development of an elastic timber gridshell of the future. Consequently, the problematic in the design process can be resolved by introducing a method that could be implemented as a design tool similar to a tested docket of guidelines.

1.3 Aims & Objectives

The aims of the research work in this thesis are elaborated as following:

a) To demonstrate how to design and build an elastic timber gridshell with hybrid information, from architecture and engineering. The methodology applied is based on the construction process (Lienhard et al., 2013) and a tectonic approach (Hurol, 2016) involving architects and engineers;
b) To create a working tool for designers who are interested in understanding these structures, regardless of the training in engineering or architecture. Resulting in a complete state of knowledge, as a compendium of dispersed information;
c) To have theoretical and practical information to solve problems found during the design process. It is not the purpose to test and to qualify what should or should not be done, what works or what does not work. Such conclusions can be applied to other areas of science, but not in architecture. Architecture is a human science, which varies according to whom will experience it. It is also not intended to create rules or restrictions, since this is a system with lot to explore;
d) To develop original knowledge with the presentation and application of design and constructive methodologies based on a real case study, which initially can both guide and facilitate architect’s work via a ‘proactive’ approach supporting the design decision making processes during the conceptual design stages indicating the features, constraints, and classification/levelling upon different criteria; and,

e) To make clear what engineering has to offer in a combined approach to prepare recommendations related with conception and design. The methodology should not be complicated but rather complex. Neither the architect nor the engineer can do this alone; it takes both to create delicate and informed gridshells. The more skilful and informed the architect is, the bolder and innovative the result will be, and the 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. One of the main goals is also the dissemination of this construction system, during and after the investigation.

1.4 Research Strategies and Methods

In order to ensure the implementation of the proposed research and to achieve the answer to the mentioned questions, some steps are defined. Firstly, to obtain an overall understanding of timber gridshells and its formal and constructive characteristics, this research initially addresses a review on the path of gridshells structures. As well, as a contextualization and presentation of different types of timber gridshells were identified. It will be presented consolidated information that could act as a tool in the following research. Major contributions in the field of timber gridshell design and construction were studied. Additionally, technical and scientific publications about all the aspects related with the design and construction of timber gridshells were analysed. The existing examples were discussed and studied in detail. The method of form-finding, the type of layer, materials, nodes used were also analysed. Furthermore, the design and construction methods used were studied and summarized, where some theoretically methods were also recorded. Particularly, in the design phase, the form-finding and parametric methods for timber gridshell will be described. In the design phase the amount of information about the structure is very small and therefore this tools can be used to explore the geometrical possibilities. Parametric Design is a process of making a geometric computational representation of the geometry which either can be fixed values or parameters. In this process the typically constrained geometrical entities have been parametrized. With this process the designer has the possibility to change the parameters in the parametric model to search for different alternative solutions (Shea, Aish, & Gourtovaia, 2005). A methodology that will be used later in the case study, where the consequences of these decisions will be identified, suggesting proposals to address gaps in this area. 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 (Jesen, 2001). In the construction phases, all the already used or theorized construction methods will be described and schematically represented. These will be reinforced with some new proposals. In addition to the divisions in subgroups already made, also the purpose factor of gridshells will be presented separating them in short term/ long term life long lasting structures,

The main achievement of the chapters 2 and 3 will be the creation of a good base with the state-of-the-art regarding timber gridshells, as to their design, construction and maintenance. This is followed by a more practical part, where the construction of different reduced and full scale of timber gridshells. These models are developed to provide support information to learn more about the capabilities of the material, collecting their data more faithfully. The post-tensioned solutions are analysed (installation of elements and apply tension after) intending for a global understanding of the behaviour of the structure to the application of tension in its construction. A case study will be presented to apply all the proposed steps in the design of a timber gridshell. This case study will be divided between two chapters, in the interoperability between the real characteristics and the digital model and in the chapter of the design and construction of the case study. This model will be used as a method of testing and approving the improvements applied to the case study. The parametric tool which will be used in this project is the plug-in Grasshopper for the 3D modelling software Rhinoceros (Robert McNeel & Associates, 2016).

From a structural perspective, the most convenient plug-ins for Grasshopper is the physics engine Kangaroo(Daniel, 2011) and Karamba (Preisinger, 2016). Kangaroo's main application is structural form-finding which allows the architect or engineer to explore a variety of geometrical shapes. Form-finding is an optimization process where the geometric form of a structure is based on mechanical behaviour. The geometry is not known in advance; therefore, the form-finding process is the generation of geometry in between the given geometrical and physical constraints. The challenge in form-finding a shape is that there may be infinite number of solutions, which are far better than the quality of an initially flat element.

The described method should contribute to clarify current uncertainties in the design planning process and will highly improve the confidence of engineers and architects in conceiving and realizing this type of challenging lightweight spatial structures. It is important to notice that the structural analysis methodology using Grasshopper and Karamba is based on a linear analysis, however structural analysis of elastic gridshells requires a non-linear analysis (Lienhard, n.d.). This complicated issue has also been considered by researchers (M. Kuijvenhoven & Hoogenboom, 2012) where form generating methodologies have been developed based on a pseudo physical modelling approach.

Chapters 4 and 5are a great opportunity to deal directly with all challenges raised by the design and construction of timber gridshells. It is a unique experience to deal with the complex process of the geometry definition of the grid, to go through the stability verification and to assess on site difficulties imposed by the erection of timber gridshells. The proposed methodology is improved to reach the ultimate goal of designing and building efficient timber gridshells.
Finally, it is intended that some results will be presented in a docket of notions about the design of elastic timber gridshells.

1.5 Case study

Chapter 4 and 5 of the present thesis contains an application of design and construction approach methodologies to a constructed case study. An elastic timber gridshell with regular geometry. Which is built within the scope of this work and structurally works to compression in two axes and presents 4 supports. This structure serves as a reference to address various issues around gridshells, contributing to a practical knowledge.

1.6 Thesis structure

The layout of the thesis it is summarized in the following chapters:

a) 2: Provides an overview on timber gridshells. It presents a state of art with a historical context and a structural and geometric definitions of different possible typologies;

b) 3: Introduces and explains elastic timber gridshells. As well as, approach methodologies, design methods, constructive process, applications and considerations about the tectonic concept;

c) 4: Based on a case study, it is demonstrated how reliable and compatible real timber characteristics are with the computational models;

d) 5: Provides the experimentation of the design and construction method applied during the construction of the case study. In addition, it presents critical considerations to this experience and redesigns the case study; and,

e) 6: Concludes the thesis with a summary of what this study has delivered and discusses future ideas.

2 Background Review

In this study it is intended to address and promote elastic timber gridshells, however first it is necessary to contextualize them. Taking that into account, the historical and technological background will be presented here as a brief chronological approach referring the examples the most important milestones in the history of gridshell. It is intended to clarify the reader about the extended experimental work with these structures, as well as, the research about the methods that surround and leverage them.

2.1 **Gridshell**

"The art of molding materials we do not really understand into shapes we cannot really analyse, so as to withstand forces we cannot really assess in such a way that the public does not really suspect." (Brown, 1967)

The gridshells, as other structures, can be classified in several ways, according to their geometry, their function and the materials from which they are made. From the figure below, it can be seen that gridshells structures derived from the shells, an ampler structural group (see Figure 2.1).

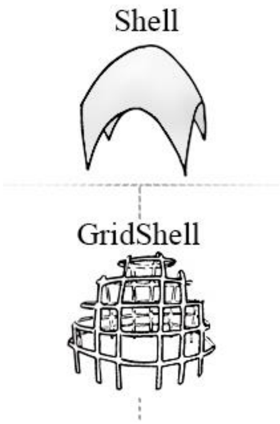


Figure 2.1- Framework of the structural system

A shell is a column-free organic shape with a space that provides unlimited design freedom to architects and structural engineers. The shape directly derives from the flow of forces which defines the load-bearing behaviour and lightness (Michalatos & Kaijima, 2014). The shell structures are one of many different, interesting structural systems, and the most obvious way to define a shell might be through its geometry (Figure 2.2). The importance of the geometry of shells cannot be overemphasized. The form decides whether the thin shell will be stable, safe and sufficiently stiff. Finding the 'right' geometry under the chosen loading (usually gravity) means that under this design load, any bending is eliminated and only advantageous membrane action results. The structural challenge lies in the determination of a three-dimensional surface contour, where the shell can be inserted. Architects as well as engineers have been trying to develop physical and numerical methods that can generate structural, constructive efficient, three-dimensional gridshell shapes rather than the 'simple' geometries., see Figure 2.2.

Figure 2.2- Geometrical variations of shell structures (Michalatos & Kaijima, 2014)

A shell is a structure defined by a curved surface. It is thin in the direction perpendicular to the surface, but there is no absolute rule how thin it must be. It might be curved in two directions, like a dome or a cooling tower, or it may be cylindrical and curve only in one direction (Adriaenssens, Block, Veenedaal, & Williams, 2014). The difference between a shell and a gridshell is that the shell structures consists of a continuous surface, while gridshells contain discrete members that connect the nodes, as shown in Figure 2.3. Another difference between a shell and a gridshell structure is the fact that, due to its free form and, therefore, due to the presence of bending forces, gridshells, need to withstand the load through it's the cross sections of the elements. Membrane structures and network / cable structures, structural shells and gridshells are all part of light structures (Bulenda & Knippers, 2001). These structures are highly characterized by having the shape and strength of a shell with double curvature (Douthe, Baverel, & Caron, 2006). Because of that, their loads are distributed to generate predominant forces of tension and compression type (Richard Harris, 2011)

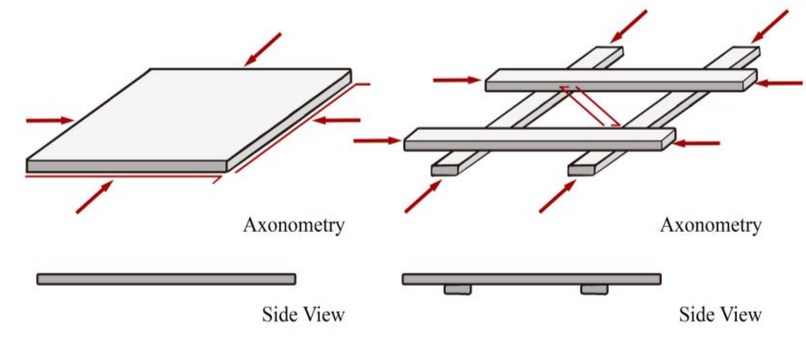


Figure 2.3- Continuous shell and grid shell elements(Glisic & Adriaenssens, 2013

Based on the different possible types of materials and the available construction processes, structural gridshells can be classified in two groups: structural gridshells of continuous or discontinuous elements (Dragos Naicu, 2012). See fig. 2.3 the main difference between these two types of gridshells is that the ones of discontinuous elements usually require individual nodal connections, that is, connections of different geometries due to the variation of the gridshell shape. In the case of continuous element gridshells, there is the possibility of standardizing the panel points leading to large reductions in the cost of the structure. Some examples of these two types of gridshells are given in Table 2.1 and one of each kind can be seen in Figures 2.4 and 2.5.

Table 2.1- Examples of continuous and discontinuous structural mesh structures (Dragos Naicu, 2012)

	Examples	**Material**	**Place**
Structural shells with continuous elements	Mannheim Multihalle	Timber	Mannheim, Germany
	Japan Pavilion	Cardboard	Hannover, Germany
	Experimental pavilion	Fiberglass	Institute Navier, ENPC, France
Structural shells with discontinuous elements	Pods Sports Complex	Timber	Scunthorpe, United Kingdom
	British Museum Great Court Roof	Steel	London, United Kingdom
	Smithsonian American Art Museum	Steel	Washington DC, USA

Figure 2.4 - Structure with discontinuous elements, The Pod Sports Complex (Archello Site, 2015)

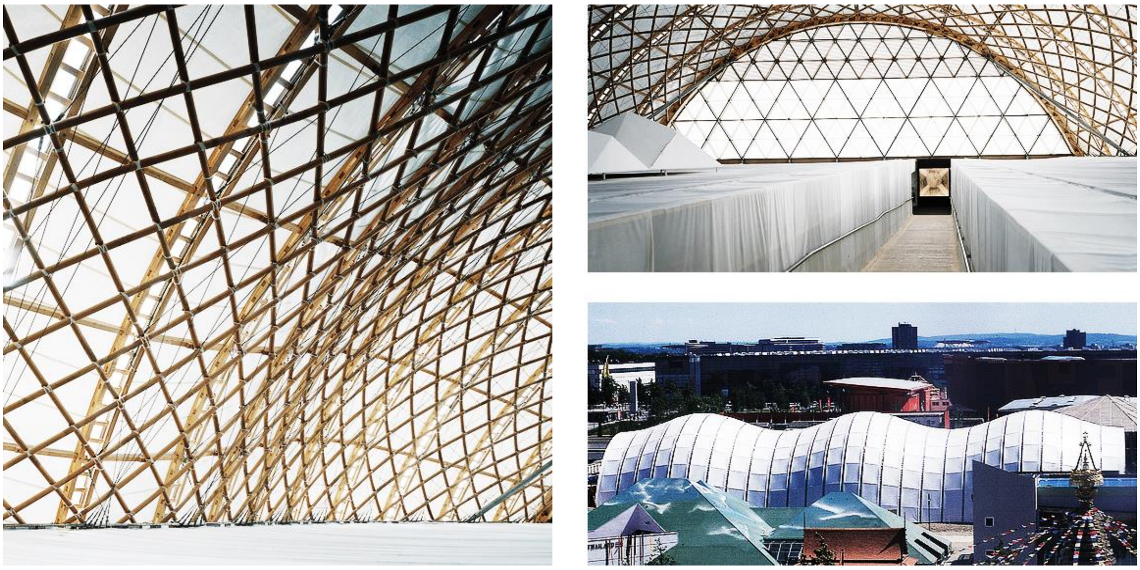


Figure 2.5 - Structure with continuous elements, Japanese Pavilion (Detail, 2016)

A gridshell is a natural, extremely strong structure that, apart from being a shell structure which advantageously benefits from its geometry to become self-standing, it can also be lighter, cheaper and a saving material resources. To make it simple, a gridshell is essentially a shell with holes, with structural system concentrated into strips. Basically, shells are where 'material has been removed' in order to create a grid pattern ("Weald and Downland - Open Air Museum," n.d.). Whereas in a plain shell an infinite number of load paths are available, in a gridshell the internal forces are carried by members and therefore must follow a restricted number of paths. It is possible to understand what a gridshell is, by observing small objects of everyday life. A colander is a curved surface structure. It contains holes for draining food, but these holes do not stop it from being a shell. It is a continuous surface with a relatively small area removed. A sieve is very similar, except that the surface is made from a large number of initially straight wires which are woven into a flat sheet and then bent into a hemisphere. It is also a shell, a gridshell. There are some similarities between a sieve and a spider web – they are both lattice-like and are intended to catch things. The spider web is essentially flat and made up of straight elements and when the wind blows, it bows outwards like a sail and becomes curved. It therefore adjusts its shape to the loading. We call this a 'form-active' structure.

This feature is characteristic of tension structures. The sieve may be in tension, compression or a mixture of the two, but it appears rigid. It does not significantly adjust its shape to the applied load and, therefore, we call this a 'form-passive' structure. When it is in compression, deflections affect the structure by making it less capable to carry the load, possibly leading to buckling. Columns carry loads via axial forces. but bending stiffness is required to restrain from stop buckling. Simwith shells, buckling is resisted by a combination of bending and in-plane action (Michalatos & Kaijima, 2014). It is a three-dimensional structure that resists to applied loads through its inherent shape, enabling the load transfer largely through the membrane action of direct in-plan compression and tension. Shear stiffness is provided by adding diagonal members to triangulate the grid cells. (Paoli, 2007). This is easy to understand by observing the known geodesic structures that can be considered as one kind of gridshell. Gridshells can assume different curvatures at each of the two orthogonal directions and the wise use of geometry enables large areas to be covered by extensive.

They provide all the efficiency, with smart shapes. Gridshells are also known as freeform domes, cupolas freestyle, structure shells, or reticular domes. The *Geometrica* calls his gridshells "Freedoms", his trademark for these structures, are in use since the mid-1990s ("Geometrica," n.d.).

2.1.1 **History of the gridshells**

Robert Hooke, a British engineer and scientist, published the earliest known examples of the inversion method in 1676. He published these as ten different inventions, where the most know today is Hooke's law of elasticity (Figure 2.6). The gist of these inventions was a simple idea. Which was later published by Richard Waller (1705)- "*Ut pendet* *continuum exile, sic stabit contiguum rigidum inversum. (As hangs the exible line, so but inverted will stand the rigid arch.)"* (Hooke, 1679).

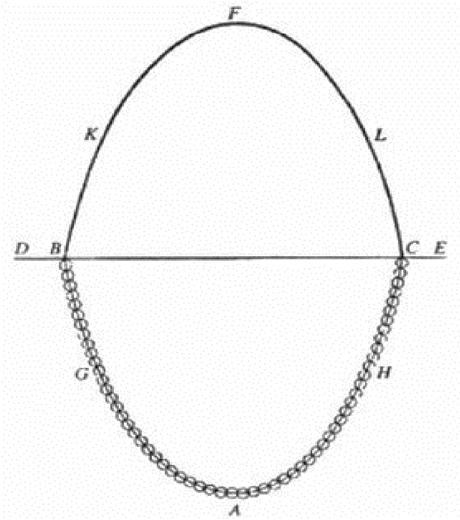


Figure 2.6– Sketch of Hooke´s hanging chain principle by Poleni, (1748) (Block & Ochsendorf, 2016)

Invert the shape of a hanging chain, which by nature will be free from bending forces and only have axial tension forces. This will result in an arch with pure axial compression forces, see figure 2.6.

A model-based form-finding method, was a common approach used by for Frei Otto and Heinz Isler which are the pioneers of membrane and shell structures. With the rise of simulation strategies and computational tools, a new design approach by using numerical form finding in architectural systems is getting more recognized by structural engineers and architects. A numerical method makes use of the digital simulation techniques to analyse the elastic bending deformation, which enable full control of the material behaviour based on the geometry(Analysis, 2017). In this way, the best elastic timber gridshells are obtained, the use of few material and technical resources to build a thin structure, light and with great behavioral efficiency.

In the centuries that followed Hooke's law, this simple suspension chain has been used to understand and inspire numerous works of architecture and engineering design. In 1748, Poleni applied this system to prove the stability of the Dome of St. Peter, in Rome, despite the existing southern cracks. A simple model was made by hanging a flexible chain with uneven weight proportional to the weight distribution in the arch and lantern. From the use and development of these models, two decisive personalities are mentioned as they exercised a great influence on the contemporary application of these techniques: the work of Antonio Gaudi and the innovative light structures created by Frei Otto (Roudavski, 2014). In the late nineteenth century, Antonio Gaudi devoloped his own method for creating masonry compression structures, by extending the use of models hanging from very complex chain three-dimensional structures. For the *Colonia Güell* chapel, he made a funicular three-dimensional model using ropes and small bags of shot pellets, representing the different weights of each element, which gave him a stable arrangement of masonry columns and vaults, see Figure 2.7.

Figure 2.7- Colonia Güell, funicular three-dimensional model (N. M. Larsen, 2012)

This is a process where geometry is stabilized by the generation of forms (form-finding) a technique that ensures static equilibrium.

The first recorded built gridshell is from the 19th century (1896), was created by a Russian engineer, Vladimir Shukhov (Fernandes et al., 2016) (see Figure 2.8). He draw the first hyperboloid structure, a construction which was displayedin the pavilions of the *All-Russia industrial and art exhibition*, in 1896, in Nizhny Novgorod (Graefe, 1990).

Figure 2.8- Pavilions built for the Nizhni Novgorod exposition (Edemskaya, 2014)

Two pavilions of this type were built for the Nizhni Novgorod exposition: one oval in plan and one circular. However, only the structural related this system is to this subject, since it was not built in timber but in steel. Since the 1880s, Shukhov was trying to solve the design of a roof system by optimizing materials, time and labour during construction. In 1895, Shukhov submitted the claim for a patent on steel lattice coverings in the form of shells. They were used to build hanging coverings and lattice vaults with big spans. The development of these lattice coverings marked the creation of a completely new type of structure (Edemskaya, 2014). The patent of this system, for which Shukhov applied in 1895, was awarded in 1899, his work represented a significant step forward to the development of these structures. Christian Schadlich, a German architect, notes that Shukhov's structures finished the efforts of 19th century engineers to create new and original metal structures (Graefe, 1990). The construction of these types of structures was very commonly used in vaulted ceilings. Was observed with this construction solutions. During the twentieth century a significant evolution. Between 1912 and 1939, different types of shell structures were derived from the domes and vaults (Bechthold, 2008), and were developed due to the growing interest in its free form and the ability to cover large spans in a time, where there was a large construction boom with new factories, warehouses and aircraft hangars (Dragos Naicu, 2012).

In the early 20^{th} century, reinforced concrete had a particular application in order to investigate models linked to the development of concrete shells, a leading innovative way that has emerged with the appearance of new materials. Since Dischinger and Finsterwalder reservoirs in the early twenties, the historical development of concrete shells are linked to some of the most important engineers of the 20th century, such as Pier Luigi Nervi, Eduardo Torroja, Ove Arup, Nicolas Esquillan, Heinz Isler and the architect Felix Candela (Larena, 2009). These engineers set new structural forms that were appropriate for the characteristics and potential of the new material, establishing firm criteria for structural efficiency. Within this criteria, a particular form was established due to their efforts, where the structural characteristics of the applied material and the beauty of the building resides in optimizing its structural behaviour (Peerdeman, 2008). It is interesting to note that the Swiss engineer mentioned above, Heinz Isler, applied a wide variety of physical models and methods to generate free curved surfaces with reinforced concrete shells which have no geometrical or mathematical representation. The only satisfaction being a mechanical base in which the only stresses under gravity loads are of compression. Type in this technique, the work of H.Isler extended the range of possibilities in the field of concrete shells, offering greater freedom and geometric complexity, while preserving its structural efficiency and "natural" origin.

Later, mainly in the 60's, experiences with form were at their peak, and this type of solution was extended to buildings such as sports pavilions, schools, etc. (Dragos Naicu, 2012).

With this remarkable evolution of shell structures and the search for new structural forms, came the need to optimize these solutions. In order to make the shell structures lighter and, in certain cases, reduce their cost, the structural gridshells emerged again.

One of the most important names for this contribution was Walther Bauersfeld, who, in the late 20s, created the first geodesic dome, as the formwork for a planetarium in Germany. Inthis century, Buckminster Fuller took part in promoting this structure (“Weald and Downland - Open Air Museum,” n.d.). Already halfway into the 60s, Douglas Wright (founding director of *Geometrica*) published an article about *the design of gridshells, Membrane Forces and Buckling in Reticulated Shells*, in the Journal of Structural Division of the American Society of Civil Engineers. He explained how these beautiful structures can be designed based on the principles of mechanics, even before computers were powerful enough or able to play a role in the process (“Geometrica,” n.d.).

During this time, this matter became widely discussed and allowed for the rational use of this structural form. In the years following Douglas Wright's seminal research, computers were made available and gridshell construction became popular. Architects from around the world could now imagine and design amazing curved surfaces, extending for hundreds of meters, without intermediate supports ("Geometrica," n.d.). Light is brought into the interior space as never before thanks to the lightness and thinness of metal gridshells. Although, there is still one problem that prevails regarding the use of gridshells; its structural efficiency does not translate well into cost efficiency. It was very difficult and expensive to manufacture and assemble structures with hundreds of thousands of components, in which each part is different from all others. Due to this, and despite its potential, gridshells were often limited in their use in high-end projects with large budgets.

While using the research of Douglas Wright, F. Castano (father of the *Geometrica* CEO) and Wright collaborated on several gridshells of hyperbolic paraboloids in the late '60s, including the Mexican Pavilion at Expo 67, in Montreal, the Mexico City Sports Palace, in 1968, and on various other exhibition buildings. Perhaps the first real gridshell freeform was the Toluca Auditorium. The architects were Gallo and Azorín, and Wright and Mr. Castano the engineers. It was designed as a rectangular building plan, with an arbitrary, non-algebraic lattice surface that had a continuously variable radius of curvature. The Castano Company, the forerunner of *Geometrica*, built this remarkable gridshell in 1967. The result was impressive. It won the National Award for Architecture, in Mexico, in 1967. The *Geometrica* carries this heritage to this day, by building large and lightweight gridshells. The gridshells of *Geometrica,* base themselves on the three-dimensional structural behaviour to achieve the intended architectural goals as well as a budget on construction projects, as explained below ("Weald and Downland - Open Air Museum," n.d.).

Finally, the work of the architect Frei Otto, deserves to be mentioned in the field of tensile structures and light membranes, much of it developed in collaboration with the British engineer Edmund Happold. This type of structure has greatly influenced contemporary architecture and interest-form design engineering. Frei Otto was an architect who highly based his research on shapes that emerge of natural origin, (Figure 2.9) with the objective of creating of greater structural forms of efficiency with a minimal use of materials. For this purpose, he used various models to generate minimal surface tension structures, cable-networks or optimal compression forms. Much of Frei Otto's work was dedicated to lightweight structures, pioneering the development of new innovative structural types and architectural forms (Isaacs, 2013).

Figure 2.9- Natural origin and forms

Frei Otto has shown that science and beauty are essential parts of architecture and the co-operation between both components resulted in the desired tectonic built shapes. He developed a gridshell form finding process that involved hundreds of scale models. He developed a catalogue with several forms and shapes that the gridshells could generate when hanged. Just like Gaudi, Otto worked on scale models to see the behaviour of the grid he was working on (see Figure 2.10). The studies he did were about form and shape but also included architectural basic needs such, as space and light.

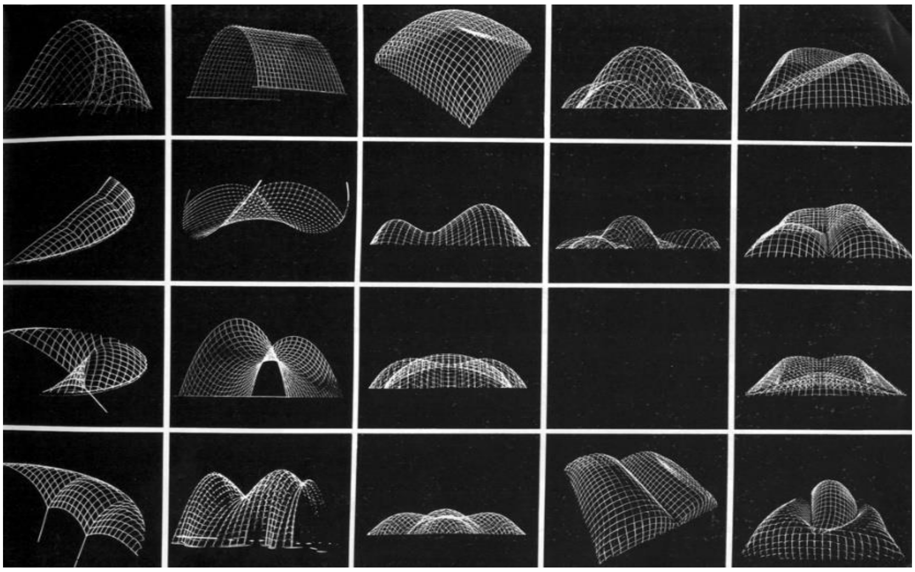


Figure 2.10- Frei Otto models experiences (Copeland, 1991)

In 1975, Frei Otto made a huge contribution, with the first recorded timber gridshell work the Manheim Multihalle Pavilion, which will be discussed later in this work. The Mannheim project in Multihalle comes at a time when Otto was already a experienced designer. However, this project led him to work with a new material: timber. This caused the work to be of great importance. Along with Edmund Happold, Otto proposed a continuous timber gridshell adopting a geometry-generated model with a catenary made from fine suspension chains. The purpose of using reduced scale models was to reduce bending stresses to a minimum in the hollow timber railing under its own weight, and in the process turning the rectangles of the starting grid into the shape of a lozange, which adapted itself more easily to the geometry free curve complex. However, for the final control of the geometric design and the structural behaviour it was necessary to use computer analysis too. The result was a continuous shell with a maximum spanning of 80 meters, with high degree of structural efficiency. He believed that the computer model could only calculate and verify what was already conceptually inside of it, only to find what was wanted to look for in computers, nevertheless, it is possible to find what we haven't searched for with free experimentation. Forty-one years later, and with several developments in the area of production and 3D modelling, we can now present workable models susceptible to find the accidental.

2.1.2 **Different Methods**

It is fair to refer that the existing software are just an extend of the work of Antonio Gaudi, Heinz Isler or Frei Otto, replacing the physical models by computational analysis. By these techniques as design tools, a logic is established relation between the architectural shape and its structural support in contemporary architecture.

This change in the applied methods does not make a big difference *per se*, since the main purpose and the general concept remains the same: to define or modify a shape to achieve a state of minimal stress and deformation, under the considered combination of load cases. Nevertheless, the greater speed and precision of analysis and calculation that computational analysis implies, gives a higher control of the model in this case. This control allows for the definition of more accurate shapes, since a small variation in the model can easily and precisely be considered, adapting the form in consequence. Besides, the possibility of quickly analysing the effect that a small variation in one of the parameters of the model might have in the resultant shape, turns computational analysis systems into powerful design tools, enabling to explore new possibilities or forms from different initial conditions. There is not a single optimum solution, but multiple, depending on the initial parameters considered. All these solutions can be easily explored and defined. However, the main difference between the historical and contemporary application of shape design methods does not come from the procedures applied, those are no more than a design tool, but from the different architectural and engineering contexts where their application takes place.

From the literature, it is possible to create a list 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 (Wehdorn, Roithmayr, 2003). 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 geometry, the material and in the reduction of the structural section.

According to the work of Richard Harris and Chris Williams (Wehdorn, roithmayr, 2003), and other important designers, it is easy to summarise the following approaches to the geometric design of gridshells: (1)*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 (Newton & Law, n.d.) catenary experiments. This process gives the designers information about node coordinates; (2) 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 can introduce in these reality simulation tools ; (3) a third option is a combination of the two methodologies and it was applied in the Weald and Downland gridshell (R. J. L. Harris, Mengsc, & Dickson, n.d.). This project confirms that there is still a need 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 (Richard Harris & Williams, 2014).

It is clear that all the designers should be familiar with the drawing tools, scale and proportions, the full and empty volumes and the atmosphere that they idealize, as it is possible to perceive 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 adjust the mismatches between the model and reality. Here, from the methods that were presented, it is important to explore, in this work, the digital techniques, such as (a)parametric design, (b) form-finding; and (c)digital optimization. Since the design problems defy comprehensive description and offer an inexhaustible number of solutions, the design process cannot have a finite identifiable end. Designing cannot be understood as a straightforward activity for problem solving, but rather as a solution-orientated process where expert input is required for identifying and evaluating complex design issues. Thus, computer technologies will facilitate the different phases of the project, from the moment of idealization, the proposal, the construction and the delivery of the finished object (Bechert, Groenewolt, Krieg, Menges, & Knippers, 2018). It saves time in a work that was exhaustive and non-practical, attaining better accurate results and easily transforms the implementation of ideas into something visual.

2.1.2.1 Brief history of parametric design

Parametric design is not an unfamiliar territory for architects. From the ancient pyramids to contemporary structures, buildings have been designed and constructed in relation to a variety of changing forces: technology, use, character, setting and culture. The computer did not invent parametric design, nor did it redefine architecture or the profession, it provided a valuable tool that has since enabled architects to design and construct innovative buildings with more precise qualitative and quantitative conditions (Architects, 2012).
Complex geometries and free form surfaces appeared very early in architecture – dating back to the first known dome like shelters, made from timber and willow about 400,000 years ago. Double curvature surfaces have existed in domes and sculptural ornaments of buildings through the ages.

Gaudi has studied Nature and transformed the organic forms into his use of ruled geometrical forms, such as, the hyperbolic, the paraboloids, the hyperboloid, the helicoid and the cone. Lined surfaces are forms generated by a straight line, as it moves over one or several lines known as directives. These forms are at the same time functional and aesthetic. He discovered how to adapt the language of nature to the structural forms of architecture and evolved from plane to spatial geometry, to ruled geometry. The questions for new structural solutions culminated between 1910 and 1920, when he exploited his research and experimented it in his masterpiece, the *Sagrada Família*, as mentioned. He conceived this cathedral as if it was the structure of a forest. Thus, achieving a rational, structured and perfectly logical solution, creating at the same time a new architectural style that was original, simple, practical and aesthetic.

The development of NURBS (Non-Uniform Rational Basis Spline) began in the 50s by engineers who needed a mathematical representation for free surfaces such as those used in car chassis, which could be used when they wanted. Previous representations of such surfaces only existed as a unique model created by a designer. The pioneers of this development were Pierre Bézier who worked as an engineer at Renault, and Paul de Casteljau who worked at Citroën, both in France. Real-time, interactive interpretation of curves and NURBS surfaces were only available in workstations in 1989. In 1993, CAS Berlin, a small business cooperating with the Technical University of Berlin, developed the first interactive NURBS for PCs, called NöRBS. Today, most computer graphics offers NURBS technology. This allows representation of geometric shapes in a compact form. They can be efficiently used processed by computer programs and still allow for an easy interaction with the user. NURBS surfaces are functions of two parameters mapped to a three-dimensional surface. Control points determine this surface shape referred to important a plane surface.

The field of architecture and engineering needed to meet the necessary conditions to follow, the advances made by the industry in relation to digital production, used in other areas such as automotive, aerospace and shipbuilding. These conditions highlight the importance of research in this pseudo-type, technique yet to be explored by the various stakeholders. Paradigm shifts, currently at play in contemporary architectural design, are fundamental and inevitable to displace many of the well-established conventions. During the 1940s and 1950s, practical needs in the aeronautic and car-manufacturing industries initialized the development of mathematical descriptions of freeform geometry. To solve tasks such as “how to store a surface design digitally “or “how to communicate a designed freeform geometry to a numerically controlled milling machine”, it was necessary to create appropriate mathematical algorithms that could be introduced into a computer. R. Liming and J. Ferguson at Boeing, S. Coons at MIT, M. Sabin at British Aircraft Corporation, P. de Casteljau at Citroën, and P. Bézir at Renault developed solutions for these tasks. In the case of CAGD (Computer Aided Geometric Design), the requirements for manufacturing drove the mathematicians – and led to the development of mathematical tools that could describe the types of freeform surfaces widely seen in products today.

In a digitally mediated design, as manifested in buildings and projects of F. Gehry, "digital avant-garde" past practice appear suddenly inadequate. All continuous and dynamic design models capable of consistent processing, are replacing static standards of conventional processes. Computer generated complexities lead to the abandonment of the predictive relationship between the project and its representations. Topological, curvilinear geometries are produced with the same ease with Euclidean geometries of flat and cylindrical, spherical or conical shaped forms.

Digital architecture is profoundly changing the design and construction processes. By integrating the design, analysis, fabrication and erection of buildings with digital technologies, architects, engineers and builders have the opportunity to reinvent the role of a "master-builder" and reintegrate the currently separate disciplines of architecture, engineering and construction in a relatively collaborative digital enterprise. Thus, reducing the "gap between design and production that opened when designers began to draw pictures," as noted by Mitchell and McCullough (1995).

2.1.3 **Timber gridshells**

At a first glance, a gridshell could be made of any construction material but the specificity of the construction scheme requires members to be flexible enough so that they can be handled during the construction phase and to acquire the final desired shape. Concrete or steel, even if they behave very well under axial stress, cannot bend easily. A concrete gridshell would have to be cast on site whereas the members of a steel gridshell would have to be assembled in a plant before the beginning of the erection. Steel and concrete gridshells normally require relatively expensive temporary formwork to achieve their final form. In the case of triangulated steel shells, it is also necessary to fabricate the nodes and interconnecting members to obtain a precise final geometry. Such requirements have obvious impacts on tolerance, cost and rate of construction and are reliant on the accuracies of CAD/CAM prefabrication at the nodes. Therefore, timber appears to be the most indicated construction material for these structures.

Timber gridshells are very efficient in spanning large distances with a minimum of material due to a fine stiffness per unit weight. Their load bearing efficiency results from the double curvature, which provides membrane action. There is less waste in material due to the shell behaviour. Furthermore, timber gridshells are in vogue and its advantages for quality space design and the new creative potential for designers are of great interest (Science, Trust, & Lowenstein, 2003). In fact, in the last few years, the timber gridshell has gained wide popularity. As it will be possible to realize by analysing the examples shown in the Figure 3.3 a gridshell can display elegance and style, with its slender ribs curved into shape (R Harris, Dickson, & Kelly, 2004). In parallel to the structural and technical evolutions, the use of timber gridshells has also changed. From being an architectural and structural statement in the context of renowned expositions, gridshells have evolved into a more commercial product. In fact, the outstanding aesthetics of a gridshell has everything to attract developers. These are lightweight solutions which are prefabricated and mass-produced, that ensure high standards of quality and cost control. Furthermore, these elements are also mounted with lute, allowing easy flow of product demolition / dismantling; taking advantage of the features already associated with timber such as "sustainability". The ephemeral character of this type of building is a great choice as an alternative to more conventional constructions.

2.1.3.1 Typologies of Timber Gridshells

All the variants of timber gridshells can cover large spans and ensure a high spatial flexibility. It is possible to design structural timber shells, starting from the knowledge of traditional techniques (e.g. basketry), using digital tools and industrial production. With these tools it is possible to optimize the shape and geometry of the spatial structure, creating new environments and bringing different language opportunities, which was more conditioned in the past.

The description of "timber gridshell" includes several kinds of structures belonging to this group. However, it is necessary to understand that they can take many forms and they can have different constructive and structural runs. Due to this, four categories were considered within timber gridshells, briefly displayed in Figure 2.11. There are the geodesic structures; reciprocal structures; unstrained gridshell, and the one that is the main reference in this research, elastic (timber) gridshells, as observed in Figure 2.11.

This organization considered the resulting geometry of each one of them, their constructive process, the structural behaviour and, finally, the different constructive details.

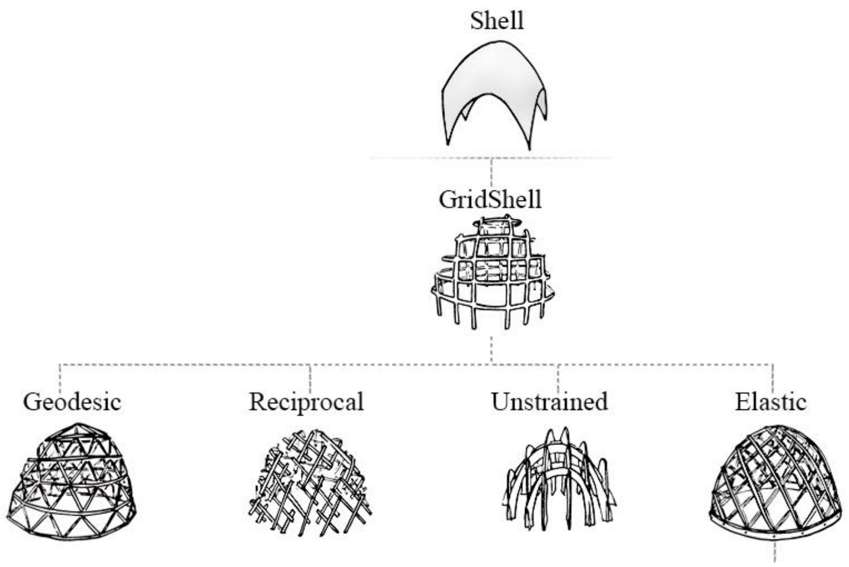


Figure 2.11- Framework of the structural system

2.1.3.1.1 Timber Geodesic structure

Geodesic structures are a very simple and high-quality spatial structures. Their design applications range from children toys to mega-structures containing settlements (Tarnai T., 1996). It is a geometric structure that supports itself without needing internal columns or interior load-bearing walls (see Figure 2.12). This property makes such structures very appealing for several applications like sports arenas or/and exhibition halls. The aesthetic appeal of lofty ceilings makes them attractive as homes and full or partial second-story floors, which are easily suspended halfway up the enclosure, without any support other than the attachment to the dome itself.

Figure 2.12- Geodesic geometries (Vrontissi, 2009)

In the 1940s, Buckminster Fuller widely explored the potential of spherical geodesic patterns for a new type of spatial structures, known as geodesic domes. He essentially explored its geometry, in which he tested different materials, including which timber. The primary uniqueness of Fuller's patented version of the geodesic dome is in the geometrical alignment of the individual structural elements in a geodesic pattern of close proximity circle arcs, intersecting to form a three-way grid (Wong, 1999). A geodesic dome is a hemispherical thin-shell structure (lattice-shell) based on a network of geodesics (great circles) on the surface of a sphere or a hemisphere. The geodesics intersect to form triangular elements, which have local, triangular rigidity and as such distribute the structural stress throughout the geodesic sphere. One of the differences in strength between a rectangle and a triangle resides in the fact that when pressure is applied to both structures, the rectangle will fold up and becomes unstable, but the triangle withstands the pressure and is much more rigid. In fact, the triangle is twice as strong. This principle directed Buckminster Fuller's studies towards creating a new architectural design, the geodesic dome, based upon his idea of doing more with less. Fuller discovered that if a spherical structure was created from triangles, it would have unparalleled strength. However, an important condition of the geodesic structure is its geometry, it is always approximate to a sphere ("Reciprocal Fram. Struct. Nat. Build.," n.d.).

The base of the geodesic structure consists of a ring element on ten poles directly located beneath a respective number of nodes. The assembly of the geodesic dome is basically composed of five identical sectors. Starting from the base, mounting is to be performed by levels, adding five identical pieces or geometric entities in each step, as can be seen in Figure 2.13. Subsequent tasks include the mounting of brackets, rings and plates (Vrontissi, 2009).

Figure 2.13- Scheme of the assembly of a geodesic structure (Vrontissi, 2009)

The constructive detail is quite simple and offers many options, from the use of metallic plates to pieces for embedding the elements (Figure 2.14). All the connections can be identical which facilitates the construction and makes it cheaper.

Figure 2.14- Examples of nodes (Vrontissi, 2009)

Geodesic gridshells can be considered as an already much-studied system with countless available research results. It is a system that works with different materials besides timber, with an inexpensive standard solution which is accessible and quick to construct.

2.1.3.1.2 Timber Reciprocal structures

The reciprocal structure is defined as a total of self-supported elements in a closed structure, a rather comprehensive but difficult to assimilate definition without a good drawing as an example. Reciprocal structures were proposed as an ingenious solution to the problem of covering a distance, or rather a surface, using elements of limited size ("Daruma Natural Building," (2014)). The grids are formed by elements with a smaller dimension than the span to be covered, with a geometrical arrangement, that enables a stable structure. As can be seen from Figure 2.15, there are several grid variations.

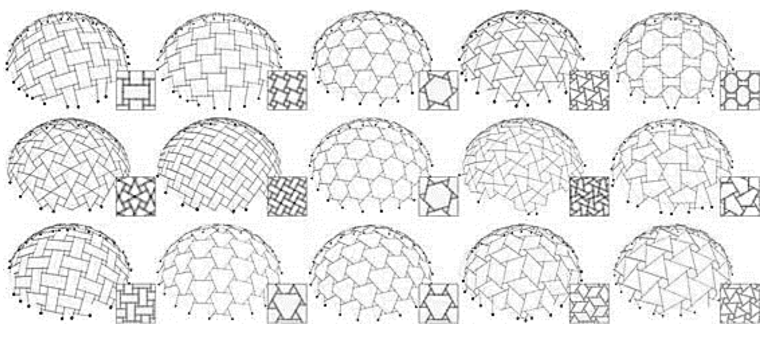


Figure 2.15- Variations of a grid pattern (O. P. Larsen, 2008)

A timber reciprocal structure is a class of self-supporting structure made of three or more beams and which requires no centre support to create roofs, bridges or similar structures (see Figure 2.16). A reciprocal structure is assembled by first installing a temporary central support that holds the first rafter at the correct height.

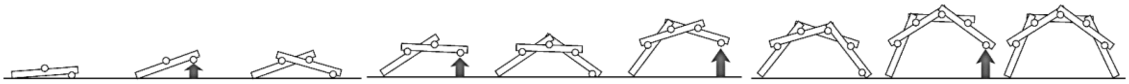


Figure 2.16- Assembly scheme of a reciprocal structure (O. P. Larsen, 2008)

The first rafter is fitted between the wall and the temporary central support and then further rafters are added, each resting on the last. The final rafter fits on top of the previous one and under the very first one. The rafters are then tied with wire before the temporary support is removed. The failure of a single element may lead to the failure of the whole structure (O. P. Larsen, 2008).

Systems consisting of beams mutually supporting each other have been known for centuries and numerous illustrations of such structural systems can be found (Douthe & Baverel, 2009). Reciprocal systems are not very common structures and not many designers and researchers are familiar with them. Due to their non-hierarchical nature, the geometry of reciprocal assemblies cannot be described conveniently with the available CAD modelling tools or by hierarchical, associative parametric models. The geometry of a network of reciprocally connected elements is a characteristic that emerges, bottom-up, from the complex interaction between all the elements, shape, topology and position, and requires numerical solution of the elements geometric compatibility (Kirkegaard & Parigi, 2014).

These structures are made from very low-cost materials and connections may be made in various ways, as slots or clamps, as can be seen in the examples provided in Figure 2.17. It can be appreciated that the complexity of its design does not use constructive solutions, as the links can be made from bolting, nailed, notched or tied solutions.

Figure 2.17- Connections examples.

2.1.3.1.3 Timber Unstrained gridshell

The simple, unstrained gridshells are assembled from prefabricated curved pieces just like a puzzle (see Figure 2.18). Its construction is very simple, but the pre-production of the elements and its idealization is more time consuming because of the amount and diversity of elements.

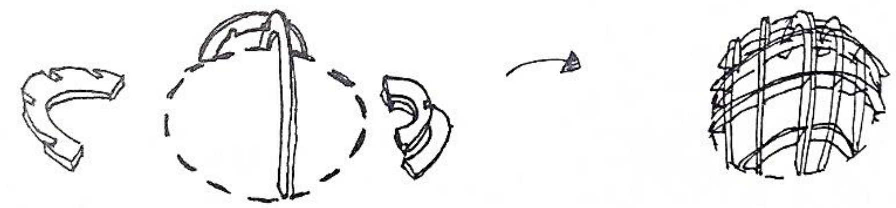


Figure 2.18- Assembly scheme

An unstrained gridshell differs from the strained system in that it is curved and unstrained in its initial state and is made from an assembly of relatively short straight or pre-bent members. The curvature can be induced in two ways. The first method uses pre-bent curved laminated timber. Alternatively, the members may be straight and the change in member direction is achieved at the nodes. The nodal connections have to be underline to prevent buckling, or the shell has to be consisted of more than one layer, producing a curved-space structure (Michalatos & Kaijima, 2014). Unstrained gridshells elements can be fabricated in the controlled environment of a workshop and assembled on site on false work tailored to the form of the complete shell surface.

The shape development of unstrained gridshells is often driven by a combination of aesthetic, geometrical, physical and constructional considerations. With computer-aided modelling tools at hand, more designers base their freeform work on aesthetic considerations that achieve scenography effects, in and around the shell (Figure 2.19).

Figure 2.19- Connections examples

2.1.3.1.4 Elastic Timber Gridshells

Finally, the main object of this research, elastic timber gridshells. This kind of structure, in addition to the above advantages of the timber shells, is also characterized by its innovative assemble scheme. The powerful concept that lies behind this grid is that the construction starts from a flat surface (see Figure 2.20). All structures can be assembled flat on the ground, to form a two-dimensional articulated mat. This means that, unlike the three previous types of grid referred, these can only be constructed in timber, since concrete and to some degree metal do not allow such bending. Timber allows the members to be easily bent into shape. Moreover, during the construction phase the members might be subjected to tighter radii of curvature than the ones they will have in their final state. The capacity of timber to bend without breaking and to remain elastic makes timber the recommended material (Paoli, 2007).

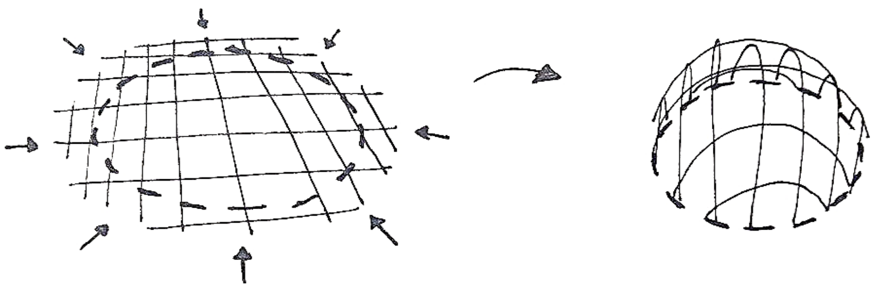


Figure 2.20- Assembly scheme of an elastic timber gridshell

The final shape is obtained very quickly by, for example, pushing or pulling thus deforming the material, and this is done without introducing any additional connection or structural member. Once in place, the surface having quite a small radius of curvature and the continuous members will act as arches. The final structure will thus benefit from the efficiency of both shell and arch scheme. In the same way as in a shell, the members of an elastic gridshell experience only axial forces.

This constructive system, not yet standardized, has shown that it has good mechanical characteristics and that the various components that make up structure have an affordable cost. However, it is expected that with a proper design all parts can be optimized both in terms of use, mechanical capabilities and price.

The timber laths naturally come in limited length, due to several reasons. To be able to carry out the construction it is necessary to make the connections, which can be the scarf, finger joints, screws, nails or straps (R. J. L. Harris, Kelly, & Dickson, 2003) (see Figure 2.21). As mentioned previously, not only can a gridshell be assembled quickly but the fact that the main connections are done on the ground and not up in the air is also a huge advantage. A more detailed survey of the node's solutions of these gridshells will be presented and explained.

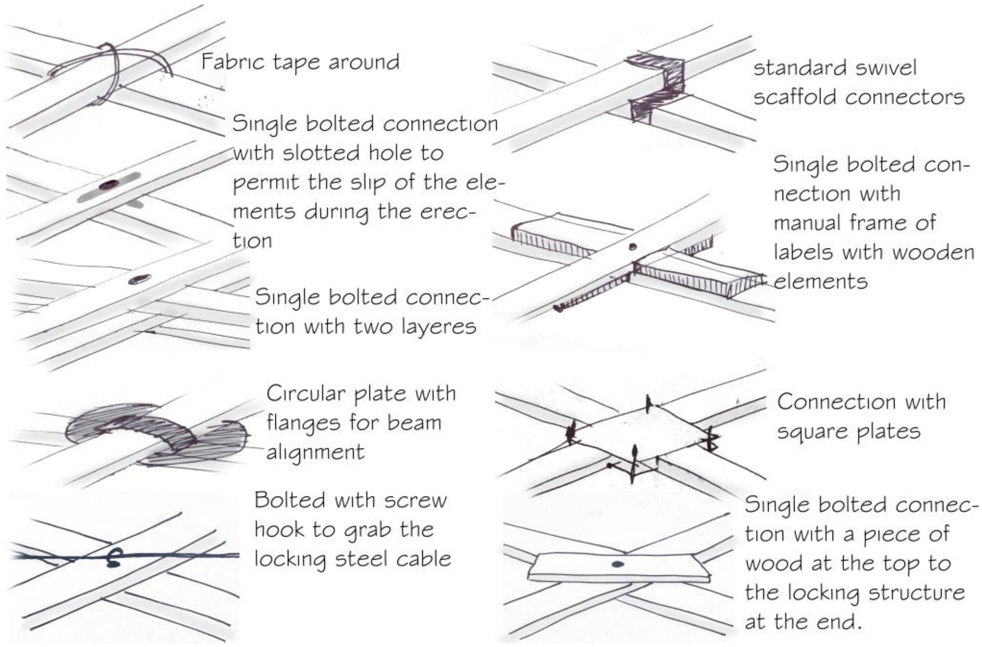


Figure 2.21- Connection examples

2.1.4 **Discussion**

The timber gridshell is an interesting structure from several points of view. Firstly, it has similarities to the conventional shell structures previously described; very fascinating building shapes can be achieved from an architectural point of view. Timber gridshells are also interesting special during the construction process, since less material is used. They are less expensive structures but still with many possibilities regarding the operation of building and the gaps between the members allow for many options of lighting. Despite all the advantages associated with the use of timber gridshells, except for the geodesic structures, very few have been built so far. Some sound reasons could justify why they are rarely found, since the forces that flow within shell structures are difficult to picture and, therefore, hard to develop strategies to counteract the greatest forces to be dealt with, such as wind or snow loads. Extensive analysis is needed to find the best fit geometry, an important step in the design process of a free form gridshell. One explanation for this may lie in the difficulties associated with the sub-project and the fact that its design process is still relatively complex, which prevents people from choosing this type of structure (Maarten Kuijvenhoven, 2009). The architect limitation in designing these structures lies primarily in the lack of digital tools and design (Pirazzi & Weinand, 2006). Still, the structural performance of a timber gridshell is so complex that even today, with powerful and affordable computers, there is still a place for physical model testing. The most rudimentary physical model can give more accurate predictions of deflections and buckling load than hand calculations. Due to the complex interaction between the membrane and bending action, the prediction of buckling loads by hand calculations is effectively impossible. However, the deflections and buckling loads can be calculated by scaling using dimensional analysis obtained from a physical model.

The designers need to challenge themselves and to experience designing this type of structure. It is necessary to give credits to those who have done it and give their contributions. In the last decade great architects have carried out these types of projects. In 2005, the well-known Portuguese architects Álvaro Siza Vieira and Eduardo Souto de Moura, were involved in the development of a proposal for the Serpentine Gallery Pavilion, where they designed a timber gridshell. Furthermore, these two latest big winners of the top prize of architecture, Pritzker, helped boost this constructive system. Laureate Shigeru Ban’s system was given this award, in 2014, and he is a defender and user of these construction methods, which works like the Tamedia New Office Building, in 2013, the Pavilion Japan, the Haesley Nine Bridges Golf Club House, in Korea, in 2010, and the Centre Pompidou-Metz, in France, in 2010. Frei Otto, who was a pioneer and already well-known author of more than one work in this area, received the most recent award. It can be concluded that there is a reduced number of built works. However, the existing examples are of great spatial and structural quality.

2.2 Summary

In this chapter an appraisal was made with an explanation regarding the history and techniques regarding elastic timber gridshells. The most remarkable designers were considered and their achievements. This framework searched for milestones, even if they are not about elastic or even timber structures. The attempt, to describe the historical path of this structures, ends with the definition of a structure and an architectural element inside of the bigger group of timber gridshells.

Right now, it can be mentioned that after the Multihalle much has been done, especially in the past 20 years, however many difficulties remain inherent to these structures primarily regarding their construction and design phases. The next chapters will address these questions.

3 Elastic Timber Gridshells

Elastic timber gridshells are described, taking into account their geometry and their structural behaviour. All the particularities associated with these structures will be presented, from the design methodologies to the construction methods. In addition to present some processes and methods already used to design these structures this chapter will also present some ideas about new tools and techniques that can be used.

3.1 Elastic timber gridshells

The known particularity of elastic timber gridshells is that they are not built in their final shape as outlined in section 2.1.3. The structure is first assembled on the ground, as a two-dimensional grid, and it is only during the construction process that it is lifted into the desired shape. The principle of the lifting process is to exert forces on the grid to deform it into the final shape. The same way as when one pushes on the edges of a sheet of paper to give it a tunnel or a hill like shape, the edges of the grid are basically pushed towards each other in order to match the predicted curve of the building (Paoli, 2007). Initially, the grid is formed from continuous, straight timber ribs connected with a uniform spacing in two directions. When flat, the grid with its scissor-pinned connections is a mechanism with one degree of freedom. If the grid members are totally rigid and connected with frictionless joints, the movement of one member parallel to another would cause a sympathetic movement in the entire grid. As a result, all squares would become parallelograms and the diagonal length between the joints would change. This grid distortion feature, combined with the grid's flexibility, is crucial to the assembling method, which shapes the initial flat grid into a three-dimensional structural surface (Collins & Cosgrove, 2016).

Despite the lack of knowledge, elastic timber gridshells overcome many of the difficulties through their specific construction system and sequence: the lattice can be initially laid out as a flat grid bolted/screwed together and then manipulated into the desired final shape. The development of the doubly curved shell form during the erection process, derives from an initial flat form, square or rectangular grid, which is possible because of the low out-of-plane bending and torsional stiffness of individual timber lath members, added by free rotation at the nodes, along with bending and twisting of the individual laths. Once formed, membrane shell action is accomplished by additional a bracing, which block the structure to provide in-plane shear strength. By bending the stiffness of the individual members helps resist the out-of-plane bending under asymmetric (non-funicular) loads from wind, snow, earthquake, etc. Often, this requires an increase of the number of layers of lath and interconnecting action across the layers of the lath (Dickson & Parker, 2015).

3.2 Examples

Although there are not many examples, it is important to present the first project carried out in 1975. Frei Otto, the Multihalle in Mannheim (Toussaint, 2007) (see Figure 3.1). The structure can be seen as a true pioneering work in the timber structure area. The geometry of the structure was determined by physical form-finding while it was constructed by pushing up the flat grid of laths by aid of scaffolding towers and forklifts. It is an exemplary and optimal case of study. Originally designed to last only two years, the structure was well received by the public and is still standing, proving that the gridshell is a solution that can have a multitude of uses.

The Multihalle is an excellent prototype of this construction method, being simple, economical and a revolutionary structure for its age. Today it still continues to be a source of inspiration (Toussaint, 2007). The project for the Multihalle Mannheim emerged as a result of a competition to host the Germany's Bundesgartenschau, a federal biennial horticulture show.

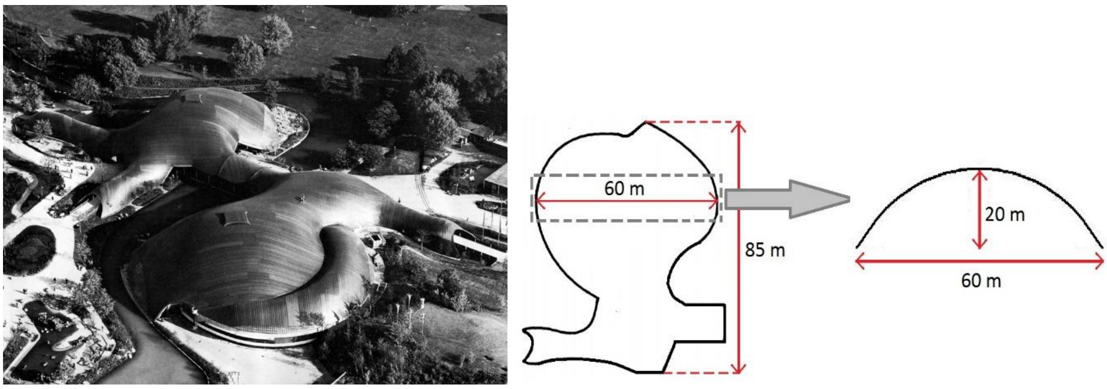


Figure 3.1- Mannheim Multihalle (Glisic & Adriaenssens, 2013)

It is essential to understand the root of their premises to make an informed analysis. The City of Mannheim was still in a post-Second World War rebuilding process and it was during this phase of reconstruction that the Mannheim Pavilion was planned and carried out. Frei Otto and architects Carlfried Mutschler and Winfried Langner embraced this project that aimed to revitalize the city and decided on a gridshell design after Otto agreed to serve as a consulting engineer for the project and its construction. Otto, as mentioned before, already had several previous experiences with raising gridshells, though they were on a much smaller scale than Mannheim's. The final design of the pavilion required a freeform roof covering three distinct areas, with the main hall (called Multihalle) measuring 60m by 60m. The construction of the pavilion began in December 1973, and the structure was gradually erected throughout April and June of the following year. The Mannheim Pavilion was successfully erected in November 1974. The garden was open to the public on April 18, 1975. The fact that it was lightweight helped reduce the overall cost of the project and thereby maintaining the building of the structure within budget (Glisic & Adriaenssens, 2013). The first dual-layer timber gridshell 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, Figure 3.2. The building has created international interest from the architects, engineers and carpenters. The project is relatively small (£ 1.3 million cost of construction), but appeared on national television, it was pre-selected for the Royal Institute of British Architects Stirling Prize of 2002 and was featured in the national press and on many leading trade journals. The project attracted so much interest, partly because of the unusual architecture of the building. The timber gridshell with dual layer technique, despite being able to achieve large spans with light construction, has rarely been used. It is also because many of the building features are innovative and can be adopted for future use or seen as example of how problems can be overcome and turned into an advantage (Richard Harris & Roynon, 2088).

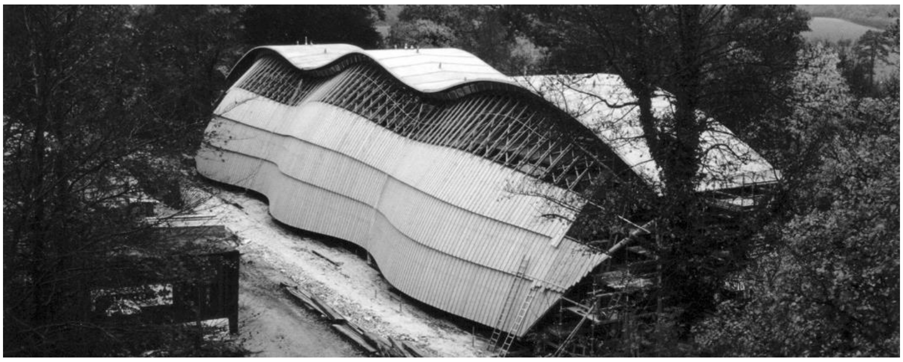


Figure 3.2- Downland to the Open Air Museum (Toussaint, 2007)

Besides Downland, there is a half dozen examples of the kind. After Mannheim was built, other good examples (see Figure 3.3) were designed such as: the Flimwell Timberland Enterprise Centre Modular Gridshell, by Feilden Clegg and Atelier One, in 2000; the Pishwanton Hand-Built Gridshell, by David Tasker and Christopher Day, in 2002; 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; the Gridshell pavillion for the Naples School of Architecture courtyard, by Andrea Fiore, Daniele Lancia, Sergio Pone, Sofia Colabella, Bianca Parenti, Bernardino D'Amico (Structural Consultant) and Francesco Portioli, in 2012; the Pavillion in Selinunte’s archaeological site, by cmmkm - architettura e design and arch. Bernardino D’Amico, arch. Andrea Fiore and arch. Daniele Lancia, in 2012; the SUTD Library Pavilion, in Singapore, by SUTD City Form Lab and engineers at ARUP Singapore, in 2013; the Tamedia New Office Building by Shigeru Ban, in 2013; the ZA Pavilion, a temporary cultural venue that was designed during a student workshop in Cluj, Romania.

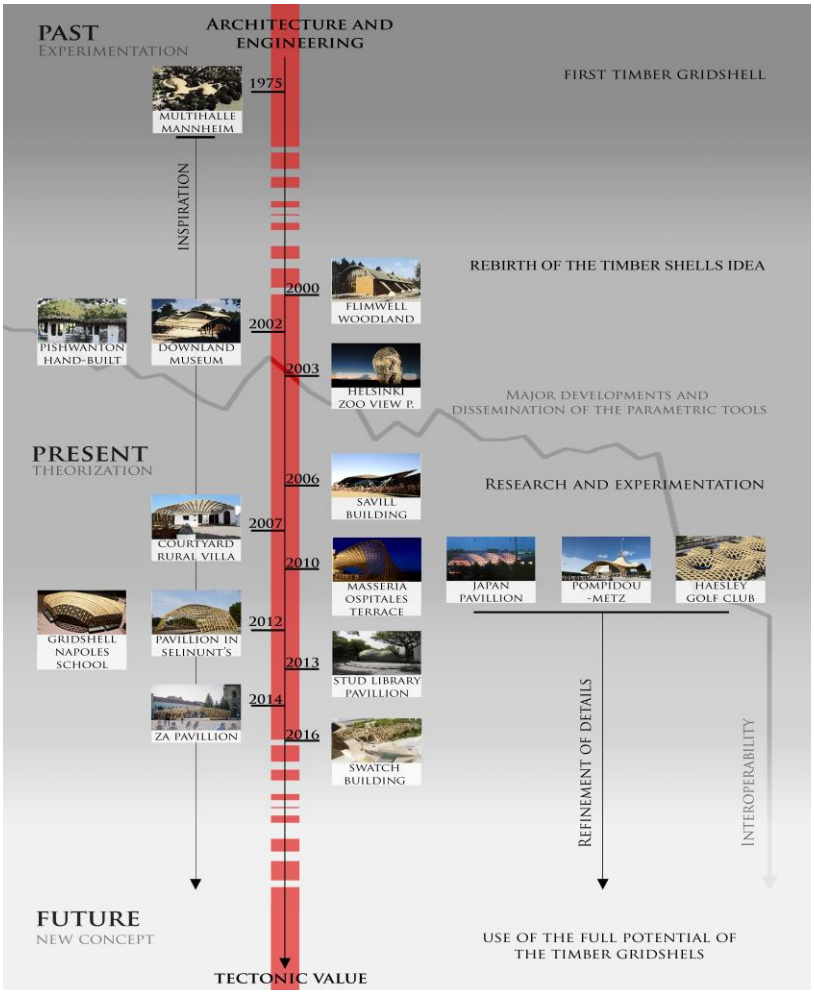


Figure 3.3- Elastic timber gridshells chronologically placed

3.3 Geometric and structural approach

Within this type of structures, it is still possibly going deeper and distinguish that there are differences between them (Figure 3.4). To define some subgroups, in elastic timber gridshells, it is necessary to understand which key elements could define the different assemblies of elastic timber gridshells.

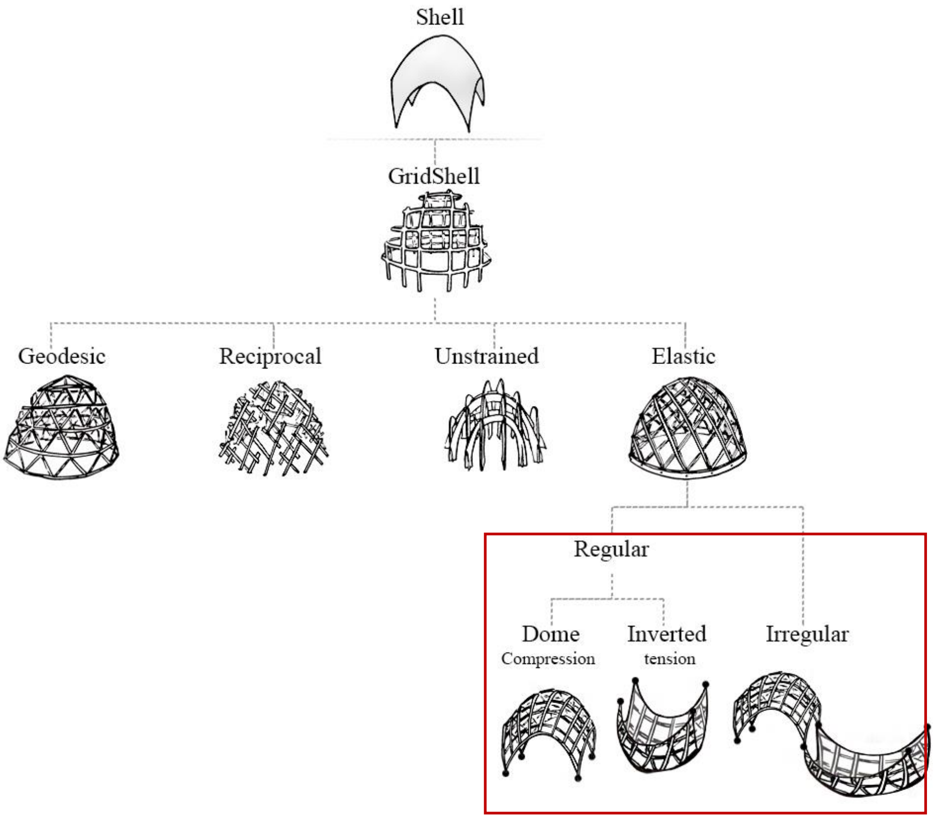


Figure 3.4- Framework of the structural system

It is necessary to understand the structural capabilities of these 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 elastic timber gridshells always work like a dome? What potential can be exploited? Does the design process depend on the size or the complexity of the shape? To understand the questions that rose, three concepts will be analysed with the purpose of representing the general and the cases. The different approaches has been made based on the gridshells geometrical shape, the structural behaviour (Hurol, 2016) 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 inside of elastic timber gridshells, which in turn are in the group of timber gridshells and these in the shell’s structures.

The approach concepts, as already mentioned, divides elastic timber gridshells into three groups, two within the gridshell 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 3.5.

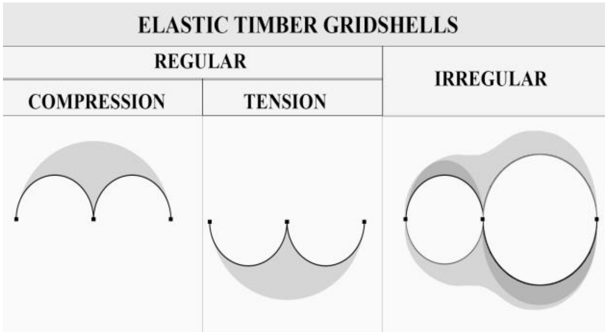


Figure 3.5- Subgroups, in elastic timber gridshells group

3.3.1 **Regular in Compression**

This division is complementary because it can distinguish elastic timber gridshells 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, which require more thought 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 the result of an informed discussion, pro-active between the idea and its materialisation. The different parts must 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* (see Figure 3.6) represents all timber gridshells with: i) at least one axis of symmetry in a section and a plan; ii) one or more lines of symmetry (symmetrical forces applied on opposite sides in order to apply force homogeneously); iii) work only in compression and iv) 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. This is probably why it is possible to find more examples of its application.

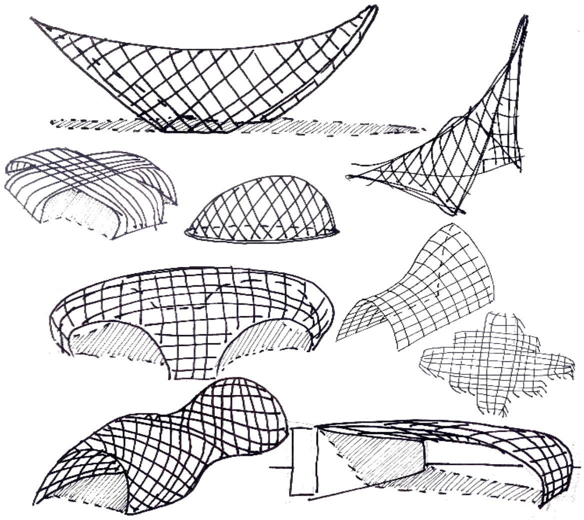


Figure 3.6- Regular in Compression examples

One of these cases is the Downland Gridshell (Figure 3.7). 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.

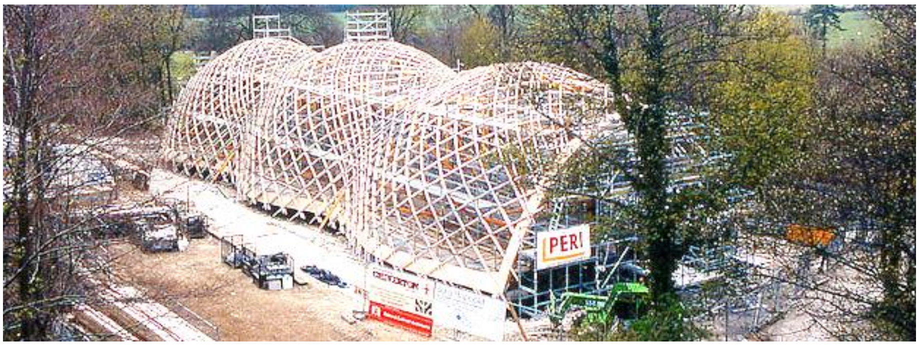


Figure 3.7- Downland Gridshell (Richard Harris, Romer, Kelly, & Johnson, 2003)

A recent example, ZA Pavilion portrayed in Figure 3.8, 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, 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 (Richard Harris & Williams, 2014).

Figure 3.8- ZA Pavilion (Richard Harris & Williams, 2014)

3.3.2 **Regular in Tension**

The second case, *Regular in Tension* (Figure 3.9) shows: i) at least one axis of symmetry in a section and in a plan; ii) a support or several supports grabbing the gridshell in order to create a homogeneous structural behaviour; and iii) it works only in tension, reached through the vertical mirror of a regular gridshell which can be suspended or hung. This typology presents a facet of timber gridshells that despite not yet having been explored in a real context; it 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, which would certainly be an ideal solution for new constructions and for interventions on built heritage. As mentioned, there are no records of construction of this kind of shell.

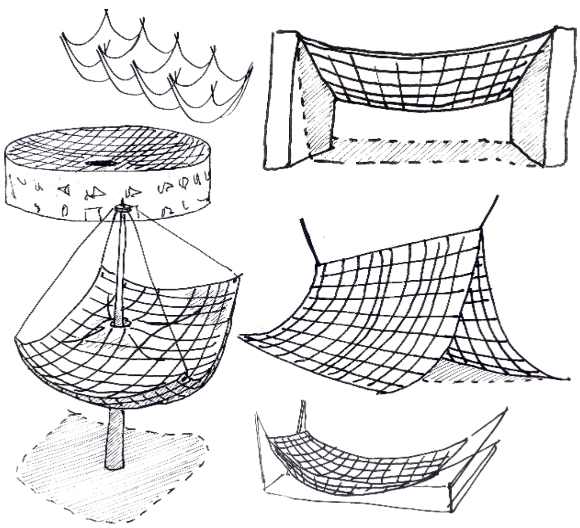


Figure 3.9- Regular in Tension possible forms

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. 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 it has been debated in this paper, Heinz Isler also believes that architecture and engineering are just two aspects of one thing (o. P. Larsen, 2003). Isler left a lot of work done in this area resulting from models that were used to find the most suitable form for shells.

3.3.3 Irregular group

Finally, the *Irregular group* (see Figure 3.10), more complex; represents 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; it often presents no axis of symmetry. The geometry presents a more complex and amorphous aspect than the first two groups. An example to identify these situations is the Pavilion of Manheim Multihalle (Figure 3.11), already enunciated for being the most famous example of a timber gridshell.

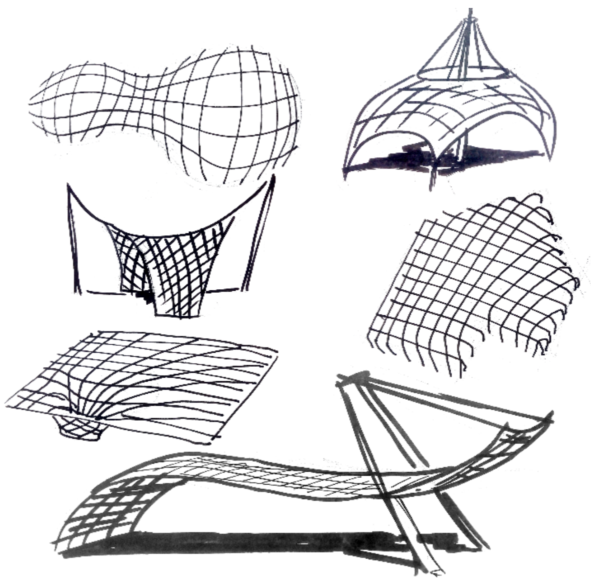


Figure 3.10- Irregular examples

This work of Frei Otto is today an icon in terms of timber gridshells. It has a strong and easily recognizable image, as shown in Figure 3.11. The geometry of the structure was determined by physical form finding and it was constructed by pushing up the flat grid of laths by aid of scaffolding towers and forklifts. Its idealization and construction were difficult (E & Liddell, 1975) but not due to the fact it was the first of its kind but because of its complexity and its scale; it brought great challenges to all project interveners, made possible only by the cooperation of all disciplines. Hence, as it can be seen to present day, timber gridshells with a more complex and irregular structure have a good performance and excellent results about the creation of outstanding atmospheres.

Figure 3.11- Manheim Multihalle (Verde & Truco, 2009)

A more recent and geometrically simple example can be observed in Figure 3.12, 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 timber panels creates a vaulted form with no internal walls or columns and is clad by 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 (Griffiths, 2013).

Figure 3.12- Sutd Library Pavilion (Griffiths, 2013)

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.

Design

Contemporary architecture takes advantage of the greatly increasing design possibilities. Construction technologies pose new challenges to engineering and design. Such challenges can be met more effectively with a solid understanding of geometry since it lies at the core of the architectural design process. It is omnipresent, from the initial form-finding stages to the actual construction. Making it fundamental to understand the broad historical conditions and actual processes of their realization in every aspect of their work.

The succeeding information outlines different steps and tools in the design process, from the idealization, sketches, models, form finding, optimization, to the constructive detail's decision, of elastic timber gridshells. This does not intend to suggest a work order and none of the tools / steps presented are mandatory to be used. It is only a summary of design methods that are considered important in the handling of this type of structures with complex geometries.

Although there is a shortage of sources in this area, the theoretical field has developed some research material around the designing of these 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 by a few already mentioned innovators (Frei Otto, Shigeru Ban). These are people that believed 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. There have been no other similar cases since the Multihalle Mannheim (G. Quinn & Gengnagel, 2014). Undeniably the digital tools have come to stay and help ease this evolution. However, there were and still exist other tools that are not accurate to be replaced by these, but rather complemented.

Because of this, we will next address some of them, such as free drawing, physical models and, of course, digital modelling and parameterization tools. It is intended to highlight the advantages that each tool can include in the design of Elastic gridshells, as well as, give different options to those interested in these structures. In this sense, some software's will also be approached and briefly described by way of example.

3.3.4 **Sketch**

The free draft serves to be aware of the shape, scale and definition of the space. It is a kind of preliminary test that allows to understand the adequacy and feasibility of the forms intended for a given context. There are great benefits to learning to draw freehand. Drawing without rulers or templates helps you build hand eye coordination and improves focus. Freehand drawing is also beneficial when drawing on site or when a ruler or template is not available for use.

Although the freehand sketch is losing space to digital design, it remains a fundamental tool. It is really the initial approach to a new project; it is almost a language, the form of expression that allows fluidity between thinking and the manual gesture that performs such thinking. A simple freehand drawing is the beginning of a whole technical process. It clarifies, orders, and structures ideas. It is a means of expression, of transmission of thought and the creations of the architect. It helps develop the surfacing of a first idea, in solving a problem and in modifying its architectural designs. This tool allows the exaggeration and the enhancement of the characteristics that are intended. However, one does not dwell on the exact representation, a kind of simulation, goes further and can be a representation of a concept.

Designers draw to present their ideas / solutions. The procedures use different tools and supports and produce different representations. By demonstrating, through graphical experiments their designs, the architects travel through various forms of representation derived from geometric tools and systems. In their training they learn technical, geometric, perspective, axonometric, etc. They select or incorporate, within these procedures of reasoning and representation, several images by which they develop their hypotheses and present their propositions (Dietrich, n.d.).

Architectural design is, in a narrow sense, a specialization of the normative technical design focused on the execution and representation of architectural projects. In a broader perspective, however, architectural design could be viewed as the whole set of graphic records produced by architects, these can be done during or not the architectural design process. The architectural design, therefore, manifests itself as a code for a language, established between the designer and the 'reader of the project'. In this way, their understanding involves a certain level of training, either by the designer or the drawing interpreter.

Regarding gridshells, freehand drawing has a huge advantage over other representation tools; the speed. The promptness of this process allows in a matter of minutes to unfold various experiences, be it in the plasticity search of the form or in the understanding of the structural operation. The fact that it does not need profound details, as sections, material, etc… which at an embryonic stage of any project is not yet decided; allows broader questions to be raised such as, the scale of the geometry and what are the desired proportions without knowing exactly - how to do it? with what? Etc…

This method also obliges the observation of the surroundings, which in a voluntary manner allows the designer knowledge of the context, and what the best inclusion of the project is in each specific place, creating harmony between the geometry and space.

Another feature of drawing in relation to gridshells is the integration of geometry methods to find their sinuous shapes. As it was referred before, in nature it is possible to find the more sinuous lines and even then, it is possible to decompose these complex lines and forms in simple figures, such as cubes, triangles and circles. Learning to correctly draw these common shapes will improve the capacity of deconstructing and creating complex geometries. Many designers begin their projects by looking for these shapes inside of complex objects and begin by drawing these shapes first. They then morph these shapes to create the more complex forms.

3.3.5 **Reduced scale models**

As previously shown, over the last few years many (inverted) models have been created to understand the shape of the meshes; their natural crudity. As the sketches, this is a tool that allows to explore various aspects. The physical models are a natural step in the design process. It is a volumetric, three-dimensional investigation with objectives different from those that a drawing has to offer. Here starts the understanding of the materiality; architecture gives space to engineering to give substance to ideas. In the Figure 3.13, below, it is possible to see a model emerge in a tank of water to facilitate the deformation of the grid without creating breaks in the elements. Demonstrating the clear importance of the link between geometry and the chosen material, emphasising how this can be a conditioning or a potential advantage.

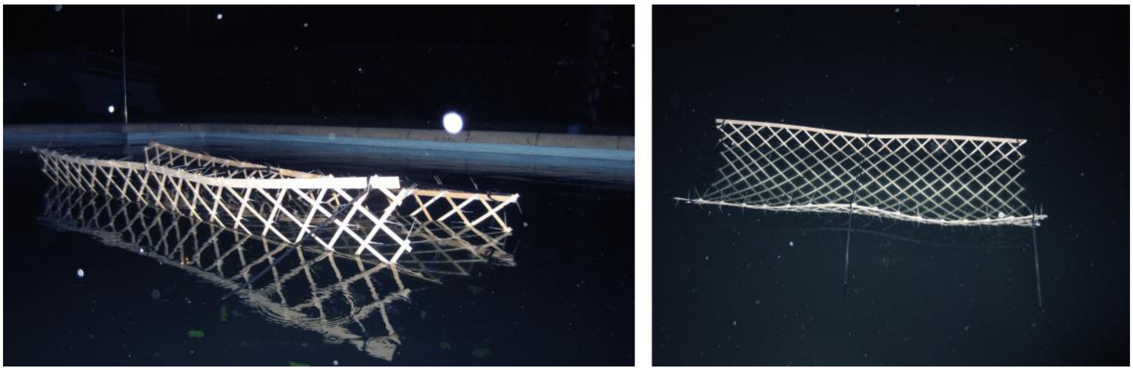


Figure 3.13- Water-submerged model to increase the flexibility of the timber

This process is the first approach to deformation of the plane (Figure 3.14) (Cosgrove & Collins, 2016). It will be possible to find several problems that may happen in the construction of the actual gridshell. However, in contrast to the construction of the real gridshell, these problems can still be achieved by redesigning the structure as well as by defining the constructive details.

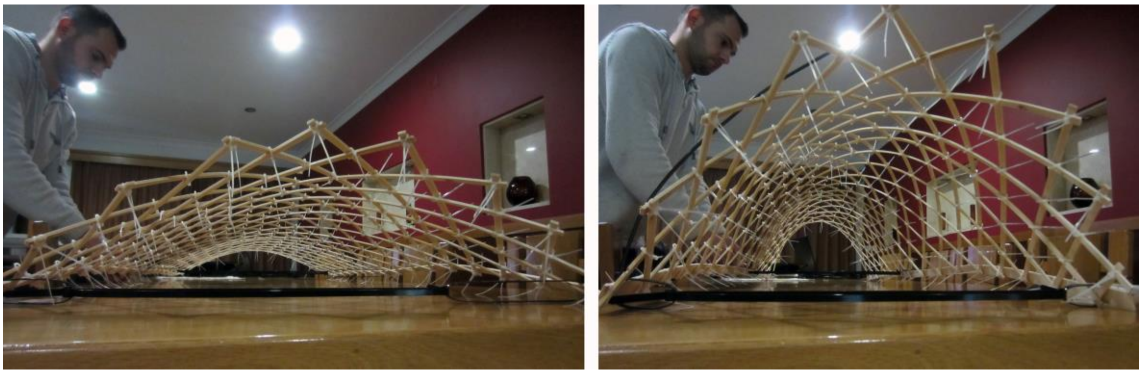


Figure 3.14- Deformaed shape model simulating the use of cables

The models, themselves, can be tested in long-term deformation simulations. Additionally, they can serve as a tool to understand how to dispose of a two-dimensional grid adapted to the desired three-dimensional shape, starting from regular and irregular perimeter grids. In Figure 3.15 it is possible to see the geometric deformation of an upright mesh based on a regular grid.

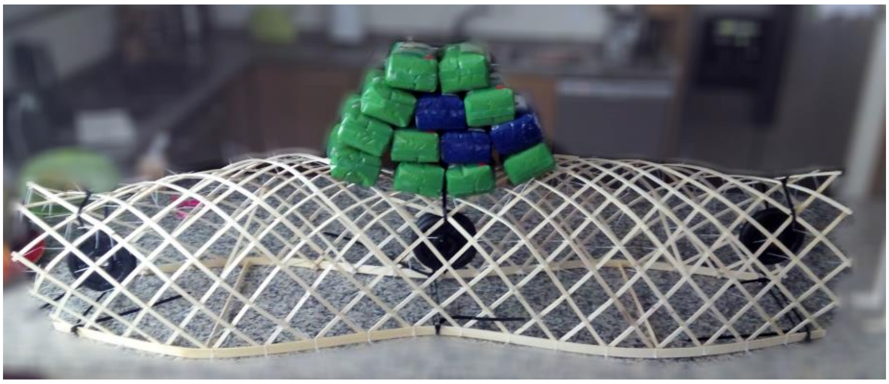


Figure 3.15- Application of weights in the model.

3.3.6 Parametric Design and Form- finding

After the choice of the overall shape of the building, form finding is the most important step in the design process (Kim-Lan Vaulot, 2016). In the case of gridshell buildings, the structure is the skin (the global external shape and the appearance) of the building. They cannot be thought as separate entities, they are a one and only element. In a typical design process, the shape of the building is optimized according to the architectural considerations and only then is the designed structure capable of supporting this shape. In the case of gridshells, both architecture and structure must be optimized at the same time. The form finding method corresponds to this process (Baek, Sageman-Furnas, Jawed, & Reis, 2018). This step consists on finding the most efficient geometry that can resist both the external loading and meet the architect's requirements. This phase is crucial since the better material that is used; the better the structure performs, which obviously leads to economical savings. Technical innovation and development can therefore be, during this phase, very meaningful and significantly impact the efficiency of the design.

During the past 50 years some extraordinary innovations and developments have occur in the digital techniques, creating a situation of architectural freedom where almost any imaginable shape can be solved and built. Leading to an increase in knowledge and control in computing, transforming the computer into a powerful design assistant, enabling the analysis, calculus and geometrical control of highly complex shapes with all kind of behaviour. However, this context of huge technical development contrasts with the fact that in this period no new materials and structural systems appeared with the relevance of the existing ones, which could suggest new shapes or typologies to be used.

Historically, shape-design methods have been used in a context characterised by the apparition of highly relevant new structural materials. In this case, shape-design methods were used as a powerful tool for the exploration and definition of new structural shapes and geometries, according to the characteristics and potentiality of the new structural materials.

Today geometrical, structural or constructive restraints are no longer a limitation on the definition of new forms. There is, therefore, a risk of incongruity between the architectural shape and its structural support that might have unfortunate architectural consequences. In this context, some engineers and architects propose to reconsider structural efficiency as a valid design tool, with the purpose of relating the structure and it shape within a rational mechanical basis. In these cases, there are usually initial shapes and design parameters that are taken as a starting point, that are then modified during the design process. This sets some initial, conditional design parameters such as height, volume, loads, support points or functional requirements, that use shape analysis methods, where the initial system can evolve into multiple directions, in order to optimise its structural behaviour. During this process the design parameters can be modified, the designers (architect and engineer) are able to choose the most interesting shape which results from these. There is not a unique optimal solution, there are infinite possible shapes that satisfy the initial design parameters, while respecting a state of minimal stress and deformation on the structure; a simple modification of one of the parameters can result in a drastic change of the shape. The purpose, therefore, is not to establish the optimal structure for a particular problem, but to apply computer analysis based on the efficiency of the structural behaviour as a design tool in the exploration of new architectural forms.

3.3.7 **Construction procedure**

3.3.8 **Erection process**

The following section outlines what has been done in the development of form finding, optimization, erection process and constructive details of elastic timber gridshells. The order in which the different phases of these processes will be presented are not necessarily in a chronological order. This research is concerned with elastic gridshells only, not just in its construction phase but also in the preparation up to this moment. It is extremely important to understand which aspects are considered before the construction in order 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 (Maarten Kuijvenhoven, 2009).

Although it is not common for most structures, in the case of elastic timber gridshells, one of the first steps is to define the constructive method to be used in the construction of the structure. Therefore, the influence of the constructive method, not only applies during the construction phase, but the whole design process. To carry out the process of idealization and design it is necessary to understand how the grid will be deformed, to be able to simulate the erection process of the same, that is, to simulate the constructive process.

As shown in the Table 3.1, below and in the figure 3.3, the processes were divided into three parts: Experimentation; Theorization; and New Concept. In the first part, Experimentation, a small historical approach will be introduced to understand the erection process of this kind of structures through the analysis of existing examples. Subsequently, in the theorization section, a theoretical overview regarding all the different ideas about the construction methodologies that are being explored, mostly academicals. Finally, the third part, New Concepts, where some ideas of the future of these structures will be presented, from its manufacturing and construction, based on the paths of other structures.

Table 3.1- Contruction processes

Construction process	***Experimentation***	***Theorization***	***New concept***
	Pull Up Push Up Easy down	Inflate Element by element constrain	Pre-fabrication Modules Robot

3.3.9 **Construction Process- Experimentation**

Elastic timber gridshell construction shows some limitations already at a 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 (Verde & Truco, 2009) leaving the costs and time to vary depending on the context.
As mentioned before, 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 (C. G. | G. Quinn, n.d.). This effect depends 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 enough 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 broke (Stuttgart, Otto, & Stuttgart, 1973). At Manheim quite a number of finger links broke on site during the erection process (E & Liddell, 1975). In the Downland gridshell, with 10000 connexions in the structure, there were around 145 collapsed bars during construction. Practically all were failures of the finger joints (Richard Harris et al., 2003). Finally, in the Savill Garden gridshell (Richard Harris & Roynon, 2088), 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 an increasingly slow and costly process (G. Quinn & Gengnagel, 2014).
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. Three of this way were already used/tested: "pull up", "push up" and "ease down".

3.3.9.1 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 gridshell was erected by means of a single mobile crane but also by timber stilts used to support the perimeter. This erection method, in Figure 3.16, 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 it 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 of its edge, must be provided by separate means. Typically, crane erection requires very calm weather and is only practical for small shells (G. Quinn & Gengnagel, 2014).

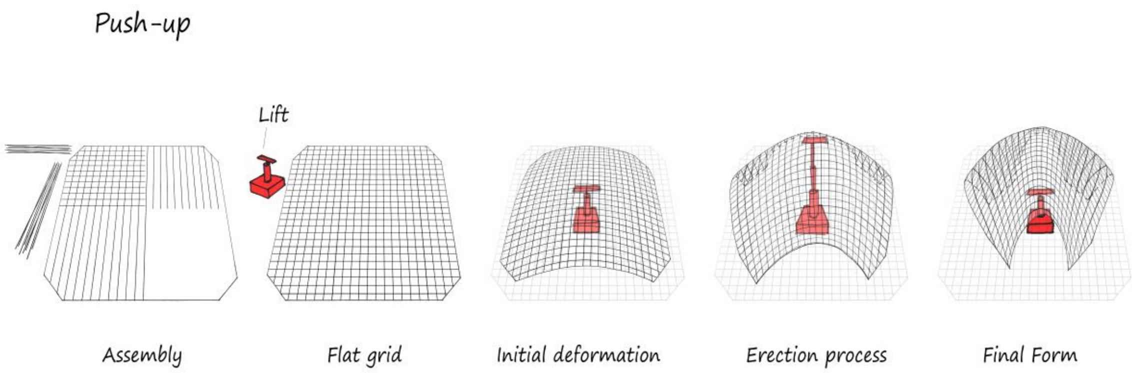


Figure 3.16- Push-Up. Erection process scheme

3.3.9.2 Push Up

Originally the Multihalle Mannheim was intended to be erected with four 200t cranes, but at the time a group of contractors and engineers devised a system of jacking towers 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 forklift trucks which were able to accommodate the necessary lateral translations of the lifting points. A key feature of the erection process (see Figure 3.17) 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 gridshell followed by the height adjustment of grid zones (G. Quinn & Gengnagel, 2014).

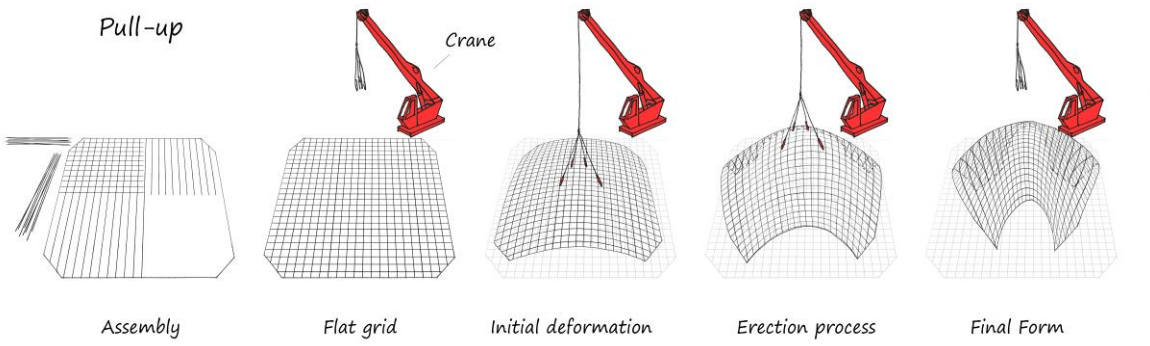


Figure 3.17- Pull Up. Erection process scheme

3.3.9.3 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 gridshell area, coupled with incremental and controlled displacement of the laths. The unique aspects of this method, seen in Figure 3.18, 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 (G. Quinn & Gengnagel, 2014).

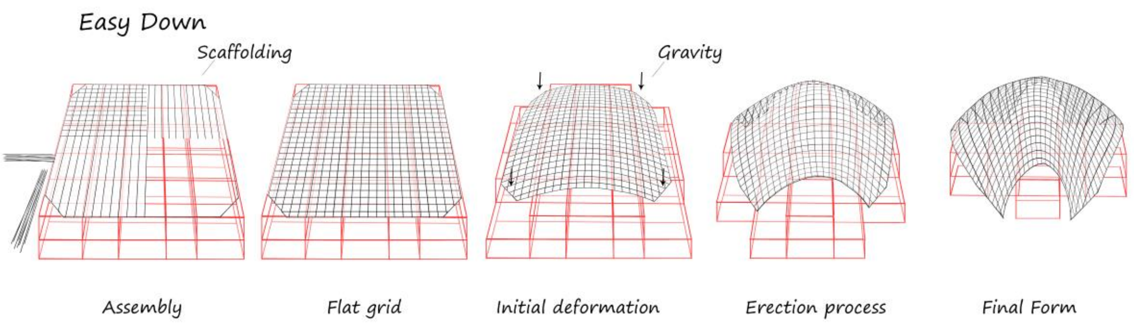


Figure 3.18- Easy-Down. Erection process scheme

3.3.10 **Present- Constructive process- Theorization**

Today, ensuring a new system can be risky, as it requires a large financial investment. So, it is necessary to evaluate and analyse the market and existing solutions, even on maintenance issues. It is necessary to choose the right timber, usually resorting to the anatomical-structural aspects, the observable macroscopic level, such as colour, aroma, weight, hardness, gloss and reflex. The identification and comprehension of each type of timber is very important to make the right choice, especially in this case with such a structural system. The designers need to challenge themselves and to experience designing this kind of timber structure. It is necessary to award merit to those who have done it and realize their contribution. In this past decade, some works have been carried out by great architects. In 2005, the well-known Portuguese architects Álvaro Siza Vieira and Eduardo Souto de Moura, have been involved in the development of a proposal for the Serpentine Gallery Pavilion, where they designed a timber gridshell. In addition, the recent big winners of the top prize of architecture, PRITZKER, helped boost this constructive system. Laureate Shigeru Ban's system was given this award, in 2014, and he is a defender and user of these construction methods, with works like the Tamedia New Office Building, in 2013, the Pavilion Japan, the Haesley Nine Bridges Golf Club House, in Korea, in 2010, and the Centre Pompidou-Metz, in France, in 2010. Frei Otto, who was a pioneer and already noted as the author of more than one work in this area, is the latest award. It can be concluded that there is a reduced number of built projects. However, the existing examples are of great spatial and structural quality. They are quite versatile to also be considered in rehabilitation, to create new buildings, roofs, small additions in non-structural elements and even partitions functioning as a mere architectural object.

3.3.10.1 Pneumatic Formwork

This method has not yet been applied to elastic timber gridshells. Therefore, it is only possible to conjecture some conclusions from its application to other systems/materials and from the empiric knowledge. It is possible to understand that the flatter zones of a pneumatic cushion are more capable of resisting vertical external loading with low static pressures than "steep" surfaces with small horizontal contact areas. Nevertheless, 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 gridshell must be developed in unison. The most critical challenges for the erection of elastic gridshells, by means of pneumatic formwork are mostly concerned with the following situations: stability and restraint of the gridshell 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 allowing the beam ends to be lowered to their supports via deflation in a controlled manner (G. Quinn & Gengnagel, 2014) (see Figure 3.19).

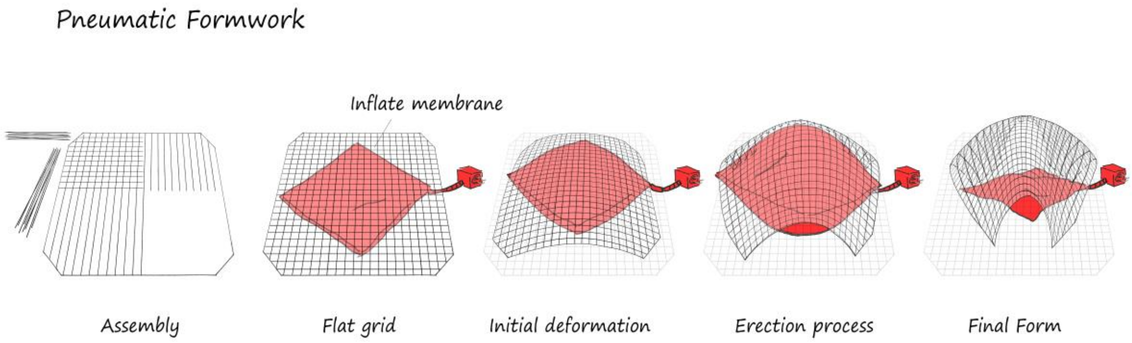


Figure 3.19-Pneumatic Formwork. Erection process scheme

3.3.10.2 By Recessing / Constraining

Now there are no built records of this system. 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 symmetry it is easy 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 needs to be fixed in two directions. Meaning it will require a greater care regarding the fixed points and the points where the force will be applied, so that the energy reaches the timber elements in a homogeneous way without applying peak loads on individual elements. This method wins by speed and because it can be applied in media with low resources to be low-tech (Figure 3.20).

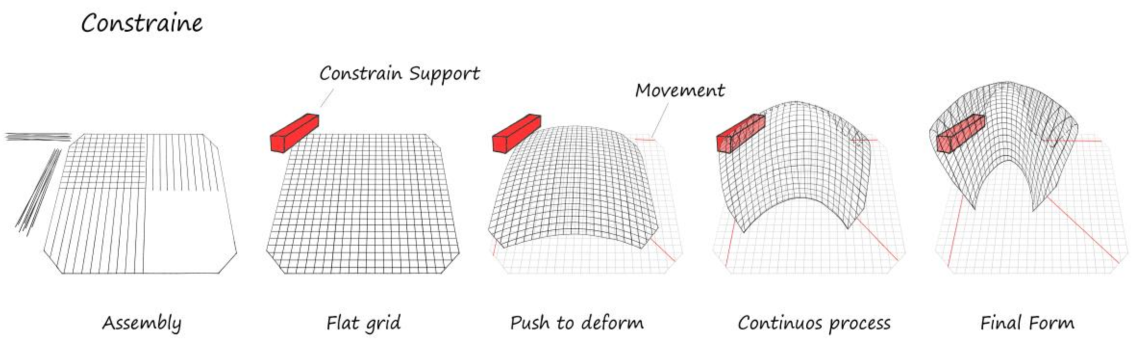


Figure 3.20-Constraine. Erection process scheme

3.3.10.3 Element By element

As the name itself indicates, this method works from the application of one element at a time. The principle is simple, just as the grid gains resistance by operating as a single surface, it also loses that advantage when it separates into individual elements. Thus, it is possible with much less effort / means to deform each element.

As illustrated in the scheme shown in Figure 3.21, this process can be performed from the deformation of all the elements in one direction, followed by a second or third direction but, it can also be constructed from the deformation and fixation of elements / parts interspersed of the gridshells. A great advantage is the replacement of elements that break during the construction.

It is possible to understand that this is a much more time consuming and laborious method, in which the gridshell only acquires the characteristics of a membrane after the deformation and junction of all the elements.

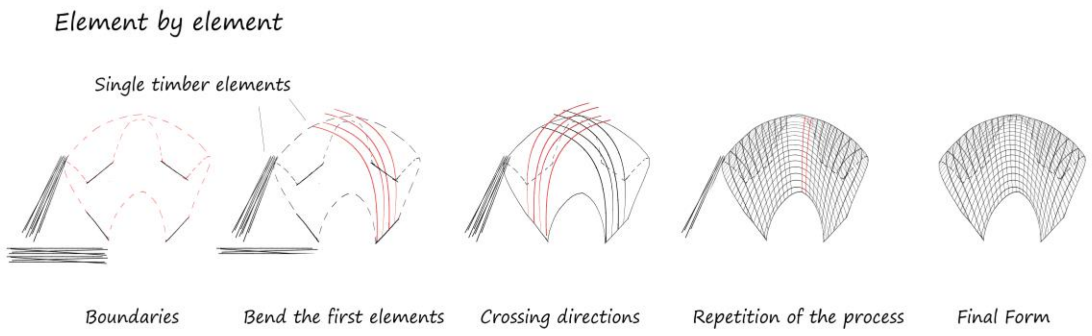


Figure 3.21- Element by element. Erection process scheme

3.3.11 **Construction Process- New concept**

3.3.11.1 Robots

It is necessary to explore how robotics could be used in the future, in the field of construction. Robotics is a synchronous combination of mechanical, electrical, and software engineering. It is a field that aims to better the lives of humans in tasks that are dangerous, dirty, or demanding. Construction is the process of creating or renovating a building or an infrastructure facility. In this area the goal is to find out how robotics can be implemented to carry out certain tasks and to identify as many robotics technologies as possible that can have some application in elastic timber gridshell construction, while also determining if any of these potential technologies can be integrated soon. This could potentially ease the construction process to make it safer for workers, taking up less time, or perform the simple tedious tasks (Figure 3.22).

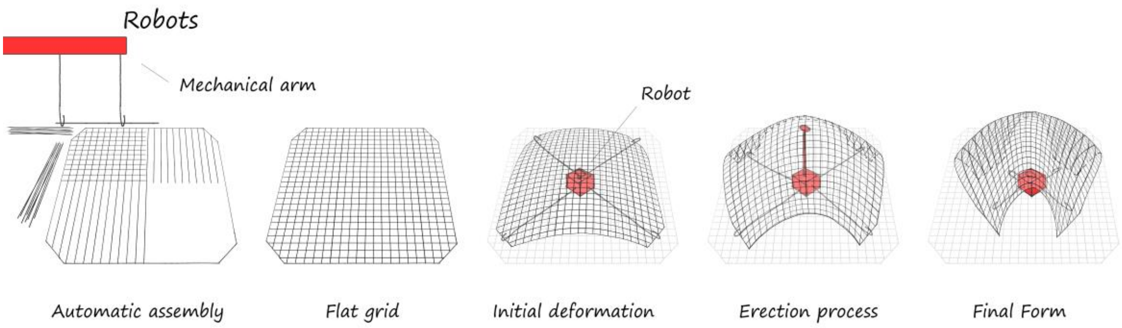


Figure 3.22- Robots. Erection process scheme

3.3.11.2 Pre-fabrication Modules

Like other materials and structural systems, timber gridshells are also potentially modular structures. Not necessarily as a whole (a dome) but also in parts previously intended and locked. Taking advantage of the rigor and quality advantage of products manufactured in standardized.

This is a theoretical process (Figure 3.23) that is still without examples, but here it is considered as a natural way for the future of this constructive solution. A solution with which you can create base pieces that depending on the fit or quantity could be derived in different spaces adapting to the contexts.

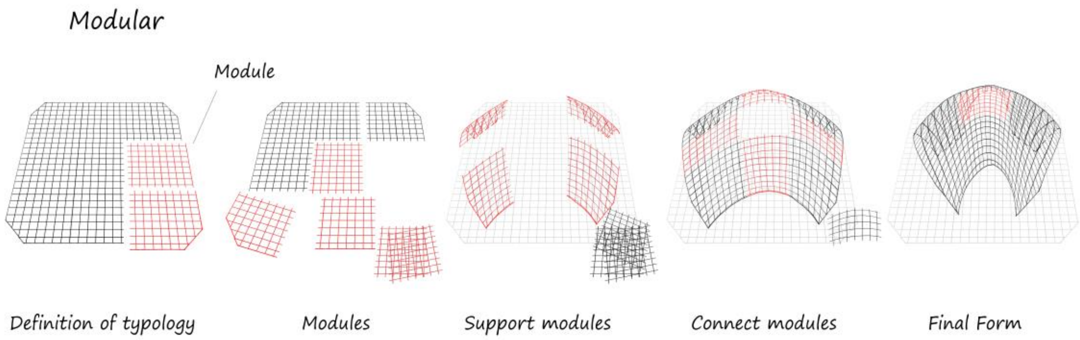


Figure 3.23- Modules. Erection process scheme

3.3.11.3 Build in the factory and transport to the site

Emerging in the robotic industry are the robotic drones. Drones are unmanned robots that are controlled remotely by human interface and are used to accomplish various tasks. They are very versatile, since they can be big or small, fast or slow. This technology can be applied in just about any field including construction. There are different types of drones (or other transportation method) that are directly applicable to construction practices: Contour crafting, transportation (Figure 3.24), surveying, and monitoring. This process may also be combined with the module process since large dimensions may be a limitation.

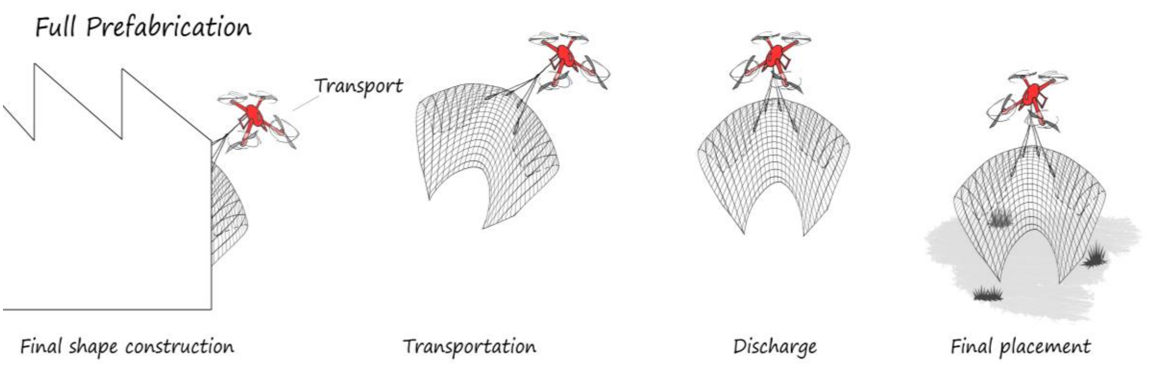


Figure 3.24- Full Prefabrication. Erection process scheme

3.3.12 Constructive details

3.3.12.1 Grid and Layers

If construction is the most important step in elastic timber gridshells it can be said that the grid is certainly the basis of the whole structure. It is the planning of the shell, a rare exercise since the other structural systems are controlled / assembled in three-dimensional form. In addition to the flexibility of the grill system, depending on the type of wood and the stiffness of the connections, it can bring even more flexibility to the construction. For example, parallelepiped base grid can obtain a regular perpendicular form or an organic shape as an '8'.

This is because the 'base grid' can vary in almost all its characteristics, the general dimension, the size of the grid, the distance between lines, their direction, the perimeter borders and the perimeter drawing, as shown in figure 3.25.

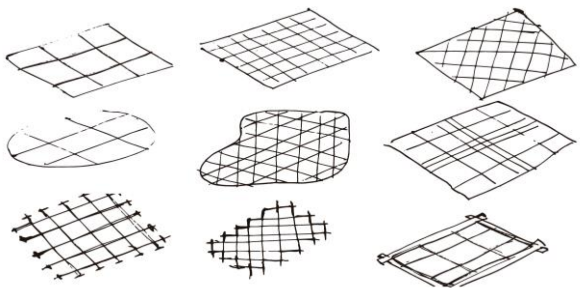


Figure 3.25- Examples of variations of a 'base grid'

The number of layers used is a decision that has a strong impact on the whole process, especially the construction phase. In the case of a single layer lattice, the stiffness of the structure during erection is close to the expected one for the final structure. Thus, the assumption the gridshell will stay in place without any additional support as soon as the boundaries are set. Only minor modifications or adjustments might be needed to arrange the overall shape of the surface or in order to minimize strain energy, redistribute some loads.

Now, considering a multiple layer gridshell, it cannot be assumed that once the edge of the shell is attached, the structure will stand and only need slight shape adjustments. In fact, the reason why multiple layers are used is because the collapse load of the gridshell was close to or even less than the self-weight of a single lattice. Additional layers are needed to provide the additional stiffness that a single layer lack. The temporary supports cannot therefore be removed before the connections between all layers are secured and that the composite action effectively occurs. As mentioned previously, different techniques can be adopted to erect the lattice from flat to doubly curve. Those procedures imply acting against the forces of gravity and require additional checking of the structure. During the temporary state, when the grid is being lifted and the boundary connections are not yet tightened, the members may be submitted to a greater stress than the ones they were initially designed for. Those additional stresses are due to intermediate stages, where the radii of curvature of certain members are greater than the final ones, including the extra bending induced in the members between two lifting points. Choosing one scheme over the other needs to consider parameters such as the size of the grid, the rental price of the equipment and the place.

The first designs of a structural gridshell of Professor Frei Otto were composed of a single layer, that is, two sets of slats, in two distinct, overlapping directions (Happold & Liddell, 1975). Subsequently, it began to develop double layer structural gridshells, through duplication of the previous system (Figure 3.26).

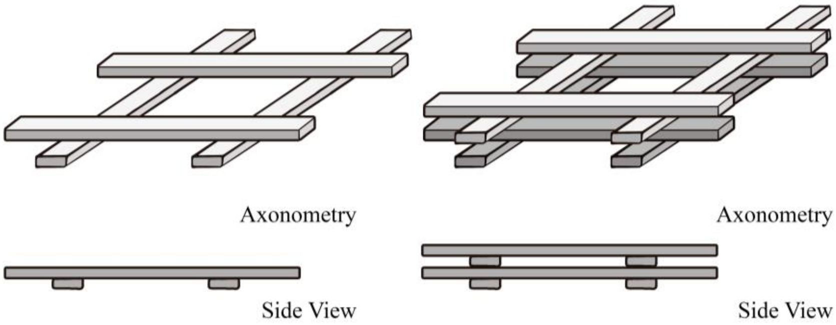


Figure 3.26- Single and double layer scheme (Dragos Naicu, 2014)

This solution arose since large spans require a greater stiffness to bending out of the plane, which would certainly cause breaks in the timber elements during the construction process. A problem that could easily be solved by increasing the cross-sectional area of the timber elements, but this would impair the execution of the constructive method, which takes advantage of the reduced section of the slats to achieve the desired curvatures. Therefore, the need for a larger section area and greater flexural stiffness has led to the idea of increasing the number of layers of the structure, a solution that fulfils these requirements, but maintains the desired flexibility of the elements (see Figure 3.27).

Figure 3.27– Elastic timber Gridshell “Alida Timber” (Gridshell.it, 2016)

In the case of the use of the double layer system there is a need to transfer cutting forces between the upper and lower slats. This transfer is achieved through the attachment elements at the nodes and the use of blocks of timber inserted between the upper and lower slats (Figure 3.28).

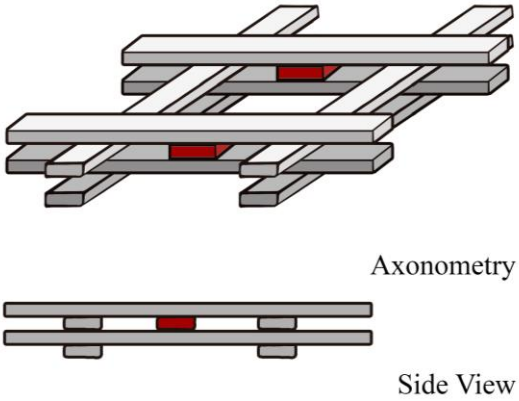


Figure 3.28 - Double layer system with blocks (Dragos Naicu et al., 2014)

In addition to this solution, the IBOIS laboratory of timber construction, École Polytechnique Fédérale in Lausanne, developed an alternative layering system, which consisted of several timber slats nailed to form a curved gridshell. This system was used in two projects, the Polydôme in Switzerland (Figure 3.29)(Natterer & MacIntyre, 1993) and the roof of Main Hall in the EXPO 2000 in Hannover, Germany (Figure 3.30)(Natterer, Burger, Müller, & Natterer, 2000).

Figure 3.29- Polydôme, Suíça (Henry, 2016)

Figure 3.30- Cover of the Main Hall in Hannover, Germany (Janberg, 2000)

3.3.12.2 Connections /Fixation

As mentioned before, another advantage of elastic timber gridshells is the use of identical connector elements throughout the structure. Nevertheless, the layered structural system requires a certain freedom in the connections (figure 3.31), so that the timber elements slide in between them. In addition, the elements require free rotation during the deformation process of the flat gridshell. These requirements had direct influence on the design of the links, where they would be capable to fulfil them without losing the stability of the structure.

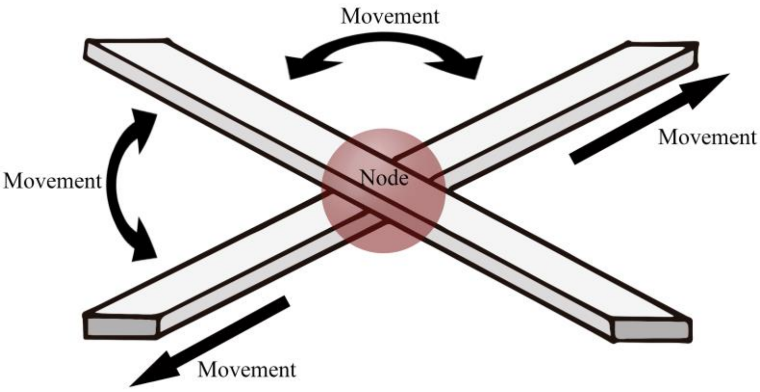


Figure 3.31- Allowable movements in the connection must allow

As it can be seen from the examples below in Figure 3.32, it is possible to create connections from different types of materials, and may require drilling, or not, on the timber elements. As already mentioned, the limitations of the connecting elements are associated with the deformation process of the flat gridshell, since they must be capable of allowing rotation in any direction while maintaining the base positions along the gridshell. Furthermore, when the gridshell reaches the desired shape it is necessary that the connections become fixed, not allowing the final geometry of the gridshell to change.

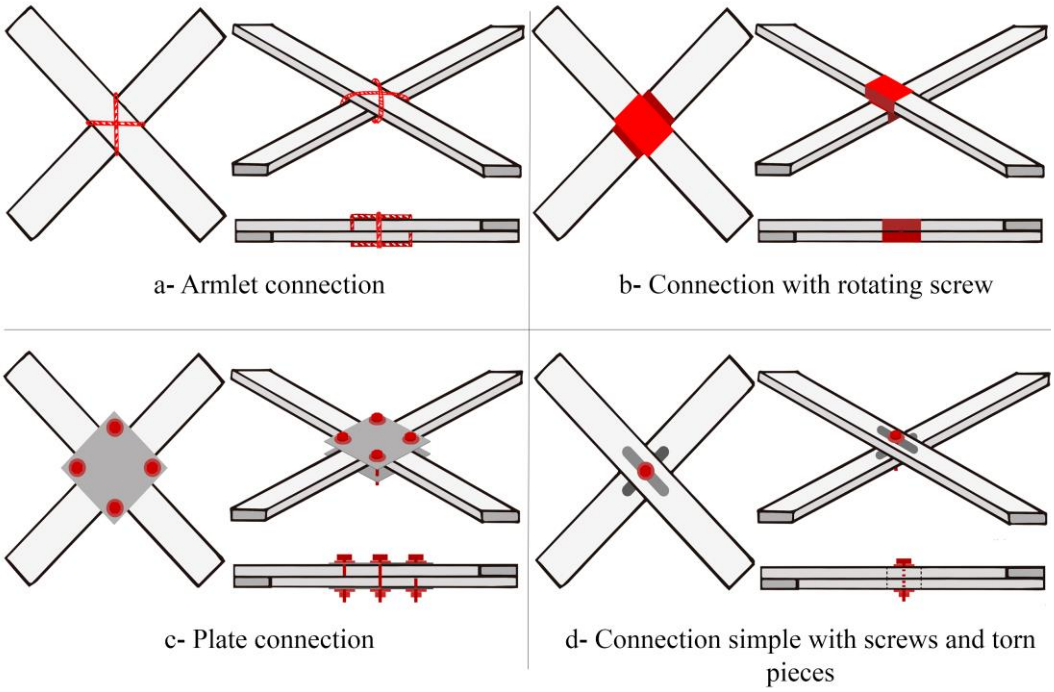


Figure 3.32- Connections between lines

The decision concerning the node detail, and, more importantly the end-to-end connection (Figures 3.33), will have some consequences as well. At the outset, it must be considered 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, these 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.

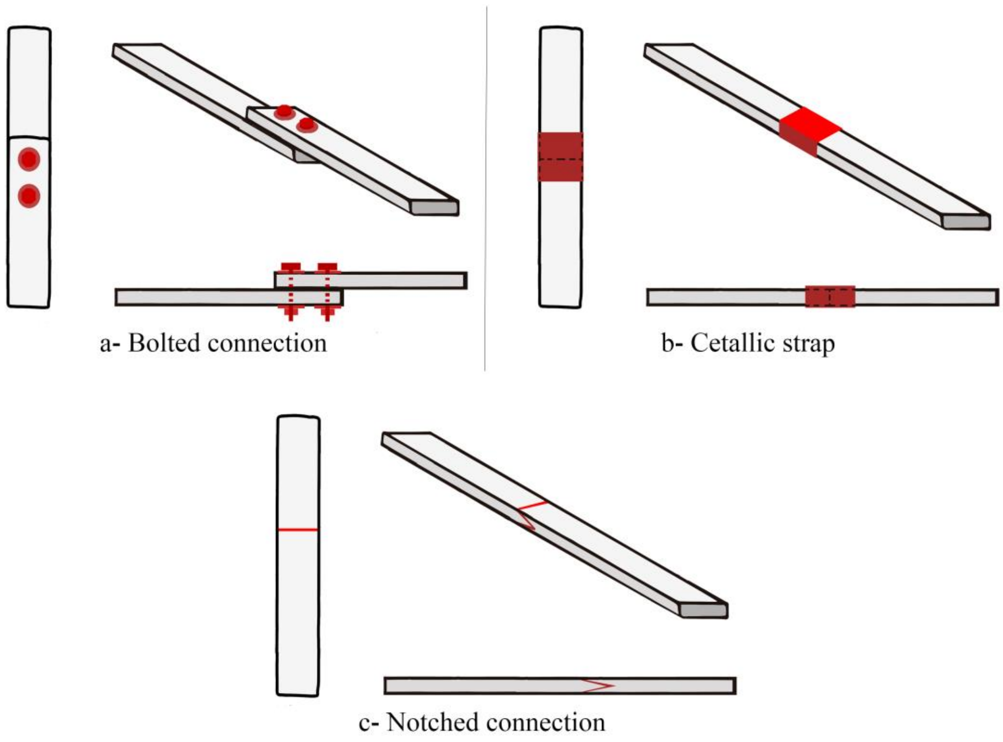


Figure 3.33- Connections in the line

There is no rule but, as it was said, there are solutions that are more appropriate than others, emphasising the importance of the communication between engineers and architects, since the erection process of this gridshell entirely relies on the quality of the nodes. The nodes must, during the erection process, be able to allow rotation in all directions while staying in a specific position along the member and, at the final stage, be transformed into moment connections.

While designing such connections is quite straightforward for a single layer gridshell, a single bolt is let loose during the construction phase and then tightened "snug tight" at the final stage. In the case of a double layer gridshell, four members end up crossing each other at a given node. In addition to having to join those four members, the connections must also allow the two layers to slide, one on top of another since inner and outer layers do not have the same radius of curvature. In addition to these constraints, the connections must also enable vertical shear to be transferred between the two layers, because they will be acting independently. In fact, not being able to transfer this shear renders the use of a multilayer scheme useless. Shear is thus transferred through connecting blocks that are added between the members of the different layers. Those timber blocks enable to have a continuity of material at the connecting points and therefore the stresses can follow through. The first connection scheme that it was proposed was for the Mannheim Multihalle. This connection featured slotted holes in the two outermost layers, the two inner layers having only a simple hole through them and held together by a bolt. The holes in the inner layer would ensure that the node is in the right position along the member, while the slots would allow the outer layer to slide as needed. This connections performed well during the erection, but they were not ideal considering the load resistance. In fact, as the structure is designed to take axial loads, the cross-section area is a critical dimension. So, not only is carving slots in the members a time-consuming process but it also diminishes the resistance of the members and of the structure. The ideal was to have a connection that would not penetrate the members. This was achieved with the use of three steel plates that clamped the members together. Two plates would be placed respectively below and on top of the joint, four bolts -one at each corner of the plate- would be kept loose to allow for the rotation and the sliding of the members and would then be fastened to create a connection on the moment. This scheme could work perfectly, but there is no way to assure that the node will stay in place and will not slide along the member. Therefore, a third plate is inserted between the two layers. A pin would be placed through the third plate, its only purpose being to fix the location of the joint. This scheme was developed and patterned by Buro Happold. The scheme chosen for the Japan Pavilion is also worth mentioning. Matching the uniqueness of this paper tube structure, the connections are very unusual and specific to this design. The connections were made of metal reinforced fabric tape and inspired on traditional bamboo construction (Toussaint, 2007).

3.3.12.3 Locking's and belts

Using the example of the ZA Pavilion, the choice of the locking system had a direct impact on the bonds and the gridshells architectural image. It is not intended to judge the architectural or structural quality of the building; it is just a pragmatic analysis. A system with two layers with screwed connections and a slot allowing the slip to occur has been used, as can be seen in Figure 3.34. 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 relationship between the interior and the exterior, the light input and the construction process. The main advantage was that this solution allowed to keep on using the same material, avoiding mixing other materials, which in turn would lead to a different visual impact.

Figure 3.34- Locking detail of the ZA Pavilion (Richard Harris & Williams, 2014)

Without additional measures, a gridshell structure could be a series of slender parallel arches, which work together to resist the applied loads. When shell action is desired, the shear forces that were present in the shell elements should be accounted by each gridshell element. By linking the laths diagonally, diagonal stiffness is introduced in the gridshell allowing the shear forces to be transmitted from one edge of the gridshell element to the opposite one. This results in a continuous shell due to the laths working together. This diagonal stiffness can be provided in several ways: rigid joints; cross ties; rigid cross bracing; a continuous layer, locking pieces or a stiff cover solution as illustrated in the figure 3.35.

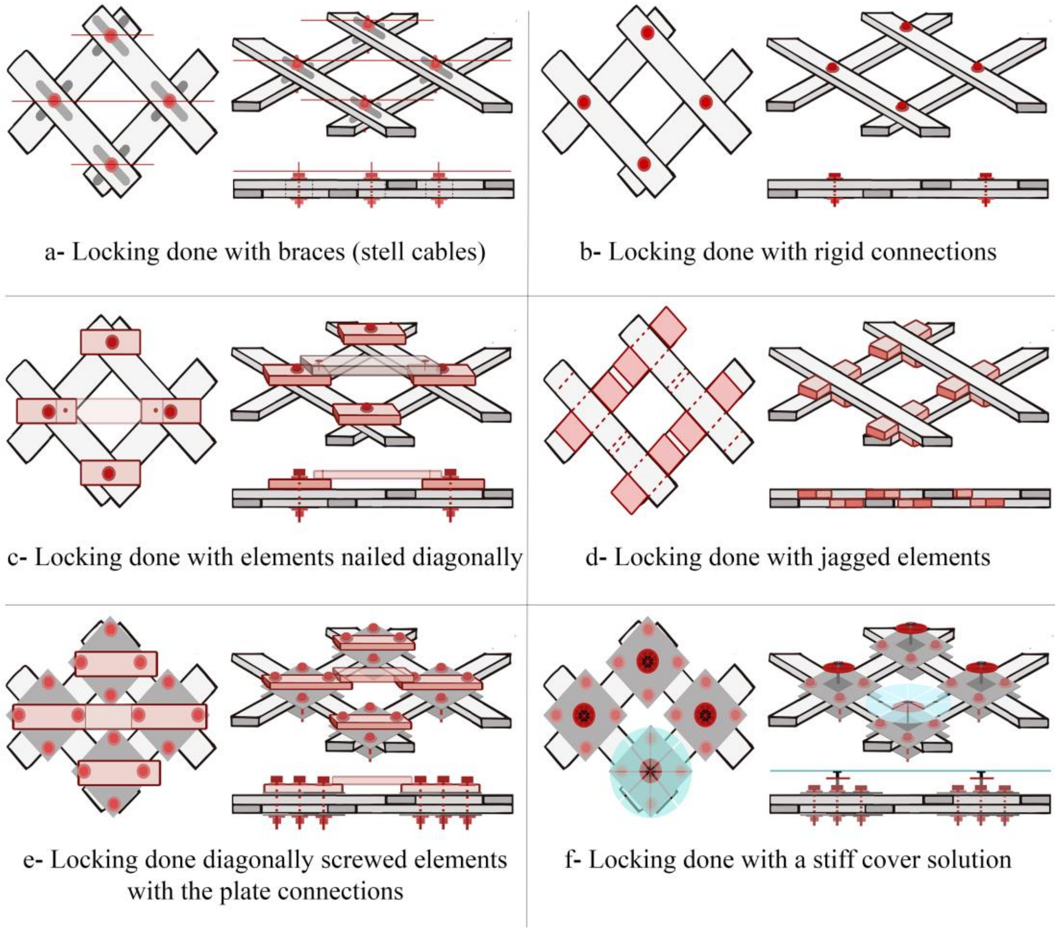


Figure 3.35- Locking connection

The locking solutions that use diagonal elements allow the transmission of diagonal cutting efforts. With this configuration the gridshell will work as a continuous shell. By applying rigid bracings or cross ties the structural behaviour of the grid would be comparable to a continuous shell, resulting from the creation of triangulating the grid. It is also possible to create diagonal stiffness by applying a continuous layer on top of the laths of the structure, while, providing the structural stiffness and cladding of the structure. Bracing with cross ties leaves open the option to vary the diagonal stiffness by altering the pre-stress, thickness or the material of the ties. Diagonal stiffness provided by rigid joints is less easy to realize because they transfer shear forces to the supports through the bending moment; achieved either with connectors or by gluing the joints. Timber connectors such as dowel type fasteners or connector plates always have a certain rotation capacity which decreases the moment resistance and thus the stiffness of the structure. Gluing can provide good moment connection, but complicates the construction process as gluing conditions have to be optimized to guarantee the quality of the joint (Toussaint, 2007).

The stiffness given by a rigid coating, referred to and demonstrated in figure 3.35f, may be a solution that is not of interest in cases where, for example, the structure is desired to stir. In such cases there are several solutions such as fabrics or polymers that can receive and allow certain movements of the structure (Paoli, 2007).

3.3.12.4 Coatings

As it was just mentioned, the coating of these structures will play a very important role in their behavior. Factors such as weight, stiffness, size, etc. can condition or extend the lifespan of elastic timber gridshells.

Since these are light weight strucutres, the coating should also be as light as possible. Please see figure 3.36 were som examples of coating are shown. If the chosen material to be applied is flexible it simplifies the process of application because it wil easily adapt to the form of the resulting shape of the strucutre, which can be a great advantage if it is a structure that has to be prepared in a short period of time. Among the possibilities, on the them could be the use of textiles, plastic tarpaulins and fiber. In the case of hard coatings, we can consider there are 2 types, those that have some capacity to bend and those that are not possible to deform. The two groups are separated by the particularity that the panels in metal panels or metal frames need to make some distance from the structure, since, depending on their size, they must ensure spacing so that the grid can maintain the curvature.

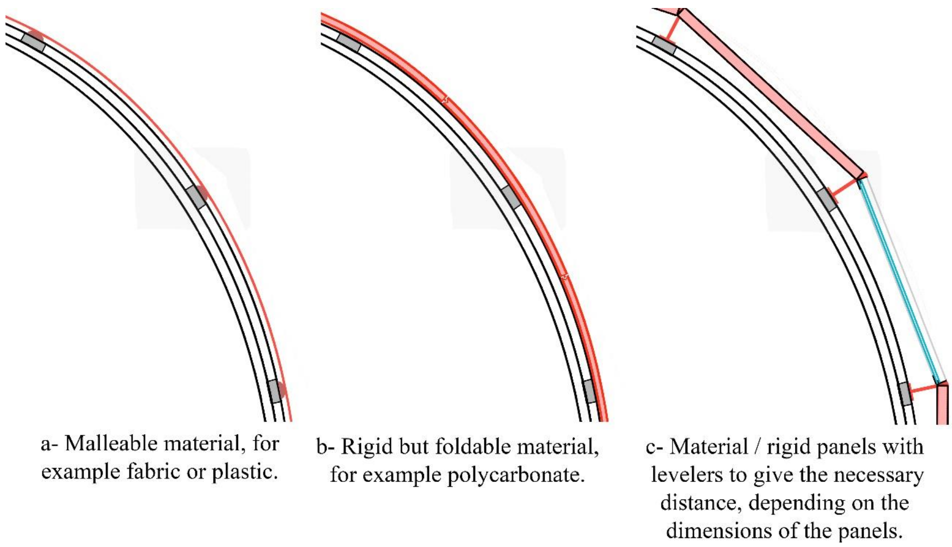


Figure 3.36- Coating options

3.3.12.5 Supports

Along with all the details mentioned so far, the support is also of great importance, considering the goal of the structure. Among the solutions that can be found, some allow for a solid fixation, whilst others enable some movement in order to accommodate the material in its new form, especially over time. As seen in figure 3.37 ‘a’ and ‘d’ have the example of two support links where the movement continues to be allowed. In the first situation the movement of the lines, between them, as a grid, continues to have some permission. In the second image we can find a similar solution but with a rotation of 90 degrees, which makes the movement allowed to be between the arches, perpendicular to the perimeter of the structure. Either option can be tightened, giving the necessary stiffness when desired. Solutions ‘b’ and ‘c’ present a rigid point solution and an equally rigid solution run.

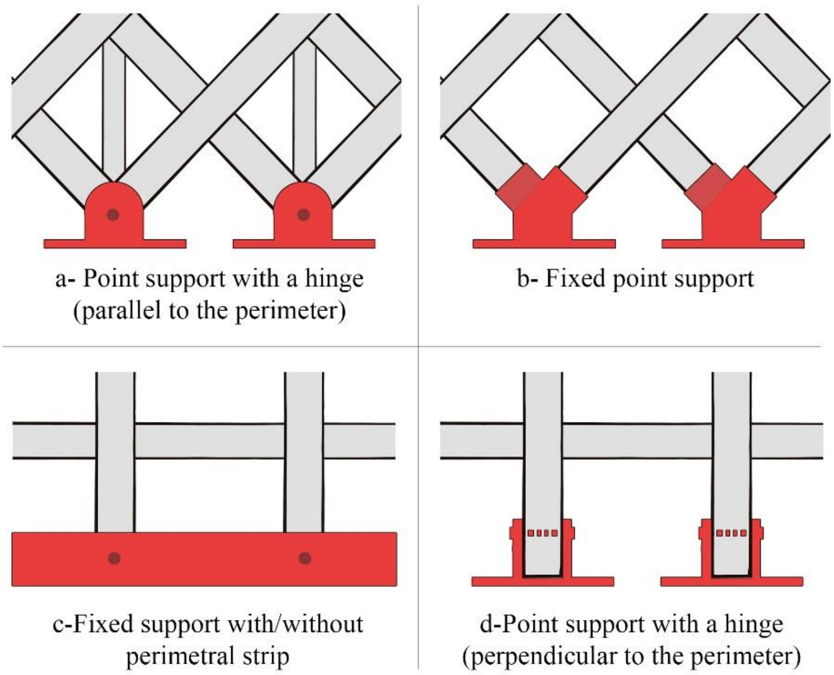


Figure 3.37- Supports / Fixation

3.3.12.6 Spans/ Openings

The spans / openings in the elastic timber gridshells can proceed from a similar decision process, besides being analysed as a constructive detail. It is a decision that will have repercussions on the atmosphere created inside these structures, as well as on the final image of the building, as can demonstrated in figure 3.38.

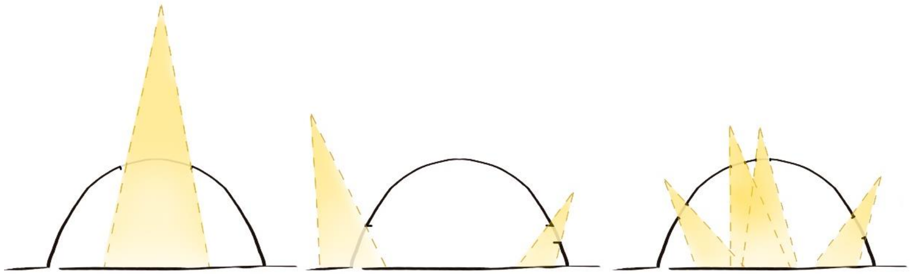


Figure 3.38- Light openings

However, depending on how they are to be made, they can interfere with the structural operation, the decision about the connections and the locking. In Figure 3.39, below, one can see in a schematic way some options that can be considered and the consequences that these options should have. Following the order of the images presented, one can see the use of the resulting holes of the grid in order to create the span, in this case it can be done until a different spacing between rows is obtained, and if a span with different dimensions is desired, and again a decision that will have consequences throughout the structure. Next in figure ‘b’ and ‘c’ is the creation of vain that continue to respect the direction of the grid, however in one case the span assumes the cut of the lines and in the other the vault hides the frame and lets the grid remain intact. In figure d, the process is inverted; the decision does not consider the apertures, but the desired shadows. In the images ‘d’ and ‘h’ there are options between spans, one which is aligned with the grid and the other option to 'open' all the interior space. Finally, in the images ‘f’ and ‘g’ a reference is made to the option to present spans with different shapes, organic or not, of the grid metric. This would have to be done on a case-by-case basis.

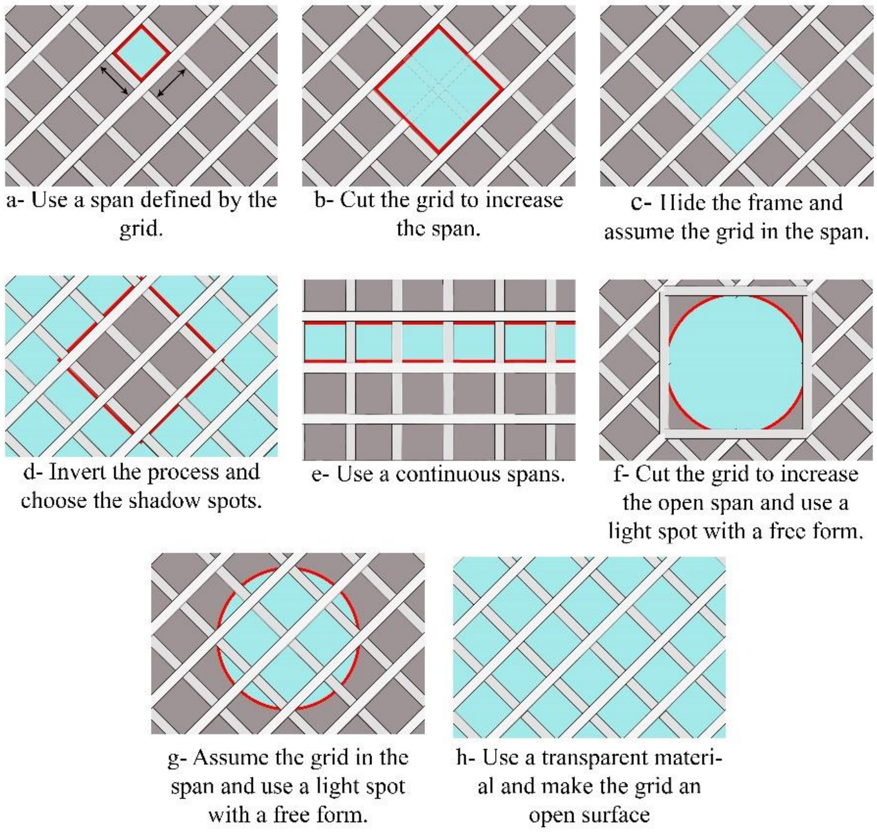


Figure 3.39- Spans / Openings in the grid

This is one of the peculiarities of these structures. The atmosphere created by them will always be different, whether it is by the way the light inputs can be worked, this idea of dark with openings presents a distinct language, certainly highly appreciated by all designers and users of these buildings.

3.4 Applicability

Today, ensuring a new system can be risky as it requires a large financial investment. So, it is necessary to evaluate and analyse the market and existing solutions, even on maintenance issues.

In the case of the timber gridshells which can be designed in different ways with a great variety of options in terms of their material choice and construction and the way these are approached must be proportional to their objective. Therefore, it is imperative to understand whether it is a new construction or an intervention in an existing one; comprehend the expected lifetime and the goal of the structure. If it is a structure with a short or long/indeterminate time life.

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 elastic timber gridshells allows them to be present around rehabilitation, to create new buildings, roofs and small interventions in non-structural elements or simply function as a mere architectural object.

Therefore, after analysing its purpose, it is possible to say that these structures can be divided into two groups, the ephemeral and the perennial elastic timber gridshells. This division considers essentially the expected lifetime and functionality, which conditions the method of erection of the gridshells, as well as the material and connections.

3.4.1 **Perennial**

Perennial gridshells are the ones considered to have an indefinite lifetime, or a long-term lifespan. These structures need to be designed considering all the security and commutation factors (thermal, acoustic, visual, etc.) that a normal building requires. These requirements shall be noted at the time of deciding the connectors, the cover, the supports contacts with the ground as well as the type of timber. It is necessary to choose the right timber, usually resorting to the anatomical-structural aspects, the observable macroscopic level, such as colour, aroma, weight, hardness, gloss and reflex. The identification and comprehension of each type of timber is very important in order to make the right choice, especially in this case with such a particular structural system (Carvalho, 1997).

For this type of gridshells all constructive solutions must be appropriate. The constructive details must be thought for the purpose that they will have, and in this case, for durable structures behaviour, less risk of fragilization of the elements weigh more in the decision making instead of prioritizing economic issues or quick construction. For example, consideration should be given to the use of plate connectors which, unlike screws with tear on the timber elements, do not weaken the elements; as well as the use of inflatable membranes or solutions like easy down are options that allow a greater control now of construction (Soriano, 2017).

As an example, and to realize some of the purposes that these building types can have, a few solutions of it use will be presented. One could assume today, that these structures can be considered as multi-purpose pavilions, which are big trend today, since they serve as a space that can host trade fairs, exhibitions, conferences, etc. They can also classify as buildings such as greenhouses and botanical cupolas. Gridshells can also be found in rehabilitation projects, such as coverings or as elements that define and set limits to spaces, or simply expand them. (Figure 3.40 a and b, 3.41 a and b).

Figure 3.40- (a) Use of gridshells in attachments (b) As a large-scale building

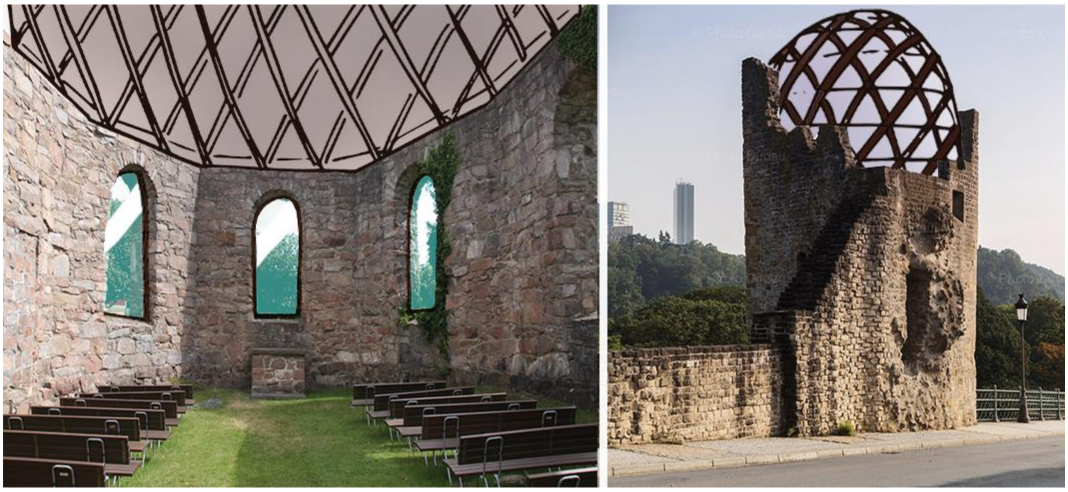


Figure 3.41- (a) and (b). Use of gridshells in rehabilitation

It is known that the public space is what contributes the most to endow the city with human scale, identity and collective meaning and the ability to shape. Gridshells allow zooming in and out of the human scale, from the private to the public space, making them a desirable coverage or public blade.

These are some examples in which gridshell have the role as a second skin of a building, where its ability to overcome large gaps is harnessed to the maximum, where it is treated as a structural or merely architectural element.
For the sake of curiosity one can see in Figure 3.42 some example of what some could be (already) iconic buildings if they were constructed with elastic timber gridshells.

Figure 3.42- Iconic buildings with the use of timber gridshells

3.4.2 Ephemeral

The short duration gridshells, or ephemeral, have in themselves an implicit characteristic, the speed and ease required in the processes of design and construction. This type of gridshells the solutions must be adapted to the use. In the case of a short lifetime gridshells, priority must always be based on the flexibility and speed of the assembly and disassembly process; the economic cost plays an important role, increasing the probability of breakdowns and damaged elements or connectors.
Therefore, methods such as Pull-up and Push-up are perfectly acceptable to be used here, since they may have some difficulties about the distribution of effort at the time of construction, making them quick and easy processes to execute. This makes the use of screw connectors a great solution for this group of structures.

It is crucial to safeguard that the examples presented are merely illustrative; some of the examples given for one case may also be perfectly acceptable examples of occurring in the other. Only a few cases are considered, clearly associated with ephemeral constructions rather than perennial constructions. One examples could be the emergency shelters, clearly associated with specific situations and for a short period of time. They can also appear as options for stage coverings of music festivals, etc., or as buildings / commemorative and iconic elements present in exhibitions or occasional actions, as shown in Figure 3.43.

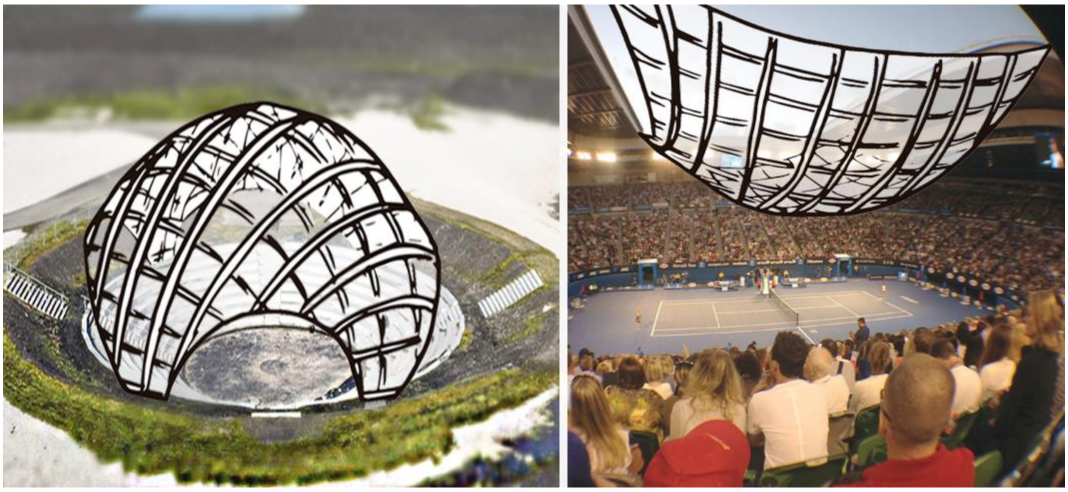


Figure 3.43- Multifunctional space coverings

Emergency shelters made up of fragile, impersonal white tents could be something of the past. The architects and engineers can now offer incredible designs for disaster shelters that are transportable, easy to assemble, strong, comfortable, flexible and made of eco-friendly materials. Proving that it is not acceptable to live with no minimal conditions when hurricanes, earthquakes and other disasters strike.

In addition to the emergency coats, also to explore, it is the constructions in third world countries. In both cases, the qualities of the timber gridshells are recognized and would be of more relevance, presenting more advantages over other solutions, they are quick to build and can ensure safety and durability. This kind of structure can be ideal in extreme situations (Figure 3.44). The rapidity of the erection scheme of gridshells, combined with the extreme light weight of Fiber Reinforced Polymers (FRP) could lead to the development of fast shelters. For example, when an emergency shelter is needed in case of natural disasters, the gridshell capacity of spanning big distances would be a huge advantage, once the connections between the members of the mat are done, the structure takes form very easily. Furthermore, as the structure itself will be very light weight, the fabric cladding put on top of the Gridshell requires very little manpower (Paoli, 2007). To build simple emergency and safe structures in our backyards, to give us maximum safety with minimum environmental impact, we must choose natural materials and, like nature itself, build with minimum materials to create maximum space, like a beehive or a seashell. However, before these structures become of common use, it is necessary to improve and optimize its concept, its level of assembly and disassembly and probably the modular construction of the parts or single elements.

Figure 3.44- Shelters adapted for different situations and locations

Ephemeral timber gridshells could also be used for various expositions and festivals organized worldwide. This field of application is probably the most favourable to allow these types of structures to develop furthermore. There is a real opportunity for the shell structures, being used in events such as music festivals, parties or large events (Figure 3.45).

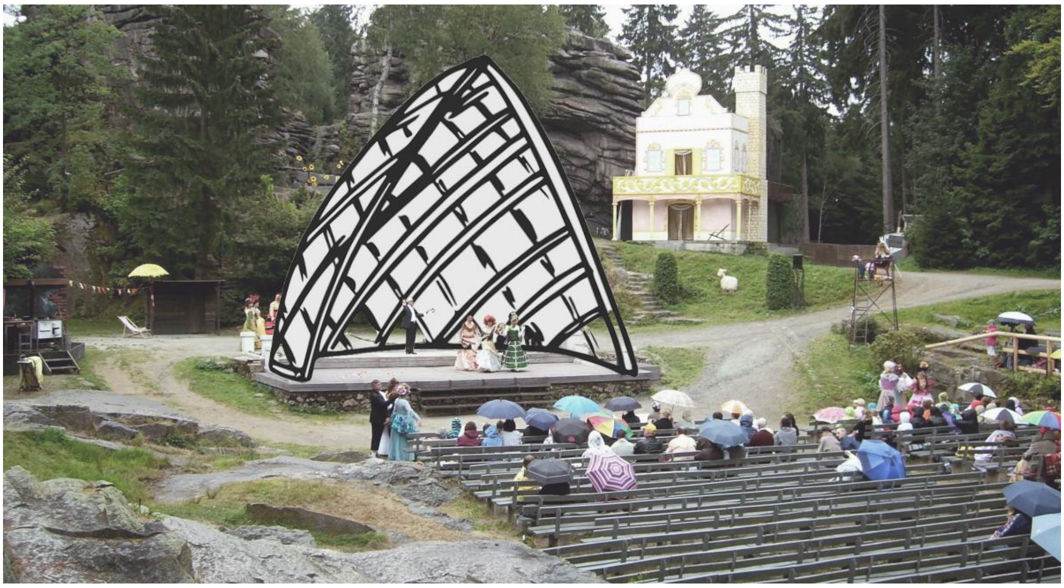


Figure 3.45-Example of covering an outdoor stage

The geometry that these structures present is appropriated for this kind of use. Acoustic gridshells are a response to this context, bringing back an old ideal, an architecture that can represent the "sound" (Figure 3.46). Acoustic shells are iconic elements seen in public spaces around the world. Looking beyond their curious form, their operation is highly interesting. Inspired by the design of the human ear, the sound waves produced within acoustic shells are originate from their form, becoming stronger and more vivid for the audience in front of the structure (Taylor-Foster & Brittain-Catlin, 2017).

The acoustic design creates a reflective surface to project the sound of the artists to the audience. From a technical point of view, sound propagation is carried out by reverberations that, when created inside the shell, are directed by the concave shape towards the spectators. In other words, after a sound is made, it hits the gridshell, and due to the shell's carefully calculated form, it is distributed to the audience (Taylor-Foster & Brittain-Catlin, 2017).

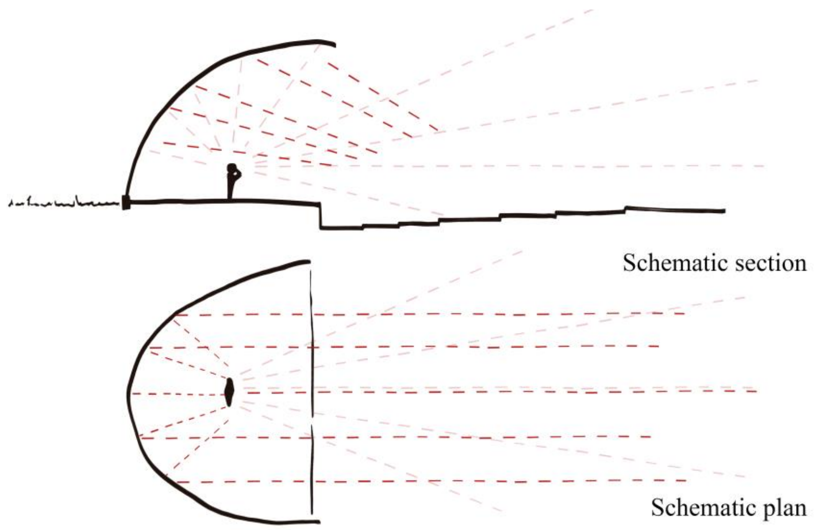


Figure 3.46- Sound behaviour in a shell.

In addition to its functional characteristics, there is still the visual part. Stage designers must create an immersive and engaging environment that lasts only hours or days but is remembered for a lifetime. As a matter of fact, these kind of gatherings are typically exceptional events during which the organizers want to make an impression on the attendees (spectators, exhibitionists, personalities...) and gridshell structures have clearly, very interesting architectural features that could only enhance the unforgettable feeling the organizers would be looking for (Paoli, 2007). They inspired ways to build differently and they can also delete several myths and archetypes as 'the tent' and 'tent' shelter 'second category'. Its ability to adapt to local environment, its versatility and reduced material, meets with the very contemporary thought 'Less is more'. The approach to nature, the effort to interpret and control it holds a deep poetry, which can translate itself into high aesthetic and artistic expressive forms. The progressive refinement of the ability to understand and realize the physical laws helps to increase the apparent and intrinsic beauty; within the pure form, in accordance with the needs of a growing technique in development.

3.5 Tectonics

Tectonics is an influential 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 (Oxman, 2009).

Over the time the notion of tectonics has been discussed and transformed. It is an old idea that has had different meanings depending on the topic being studied, which has deserved the attention of many thinkers throughout the history of architecture. In the twentieth century many theorists wrote on this subject, trying to classify, qualify, define, divide and explain the concept. There were different approaches and positions in relation to its meaning. Eduard Franz Sekler was an architectural historian and professor from Vienna who investigated and wrote about this theme. He saw structures/constructions and tectonics as separated issues and, following him another author defended the same. Carles Vallhonrat (1988) studied the impact of tectonics on techniques (structure and construction techniques), Vitor Gregotti (1996) believed that details create a relationship between tectonics and techniques. Marc Frascari (1996) explained that the tectonics significance of modern architecture is due to the developments in structural systems (Hurol, 2016). Frederic Jameson (1994), postmodern philosopher, also agreed that technology determines modern architecture by believing that modern architecture is more about structure/construction than it is about space and form. With a different opinion Kennett Frampot (2001) similar to Gottfried Semper, a German architect, art critic and professor from the XIX century, he believed that tectonics is the poetry of construction and that way, the joins are the smallest unit to affect tectonics (Hurol, 2016). He did not separate structure/construction and tectonics like the previous ones. These were some of

the thinkers who have left their mark in this discussion over the centuries that preceded us.
More recently, some authors have been giving continuity to this theoretical reflection. Roman Oxman and Yonca Hurol are some of those. Namely Oxman, has been distinguished by the approach to the theme from the new tools available to the designers and presented a new term "digital tectonic"(Oxman, 2009). Roman Oxman as a way of identifying the singularities of tectonics in material-based design, introduce another term, "informed tectonics" (Oxman, 2012). It is the idea that the explanation and transparency of information that provides the holistic integration of design, materialization and fabrication. In this novel integration, it is also the affinity between tectonics and digital technologies that enhances the design possibilities for the integration of form, structuring and material principles.

As it can be seen, it is a theme that has remained present and is expected to continue. In this work the concept of tectonics is largely in line with that which is presented by Oxman, however, it is not considered necessary to place the word "informed". Here, it is understood that tectonics is in fact a perfect symbiosis between all components of architecture from its design, structure, construction, material, light and form. In this sense, it is understood that the tectonic values start from an informed and consolidated basis that allows the fusion of the various elements. Thus, "tectonic" it is enough as a word, because this word has already, intrinsically the value of unity created by informed different parts.

3.5.1 **Gridshells tectonic value**

Usually at the centre of this idea, of tectonic value, there is a conflict between form, function and the structural needs that, in the timber gridshells do not exist, since the structure designs the 'resulting' space. This type of structure does not defragment between vertical and horizontal elements, between material and form. There is a conceptual transparency, a truth between what is seen and what happens. This ends up easing the creation of the tectonic value of the buildings due to the natural symbiosis between the elements that compose these spaces. The skill of the architect is finding how to apply aspects of design combining the artistic sensibility, his vision and the physical characteristics of the building and the environment. Besides that, since the shape is closely linked to the forces that are present in timber and the support reactions, these aspects will always be present in the final geometry. The chosen structural typology will certainly have an impact in the architectural image (Fernandes et al., 2016).

With an emphasis on the earliest timber gridshells, elastic gridshells, as the first one to exist and be registered (Manheim Multihalle), has great tectonic value. Its construction, the way in which it was erected from a two-dimensional plane to a three-dimensional shape added to the quality of these buildings. With this process the construction becomes another moment of rooting between components. It is not only how the structure works or the material that gives its characteristics to the atmosphere of space, but how the construction process helps to tell the story of the building. Gridshell structures become a habitable result of everything that has been designed by and for them. It can be said that even the conditioning factors that go forward are part of the created spaces. For all these reasons, elastic timber gridshells are a kind of structure that need to be considered with a great tectonic value, which will always remain in history as an example of an innovation that has evolved with the means that surrounded them. Inspired forms from nature, to inverted models, to full-scale models, there has been an immensity of phases / processes that have made collaboration between engineers and architects compulsory, and the result of this work as an example are elastic timber gridshells.

During the past twenty years the timber gridshells have continuously been arousing the interest and curiosity of more and more researchers and designers. Despite the lack of information, in comparison with other constructive systems and materials, these structures have been acquiring a greater refinement. Now it is possible to find more projects with an incredible level of detail and development. The new methods of design and construction have facilitated the development of the gridshells without losing its tectonic value. On the contrary, the evolution of all these tools has been increasing because of the adaptation and collaboration between architects and engineers who are making the shells a kind of new architectural expression.

3.5.1.1 New architectonic language

Nowadays it is already possible to talk about this new architectonic language. As was said the shells geometry/structure brings to the designer’s new opportunities for the tectonic composition, as an artistic expression and manifestation of the human will. Even because, tectonic is a thing of 'art', habited art, the materialization of ideas, a phenomenon of composition. The purpose of construction by itself is to make things hold together and architecture it is the idealization and creative tool that allows that, but the tectonic is what move us. When certain harmonies have been attained, the work captures everyone (Corbusier, 2008). Tectonic it is a matter of harmony, it is a pure creation of spirit and the gridshells operate exactly within this logic.

The opposite is similarly valid. Just as harmony can draw attention to its tectonic value, also when it is played with this harmony in a conscious and talented way it is possible to obtain something with great tectonic value. For example, the case of the Portugal Pavilion. It is a building, of recognized value, that is only used as an example, leaving aside any comment to the concept behind the work, making only a purely formal, volumetric and material benefit (Fernandes & Branco, 2018).

As it is known, it is a distinct and unparalleled work regarding its architecture and engineering. One can also note the uneasiness created between geometry and its materiality (Figure 3.47). Even for those who were part of their creative process, there is this sensation, because, according to Eduardo Souto de Moura - what worries in the cover is the fact that an object that should be made of lightweight materials is constructed of concrete and has a perennial air. The fact that it is made of concrete - counterattack - is what produces the disquiet (Fernandinho, 2017).

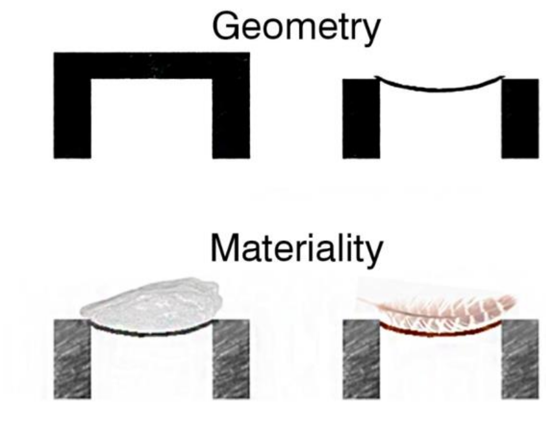


Figure 3.47- Geometric and material sustainability (Fernandes & Branco, 2018)

This proves that architecture only exists in a context, a place, and timber gridshells can understand the logics of the place and work with it. It can work with what surrounds them, physically and socially. In fact, they may even be generating new contexts. The techniques, methodologies and materials characterize epochs, and this may be the time for timber gridshells to assert themselves as a contemporary expression (see Figure 3.48). New materials and techniques have over time given way to new languages (Braham & Hale, 2007). From these timber gridshells, designers can achieve more exuberant design concepts at an affordable cost to their clients. These structures may take on the shape of various curved designs, using complex and irregular shapes that are created from a set of standard components and allow the infrastructure to be put between the duplicated lines.

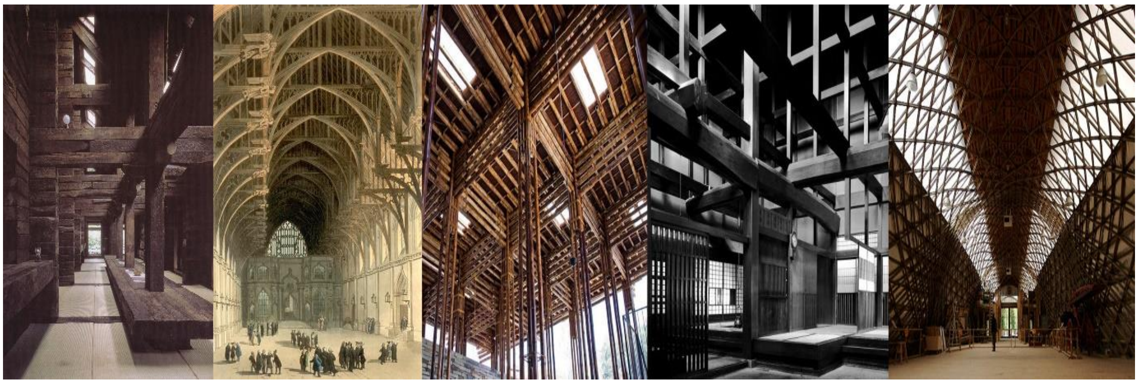


Figure 3.48- Timber examples of 'atmospheres' that have marked epochs and places

As it is represented in Figure 3.49, from the *The Essay on Architecture, a*rchitecture is one of the most urgent needs of Man, as housing has always been the indispensable and first tool that he has forged for himself. The story shows a man in his 'primitive' state to explain how the creation of the "primitive man's" house it is instinctively based on the man's need to shelter himself from nature. Marc-Antoine Laugier, one of the firsts modern architectural philosopher, believed that the model of the primitive man's hut provided the ideal principles for architecture or any structure. To him, the general principles of architecture were found in what was natural, intrinsic and part of natural processes (Laugier, 1755).

Figure 3.49- Book cover of Marc-Antoine Laugier: Essai sur l'architecture 2nd ed. 1755 by Charles Eisen (1720-1778) (Laugier, 1755).

Man's stock of tools marks the stages of civilization: The Stone Age, the Bronze Age and the Iron Age. Tools are the result of successive improvements; they embody the efforts of all generations. The tool is the direct and immediate expression of progress (Corbusier, 2008). Maybe the gridshells can make this the right time to start a real "timber age".

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 must 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 (Neumeyer, 1997). 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 (Fallis, 2013). The materiality defines the experience and gives shape to the intentions in architecture.(Braham, 2007) 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 (Hurol, 2016). 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 types of structural systems, gridshells are a variant that can be chosen for free-form and architecturally expressive design.

3.5.2 What an engineer has to offer

This emerging style needs the contribution of all those involved. Architects must present solutions and propose methodologies and design logics to supplement the progress of engineers. Also there is a need for creative engineers to achieve its global ambitions (Michalatos & Kaijima, 2014). Engineering is responsible for the built environment's technical performance, which is a basic precondition of social performance. In this sense, engineering might be argued to be primary, social performance being the goal. However, architecture might also be argued to be primary.

Both of these fields have traditionally been characterized by the development of a sequential reasoning of shape, structure and material (Oxman & Oxman, 2010). 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 material wise (Malek, 2012). Collaborative relations developed between architects and engineers contributed to the production of some of the most iconic buildings. Although the process of structural engineering has already 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 (Luyten, 2012).

Today, in most cases structural considerations only come in 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 fields to enable improvements in the tectonic characteristics of the projects (Malek, 2012).

Since the lack of design integration was previously identified, now it is necessary to make clear that this is what 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 3.50.

Neither the architect nor the engineer can do this alone, it takes both to create delicate and informed gridshells.

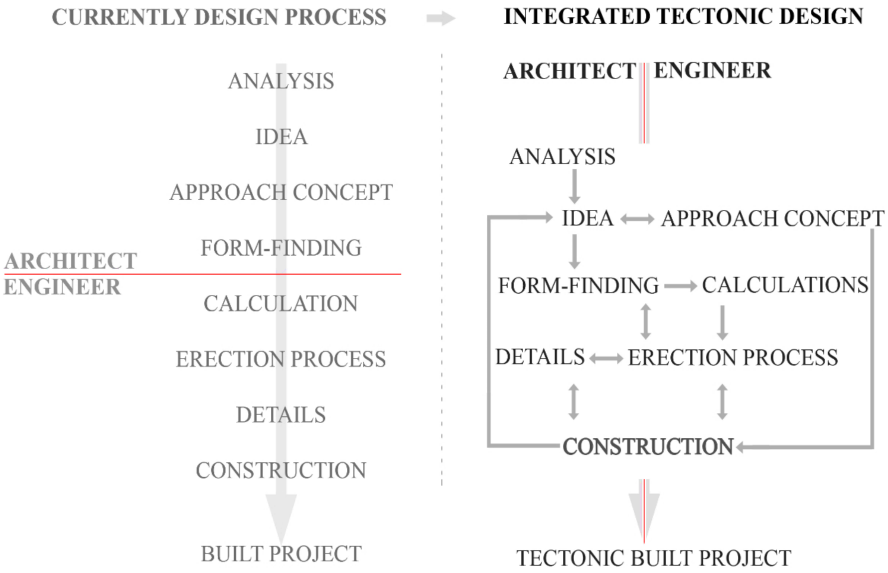


Figure 3.50- Design Process for elastic timber gridshells(Fernandes et al., 2016)

The more skilful and informed the architect is the bolder and innovative the outcome will be, and engineers should be pro-active in all phases of the project.

The architectural design is the consequence of solutions carried out through this design process to solve the individual concerns, while at the resolving at the same time the global matters 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.

Besides teamwork during the design and construction, the referred material, timber, is also a catalyst of this cooperation. More and more designers are committed to ending the myths that were surrounding the timber and presenting it as the cultural, sustainable and efficient solution it is. Timber is one of the most beautiful and comfortable materials used in architecture. It has proved to be remarkably immune to changing trends, abundantly used in virtually all periods of human civilization and is also found in both luxury residences as well as in modest vernacular buildings (Peixe & Licheski, n.d.). The growth potential of timber construction can be reinforced with standardize and systematized timber-based materials; where architects and engineers can play a key role in the development of this tectonic value. It is important that main building designers be able to see the positive aspects of timber construction, the gridshell structures and shell spaces (Roos, Woxblom, & Mccluskey, 2010). If a gridshell structure occurs to be appropriate for a project; the designer should have the capacity to design, it. An architect should not concentrate on one type of structure, and should take notice of all possible structural systems, to realize the various possibilities of each structure. Elastic timber gridshells are versatile allowing them to be present in rehabilitation, to create new buildings, roofs, small additions in non-structural elements and even partitions functioning as a mere architectural object, in any case they will be a distinct element due to the architectural language it transmits through its lightness and the special outcomes. Which means that if they are a good structural solution with a material in increasing reuse, its lack of examples is due only to this inability of the designers to create these shapes.

Two good recent examples of the collaboration between the architects and engineers, already referred, can be ZA Pavilion built in 2013, that was presented as a temporary cultural venue and was designed and built during a student workshop in Cluj, Romania (Richard Harris & Williams, 2014), and the Sutd Library Pavilion, built in 2013 in Singapore. The idea behind this building was part of a competition where its potential was realized and the project completed (Griffiths, 2013). Two buildings/spaces; very different from each other and different from the previous examples, even in terms of scale. Still, they clearly reflect the concern and importance of the details in the final image of the building. All the decisions, from the locking, material, connections and coating contributed to the reading of the space as whole. The fact that the details may be the result of the decision of an architect or an engineer should demonstrate how the differentiation of these two areas in the field of timber gridshells is difficult.

Thus, the relation cannot be brought into a hierarchy; one should rather relate the mutual dependency and dialectical advancement (Michalatos & Kaijima, 2014). The engineer, inspired by physical law and governed by mathematical calculation, puts us in accord with the universal law. He/she achieves harmony.

3.6 Summary

This chapter has addressed everything that should be taken into consideration during the conception, design and construction of an elastic timber gridshell. Trying to focus the research interest in the specific point of the timber gridshells design process, the relevance of the erection method becomes evident. In theory all the methods to go from a bi-dimensional to a three-dimensional shape in the construction of these structures were presented and even some ideas of what their future may be have been extrapolated. Still, the constructive details and its greater importance in the global behaviour were explained. At the end of this chapter some notions were left of its applicability considering the characteristics of the construction, details and finishes of gridshell structures. These notions, even if general ones, are of great importance because, like all materials and systems, they must also enhance their qualities and minimize their defects taking into account the context in which they are inserted. Finalizing with the enhancement of the support that the engineering knowledge can offer to the architectural process.

The next chapters will focus on the practical collation of the information presented so far, serving as an experiment.

4 Material and Computational Design

Case Study

After presenting the basis of elastic timber gridshell in the previous chapter, now it is intent to demonstrate how the interaction between timber characteristics and the computational models. What information are needed and how can be merged the information and characteristics of the material with the digital models.

To achieve the proposed idea, a real case study (Figure 4.1) will be presented, Gridshell 1.0, with 42m^2 (6,5mx6,5m) and a variable height of 2.1m and 3.4m in the span arches and the centre of the gridshell respectively. This being a regular gridshell, that works entirely to the compression that is mounted in a two-dimensional and deformed plane, being pushed or pulled, until reaching a certain three-dimensional shape. This application brings several advantages, from the manufacture of the elements, which are all identical, to the ease of transporting them, because they are all linear. Its construction will be presented in the next chapter, which serves as an experiment in this research.

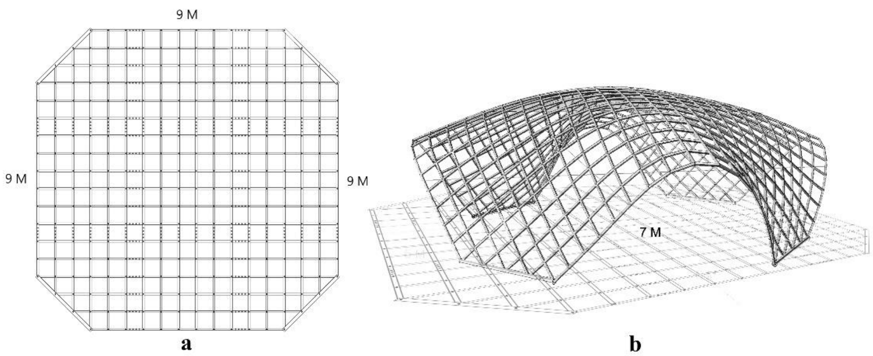


Figure 4.1- (a) Bidimensional grid (b) three-dimensional gridshell.

Contrary to what usually happens, in this case, the design did not dictate what would be the material or more specifically the type of timber. Spruce (*Picea abies*) was the timber used for this experiment, since a local company provided the quantities required for the respective trials and pledged to supply the necessary material for the construction of the full-scale model.

It was decided to make a simple characterization of the material with the aim to explore its limits in what concerns strength and flexibility of the timber used. In this context, two types of tests were defined: bending tests and buckling tests.

This chapter is divided into 5 parts. Starting with the presentation of the material (timber), the characterization tests and the respective results. Following the description of the design process of the computational models as the incorporation of the characteristics of the material used. Two models will be presented and compared in the search for the best solution, finishing this chapter with the demonstration of the load application simulations in the computational model of gridshell and the verification of the connections; proving in this manner the entire process of how computation models' approach to reality.

4.1 Mechanical Characterization of Spruce

As mentioned, bending and buckling tests were performed at the Laboratory of Civil Engineering of the University of Minho, with the aim to characterize the timber used in the case study. Table 4.1 presents the geometry and the number of specimens used in each kind of tests. It is important to point out the different values of length (L) were adopted in the buckling tests with the aim to assess the influence of this geometrical parameter, in the gridshell performance.

Table 4.1- Dimensions of the specimens tested

Specimens				
H [mm]	b [mm]	L [mm]	No. of samples	Test type
25	60	550	10	Bending
25	60	250	6	Buckling
25	60	500	6	Buckling
25	60	750	6	Buckling
25	60	1000	6	Buckling

4.1.1 Bending tests

The main objective of this test it is to quantify the modulus of elasticity in bending (*E*) of the timber, a value that will be needed for the execution of the models to be developed. For this, several bending tests were performed according to EN 408:2010 (CEN, 2010c). The scheme of this test consists of a simply supported beam submitted to a 4-point bending test (Figure 4.2)

Figure 4.2- Bending test scheme

From the bending tests it was possible to obtain the results presented in Table 4.2 and in the Figure 4.3, regarding the loads applied to the test specimens and the displacement measured by the LVDT in the center part of the free span of the specimen.

The first property calculated was the modulus of elasticity (E). The calculation of this property was made based on the process and formulas present in EN 408:2010.

The mean of the modulus of elasticity of the tests on the test pieces with l = 500mm is shown to be relatively higher than that of the test pieces of l = 550mm. However, the number of test specimens of l = 500 is half that of test pieces of l = 550mm, which in principle leads us to a greater error. Therefore, the standard deviation and the coefficient of variation for each case were calculated.

In addition, the moisture content and the density were also calculated. Moreover, the density was calculated with the purpose of calculating the mass of the structure, to help in the validation of the computational models.

In order to calculate these two properties, the standards NP 614:1973 (Repartição da Normalização, 1973a) and NP 616:1973 (Repartição da Normalização, 1973b) were used. According to NP 614:1973, 19 specimens were cut from the specimens already tested for bending and bending, with a maximum length of 5cm in order to avoid knots, cracks and other defects in them. These specimens were duly weighed, and according to NP 616:1973 their volumes, measured in Table 4.2.

Table 4.2- Results of bending tests

Specimens	**Test**	**F_{max}**	**F_{mean}**	**CoV**	**E0**	**$E_{0,mean}$**	**Mass**	**W (moisture content)**	**ρ**
[mm^3]		[kN]	[kN]	[%]	[GPa]	[GPa]	[g]	[%]	[kg/m^3]
25x60x500	1-500	6,69	6,15	7,16	16,51	14,69	24,4	13,0	499
	2-500	6,18			15,74		25,3	12,9	473
	3-500	5,60			12,95		26,7	12,7	371
	4-500	5,71			11,59		24,8	11,7	427
	5-500	6,56			16,66		19,2	12,9	380
25x60x550	1-550	4,69	4,31	20,49	12,24	13,17	18,4	12,9	401
	2-550	4,70			12,43		18,7	12,7	360
	3-550	3,60			13,04		26,1	13,0	461
	4-550	2,67			14,39		27,4	11,8	358
	5-550	5,00			13,99		31,5	12,5	448
	6-550	5,28			15,19		20,3	13,4	369
	7-550	5,29			12,86		25	13,6	363
	8-550	3,71			12,30		27	12,0	431
	9-550	3,23			10,68		23,3	13,7	354
	10-550	4,95			14,53		23,4	12,5	437

The average value of the moisture content is 12.7%, an acceptable value, considering that the wet test specimens were inside the LEST climatic chamber, at an ambient temperature of 20ºC and 65% relative humidity of the air. The average value of the density is equal to 416.12kg/m^3.

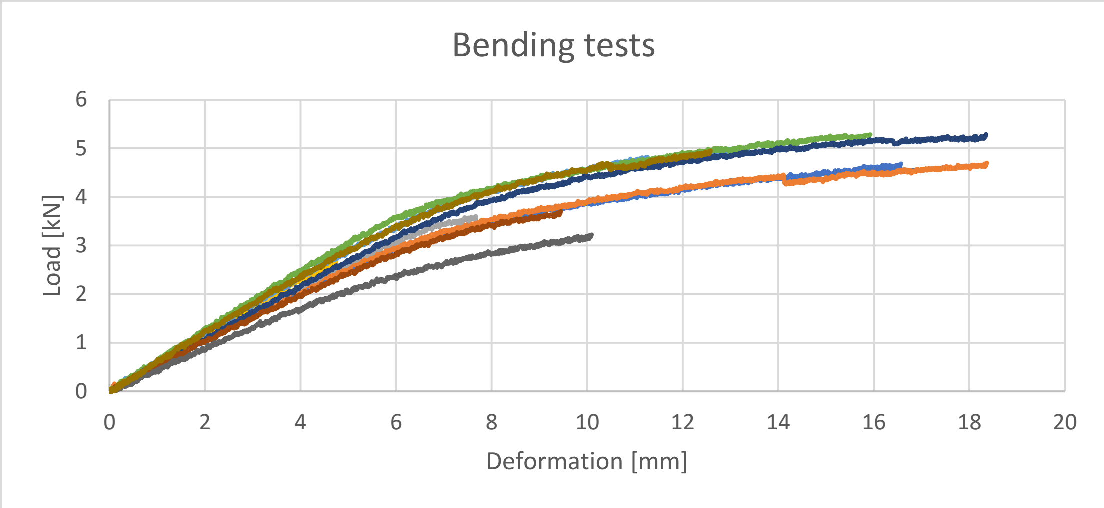


Figure 4.3- Comparison of load-deformation graphs of flexural tests of test pieces with l = 550mm

In view of the low values of the maximum load attained in tests 3-550, 4-550, 8-550 and 9-550, it is appropriate to analyse the respective ruptures to find out what may have caused these results (Figure 4.4).

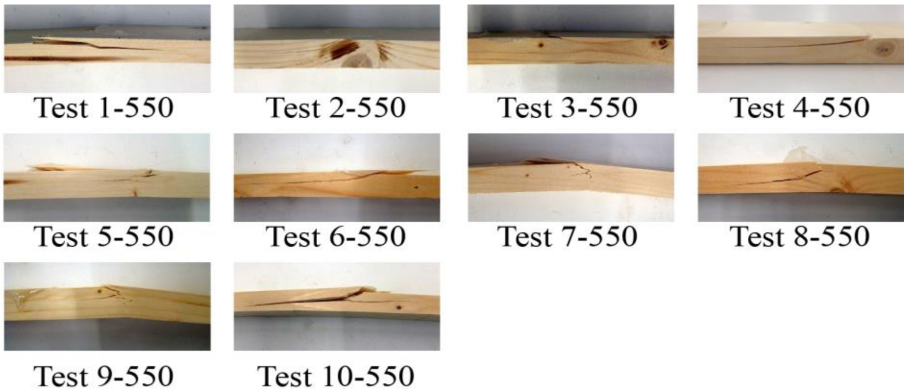


Figure 4.4- Bending tests ruptures

Looking at Figure 91 and focusing on the failures related to the four tests mentioned above, it is possible to observe the existence of knots in the zones of rupture of the test pieces. In test 3-550, in addition to the knot present in the breaking zone, it is to be noted that the break follows the line defined by a shaft also present in the specimen, and which may have assisted early breakage thereof. In the case of test 4-550 the presence of a large knot is noticeable near the breakage zone of the specimen. For test 8-550, a knot of considerable size was observed in the lower region of the specimen. The rupture of this specimen tends to have occurred at a relatively low load value due to the presence of the referred knot, which can be seen in Figure 4.5. Finally, the rupture of the 9-550 assay is analysed. For this test, it is predicted that the rupture was precocious, also due to the existence of knots. For this specimen, in addition to the knot visible in Figure 4.5, there was also a knot on the side opposite to that, increasing the ease of breaking of the element.

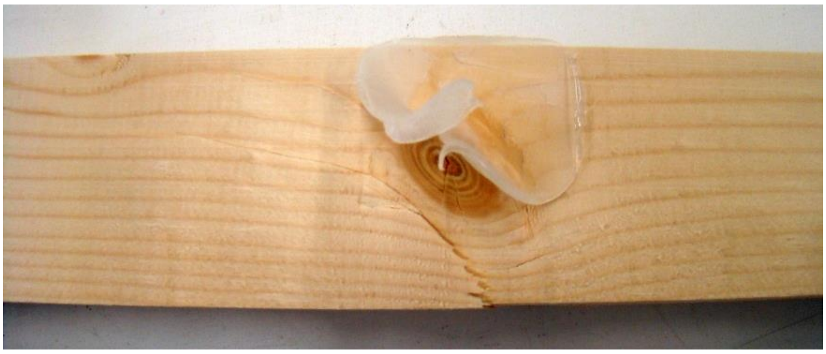


Figure 4.5- Knot presence in the break zone in test 8-550

4.1.2 Buckling tests

The main purpose of this test was to assess the critical load values (P_{cr}) to which the different test pieces becomes instable developing buckling, that is, to discover the value for which load $P = P_{cr}$. Also, it was intended to understand for which values of lengths, the elements, with the defined section, would destabilize.

Unlike bending tests, the buckling tests did not follow any specific standard, and the entire test procedure was defined based on the intended objectives (Figure 4.6). The test scheme is defined by a bi-articulated bar (l_0=l) so that the structural system was identical to the real-scale prototype that was to be developed. The specimen is subjected to a compression load until it reaches the value of the critical load, ending the test at that point, that is, it is a non-destructive test.

The first specimens tested were those of l = 250mm, however, the tests did not proceed as expected. The specimens of this length had compression fractures before reaching their critical load and unsteady by buckling. This behaviour showed that, for the chosen section, a span of 250mm would not be able to bend.

Then the test pieces of l = 500mm were tested. The first of these test specimens had the same result as the previously tested specimens, is it broke by compression before instability. This result caused an important change in the structural scheme of the mesh to be constructed. Since the spacing of the wood elements would be 500mm, that is, there would be connections of 500mm in 500mm, after the result of this test, the ease of buckling of the elements during the construction process was compromised. Taking this into account, the dimensions proposed in the architectural design, presented in the previous chapter, would undergo some changes. These changes will be presented at the end of this chapter. In order to make the remaining test pieces of l = 500mm useful, they were used to carry out bending tests, as previously mentioned.

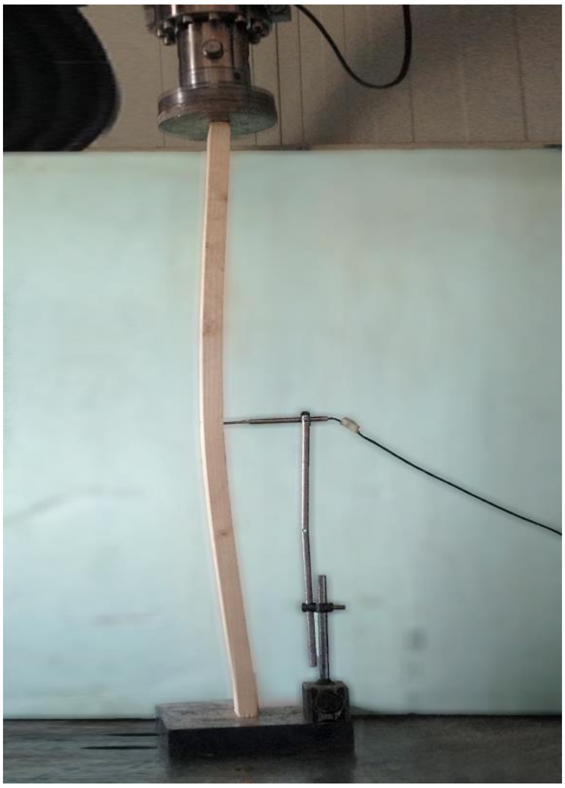


Figure 4.6- Buckling test scheme

Unlike the previous tests, the pieces with l = 750mm and l = 1000mm, presented different results after being tested. The specimens were unstable by buckling and it was possible to remove the value of the critical loads as intended. The results of these tests are shown in Table 4.3.

Table 4.3- Buckling test results

Specimens [mm³]	Test	F_{max} [kN]	F_{mean} [kN]	CoV [%]	Massa [g]	H (moisture content) [%]	ρ (Density) [kN/m³]
25x60x750	1-750	37,15	35,86	13,80	22,7	12,3	4,58
	2-750	31,25			24,8	11,6	4,47
	3-750	29,89			21,3	13,3	3,69
	4-750	37,27			20,6	12,6	3,63
	5-750	43,73			24,1	12,1	4,31
25x60x1000	1-550	11,28	21,33	38,48	25,7	12,3	3,65
	2-550	34,81			23,8	11,1	4,87
	3-550	20,48			19,2	11,9	5,24
	4-550	16,22			19,9	13,1	4,08
	5-550	25,01			25,2	11,7	6,01
	6-550	20,16			23,8	10,5	3,90

Analysing the results of the table, as expected, the average load applied to the test pieces with l = 1000mm is lower than the average load applied to the test pieces with l = 750mm, because the longer the test piece the greater its slenderness, and less is the critical load. In contrast to the average loads, the mean displacements are higher for the test pieces with l = 1000mm, since their compliance is greater, they have the capacity to achieve greater displacements. In view of this, it is possible to conclude that the test results are acceptable.

Based on the results, and since the value of the calculated mass was, although little, lower than the reference value of class C24, to be conservative, **class C18** was chosen for the development of this work.

4.2 **Computational model**

As mention in chapter 1 a non-linear mechanical approach must be used for simulation of elastic gridshells, however it is assumed qualitative understanding of the behaviour of elastic timber gridshells can be investigated using an approximate approach presented in the following sections.

4.2.1 **Template path**

Digital tools, like modelling configuration and tri-dimensional parameterization, are utensils; significantly important around civil engineering and architecture. The architects have been proved that the lead should be taken not only in design, but also in managing the techniques of advanced building systems and their detailed construction. Designing cannot be understood as a linear activity for problem solving, but as a solution-orientated process where expert input is required for identifying and evaluating complex design issues. So, these technologies will ease the different stages of the project, from the moment of idealization, the proposal, construction and finish; saving time which would exhaustive and non-practice, achieving more accurate results and transforming the implementation of ideas into something graphic.

These tools that we propose to use can help create fantastic things, however, one must keep in mind that the approach to the design and programming strategy will condition or facilitate the rest of the project. It is necessary to think carefully before starting programming, because for each target / problematic there is more than one solution and some more versatile and practical than others. Requires that if foresee some problems and difficulties associated with each methodology and the parameters that will be flexible during the design process. In this sense, were determined up some priority characteristics that help define and choose the best way for the construction of three-dimensional model. So, the priorities are: A mesh like final Image; Greater number of parameters workable; Rapid creation of automatic model and parameters; give priority to the methods that make less use of drawing in rhinoceros; Since we are in an academic scope that that somehow can bring more knowledge to the user experience. Thus, there were used four strategies to create the model:

4.2.1.1 Use of volumes

The construction process of this model foresees the creation of each body building as an autonomous volume or composed by joining several simple volumes (Figure 4.7). The result should display a cluster of volumes that composes a whole. This method appears to be simpler for the model construction, since it only deals with the creation of simple shapes, however, in a more advanced stage will be less versatile for the independence of each volume.

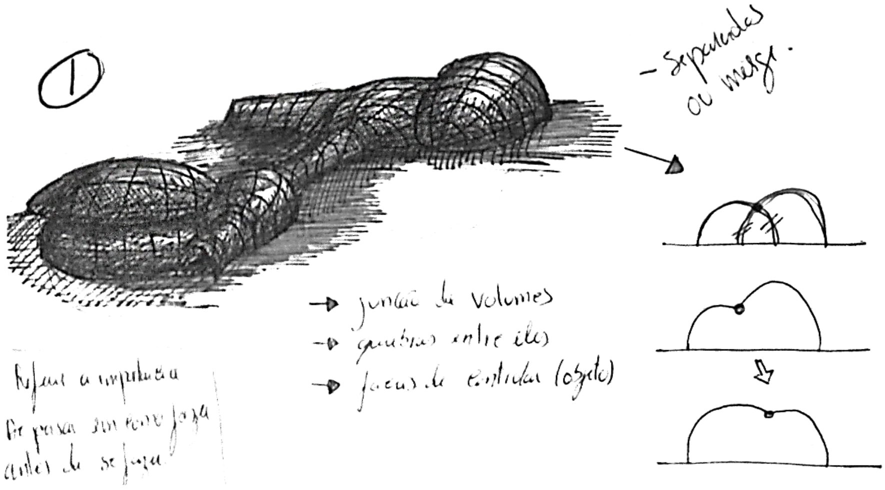


Figure 4.7- sketches of different methods 1.

4.2.1.2 Use of arches

This second method worked from the perimeter defined for the model sketching what would be the arches (Figure 4.8) starting and ending on the same limit. The expected result of this solution approach would be an amorphous form simplifying the whole process due to its flexibility, allowing a greater number of experiments. However, the resulting shape would always be dependent on the form of the arches, preventing welcome convex and concave shapes.

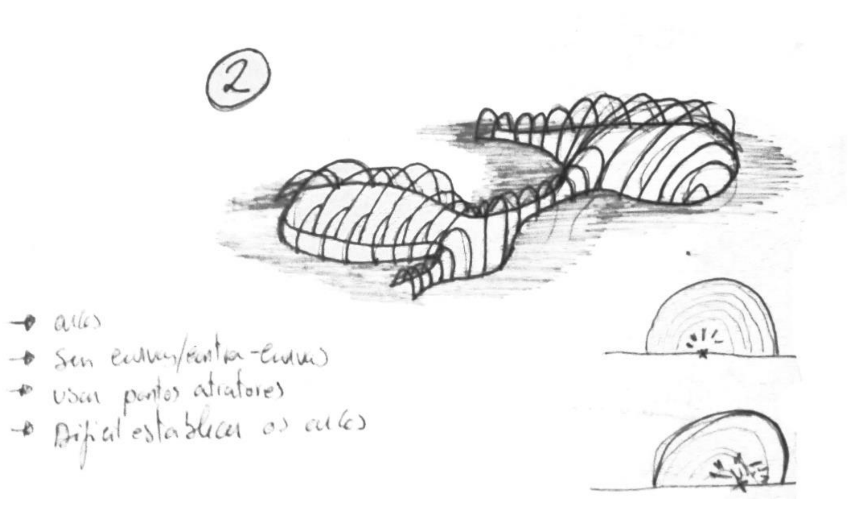


Figure 4.8- sketches of different methods 2.

4.2.1.3 Use of level curves

The use of level curves as a three-dimensional model programming strategy requires us to draw the level curves (Figure 4.9) at an early stage and over time it moves them in the vertical direction axis, so you can connect them with a surface to render the final image. This would result in a model that would be able to appear truncated by different levels. Although this strategy may seem simpler because it works in a horizontal plane, which is a common habit by most designers; hamper it's handling during the process of experiences and formal testing. Still, it would require a redesign of the curves in each new experience.

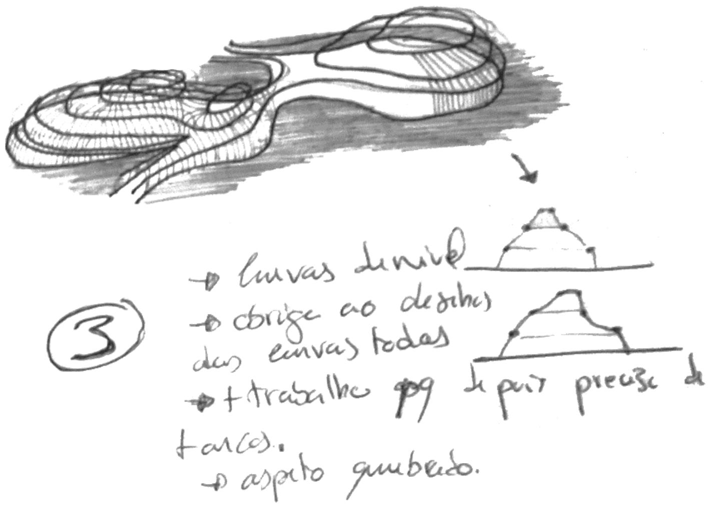


Figure 4.9- sketches of different methods 3.

4.2.1.4 Use of a mouldable mesh

Finally, to advance with this method one must create a base mesh in the vertical dimension and 0 from the use of attractor points can start to deform the grid to obtain the desired shape (Figure 4.10). It predicts the results in an organic way without breaks. This strategy allows since the beginning, where the use of parameters is easily changed during the entire process resulting in an image that matches the exact desired outcome.

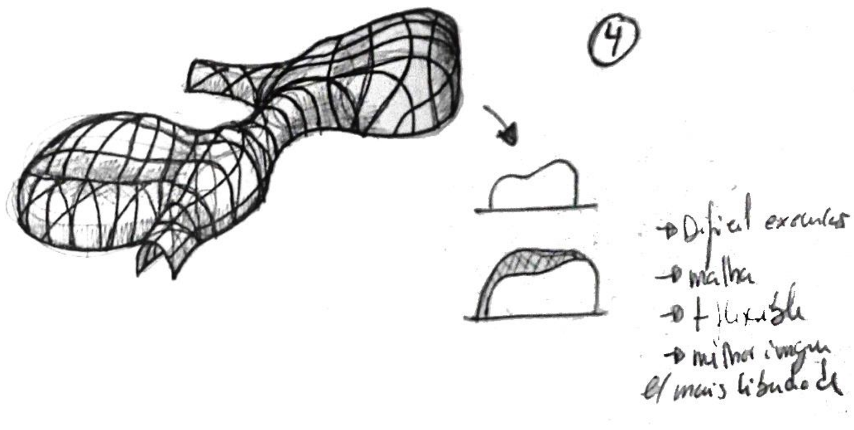


Figure 4.10- sketches of different methods 4.

Computers are tools that can help us to create fantastic things. However, one must keep in mind that the approach to the design and programming strategy will condition or facilitate the rest of the project. It is necessary to think carefully before starting programming, because for each target or problematic there is more than one solution and some more versatile and practical than others. It requires foreseeing some problems and difficulties associated with each methodology to ensure that the parameters will be flexible during the design process.

In this sense, it is necessary to establish some priority characteristics that will help define and choose the best way for the construction of three-dimensional models. It is very important that the methodology for building the parametric model to be versatile and manageable during the various phases of the project.

4.2.2 **Possible Software tools**

To make this work a useful and practical tool for readers, below we can find a brief description of some software's that could be used. The presented software deals with tools used at some point in this investigation. Today we can find in the market hundreds of options of different software's that can do the same things, however and by way of example, only those used will be presented.

4.2.2.1.1 Revit

Revit is software developed by Autodesk for use in construction projects (Soares, 2015). The software provides professionals of the various areas involved in a project with the possibility of developing their design and construction in a more structured and consistent way (Autodesk, 2016b). Revit has features from a variety of areas, including architecture and structural engineering (Autodesk, 2016b).

To date, several large and important projects have been developed with the help of this software. Highlights include the Shanghai Tower, the Botswana Innovation Center and the Bronx-Lebanon Hospital (Autodesk, 2016b) (Autodesk, 2016c), and the residences of Massachusetts College of Art and Design (MassArt) (Autodesk, 2016b).

4.2.2.1.2 Dynamo

Dynamo is a visual programming software developed by Autodesk that gives designers the ability to explore the design of parametric designs and automate tasks (Soares, 2015). This software provides support for problem resolution at a faster rhythm and more efficiently by designing workflows that guide the geometry and behaviour of design templates (Autodesk, 2016b).

The use of Dynamo, due to its characteristics, allows its users to generate sophisticated models through simple data, logic and analysis, extend their projects to interoperable workflows with Revit, solve complex geometric problems with visual logic, among other important aspects (Autodesk, 2016b).

4.2.2.1.3 Rhinoceros 3D

Rhinoceros 3D is a commercial 3D modelling software based on NURBS technology with the possibility of using and creating custom plug-ins (Robert McNeel & Associates, 2014). The NURBS technology implemented in Rhinoceros 3D is an important aspect of this program. NURBS, Non-Uniform Rational B-Splines, are mathematical representations of 3D geometries that can accurately describe any shape, from simple lines, circles, arcs or 2D curves to the surface or more complex 3D solid (Gomes, 2014). The amount of information required for the representation of a piece of geometry with NURBS is much smaller than the amount of information required for the common process of creating geometries through faceted approximations, which causes the geometry modification and the resulting representation is much faster. (Robert McNeel & Associates, 2014).

4.2.2.1.4 Grasshopper

Grasshopper is a visual programming language, running on Rhinoceros 3D. Within Grasshopper, you can create programs by dragging components on a screen, identical to Dynamo. There are several types of components, ranging from mathematical and logical operations to the creation and analysis of geometric shapes. In general, all components have a set of inputs and outputs, where the outputs of a component can be connected to the inputs of subsequent components, thus creating a sequence of instructions that repeats each time a change of a parameter occurs (Gomes, 2014).

Being Grasshopper running on Rhinoceros 3D, there is the possibility of taking advantage of the existing NURBS technology in Rhino. This feature, together with the possibility of creating user-defined algorithms, allows the creation of parametric models of complex geometries (Gomes, 2014), thus making it an excellent option to apply in the present case study.

4.2.2.1.5 Kangaroo Live Physics

Kangaroo is a Grasshopper plug-in, created by Daniel Piker, consisting of a set of custom components that integrate physical behaviour directly into Grasshopper's three-dimensional modelling environment, and allow you to run simulations as well as interact with the model during this execution (Piker, 2014). With custom components, it is possible to create elements, represented by dots, that have mass, position, and velocity that are governed by Newton's second law, and loads (Gomes, 2014). In addition, springs represented by lines, defined by their initial length, resting length, stiffness and damping coefficient can be created (Piker, 2014).

4.2.2.1.6 Karamba

Karamba is a parametric structural engineering tool that provides accurate analysis of trusses, frames and shells. This tool is fully integrated into Grasshopper's parametric design environment (Preisinger, 2016a). With this plug-in it becomes simpler to combine parameterized geometric models, finite element calculations and optimization algorithms such as the Galapagos (Rutten, 2016), component that will be dealt with above.

4.2.2.1.7 Galapagos

Galapagos is a Grasshopper command, which provides a generic platform for the application of evolutionary algorithms, to be used in a wide variety of problems by nonprogrammers (Rutten, 2016). These evolutionary algorithms are applied in a simple way, allowing to transmit to the command a problem, so that it finds the greater number of possible solutions for the same one.

4.2.2.1.8 Robot Structural Analysis

Robot Structural Analysis is a commercial software that could model, analyse and design a wide variety of structures including 2D and 3D trusses and shells. It allows the creation of advanced techniques of structural analysis, based on the finite element method and the simulation of various types of structures (Gomes, 2014). It is a widely used software that can handle large and complex structures, and which, in the context of structural gridshell, was used, for example, for the Savill Garden project (Richard Harris, Haskins, & Roynon, 2008).

4.2.2.1.9 GeometryGym

GeometryGym is a plug-in that provides OpenBIM tools and support to architects and engineers, among others in the field of construction. These tools have as main target the exchange of data of projects, among software's. Data exchange can be accomplished through the use of various OpenBIM formats and direct API interaction with various commercial software, including Revit, ArchiCAD (Graphisoft, 2016), Digital Project (digital project, 2016) and Tekla (Trimble, 2016). In addition to these, structural analysis models can be exchanged with many commercial analysis software (Mirtschin, 2016).

4.2.3 Model

The Revit + Dynamo suite proved to be extremely appealing, as both software's are signed by Autodesk, the same company that developed the Robot. This characteristic demonstrated a possible lack of interoperability problems between the tools, which would be very useful when exchanging the model between them.

The Rhino + Grasshopper set was chosen to run the models. These two numeric tools are commonly used in most of the papers and thesis related to structural meshwork. The justification for its use in this type of structure comes mainly from the aforementioned features, the use of visual programming in conjunction with NURBS technology. These features offer functions that make possible the execution of the form-finding process through the simulation of the constructive process. This aspect is of extreme relevance in the present case and makes the whole design process of the models simpler and faster.

To assist in performing the above functions, Grasshopper was supplemented with a few plug-ins. The two plug-ins used were Kangaroo Live Physics (Daniel, 2011), and the Karamba (Preisinger, 2016a), some models were developed using components that both software's had to offer (Figure 4.11).

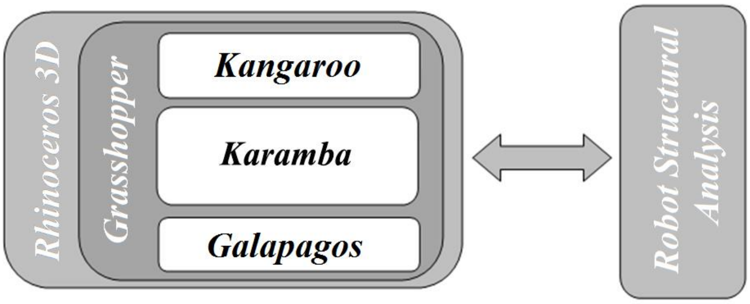


Figure 4.11- Scheme of use of the chosen digital tools (Gomes, 2014)

4.2.4 Model designed with Kangaroo commands

In this phase of the work several models were conceived with the use of the described digital tools. In order to find the final geometry of the mesh in a more precise way than in the execution of the physical model, a simulation of the constructive process was carried out in a digital form. The models were created according to the following process (Figure 4.12):

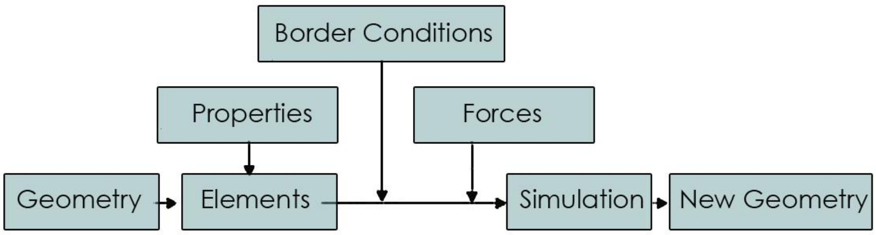


Figure 4.12- Process of obtaining the new shape of elastic structural mesh of wood simulating the constructive process (Dragos Naicu et al., 2014)

The first step was to define the base geometry of the "flat" mesh in a two-dimensional plane. For this, through Grasshopper commands, two series of lines were created, in a horizontal plane with dimension equal to 0, arranged in the directions x and y. Although

14 lines were created in each direction, spaced apart 0.7 meters, two slider components were left in order to allow changes to be made to these values at any time (see Figure 4.13). To finish the base geometry, boundaries were applied to the lines, through a curve with the desired shape for the mesh. This curve was defined manually in Rhino, which created the first limitation to the possible changes of the dimensions of the structure.

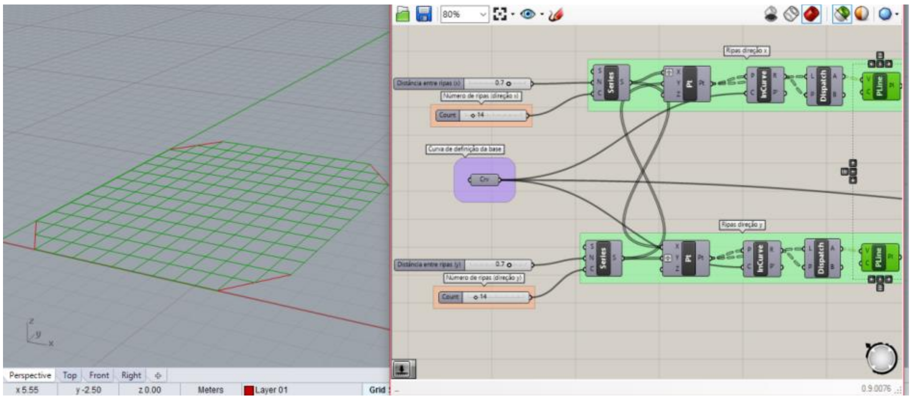


Figure 4.13- Design of base geometry

Then the base lines were cut at the points of interception between them, and transformed into elements of the spring type, with the aid of Kangaroo commands. Each of these elements were assigned two mechanical properties: rigidity and flexural strength. The rigidity took a value of 1350 kN/m, and the flexural strength of 18MPa (characteristic value of class C18), values previously calculated. Slider components were again left to easily change the properties of the material (Figure 4.14).

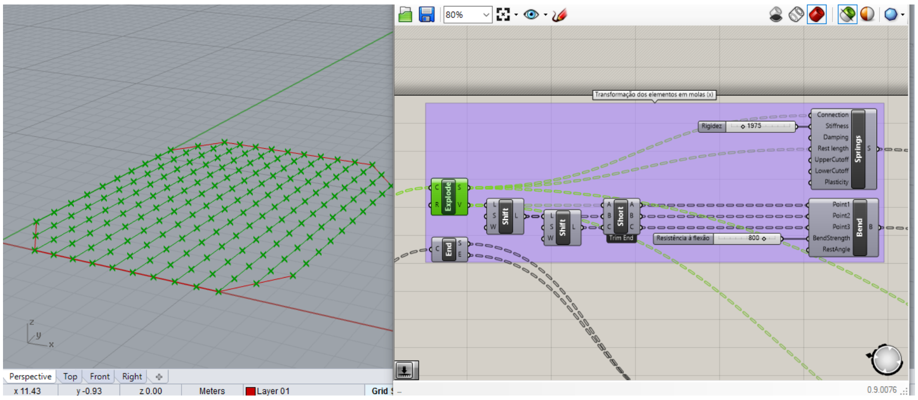


Figure 4.14- Assignment of mechanical properties

Before the deformation phase, the twelve points of the support zones were defined. These points would be responsible for the deformation that occurs on the mesh, because they represent the zones where the loads will be applied in the construction. Therefore, these points would only move horizontally, allowing rotation of the elements. An upward unit force was also applied in the z-direction, so that the mesh deformed correctly (Figure 4.15).

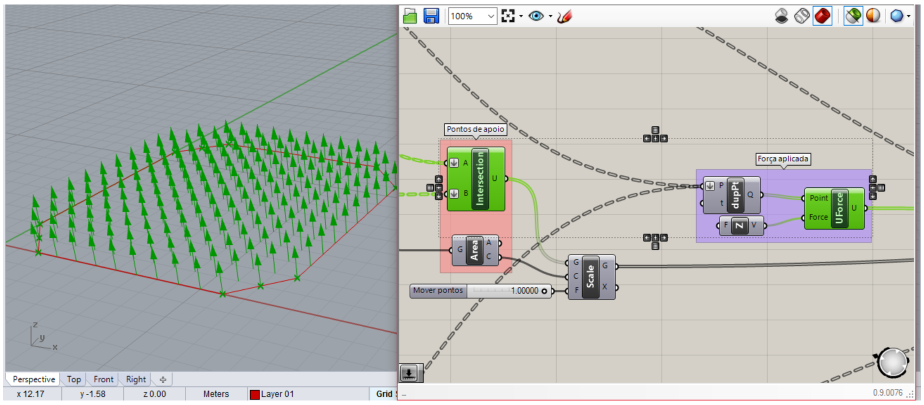


Figure 4.15- Support and unit force

To finalize the model, commands were added that allowed to simulate the construction of the mesh. During this phase the main command of the Kangaroo was used; the mechanism that activates the behaviours of the physics in the model. A simulation was then carried out until the gridshell reached equilibrium, thus obtaining the new geometry (Figure 4.16). The described process 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 and equilibrium form finding procedure (Maarten Kuijvenhoven, 2009).

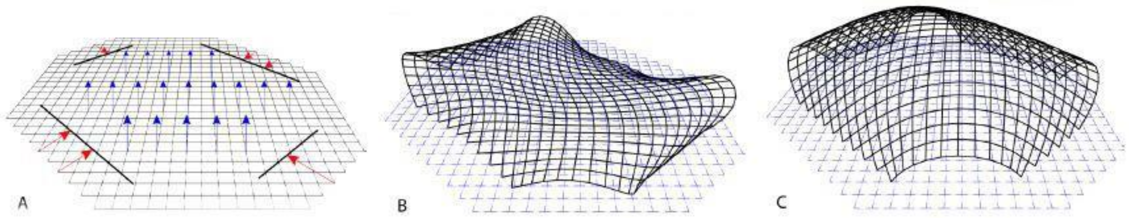


Figure 4.16- A: Initial flat shape with representation of the forces of deformation; B: Intermediate form; C: Final form (D Naicu, Harris, & Williams, 2014)

By using this mechanism, it is then possible to simulate the actual deformation of the mesh and obtain the desired new geometry (Figure 4.17).

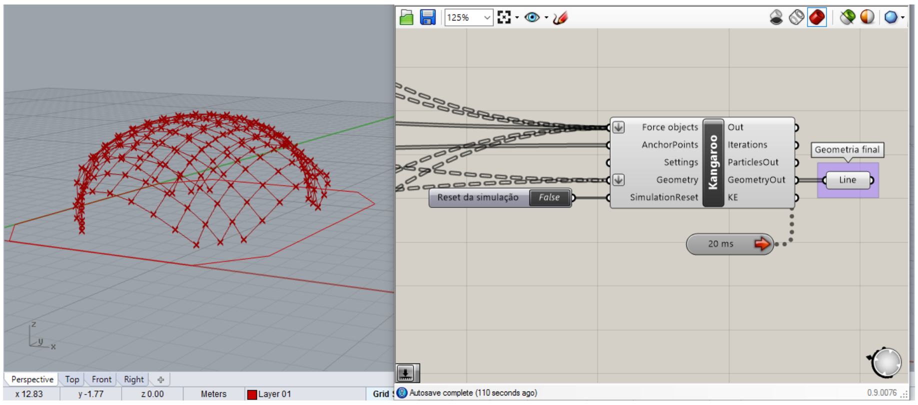


Figure 4.17- Simulation of the deformation of the mesh

Here the finalized model was compared with the physical model, to validate the final geometry obtained. Although the model had a shape like the physical model, its upper zone was much more rounded, which would mean that the height in the central zone of the mesh was superior to that presented by the physical model. Beyond this, another problem arises, related to the dimension of the squares of the mesh. Although some displacement was allowed in the bonding zones, as it will be shown later, this displacement would be limited, and would not have a value greater than 25mm. In this model in some areas this value reached 120mm, which was not acceptable. Both problems were generated by the way the mesh was designed in the model, through series of individual lines that had no limitations with respect to the displacement between the points of intersection, that is, the points that represent the links. With this free displacement the model did not present the behaviour desired, during the deformation, to what would be desired for the structure to construct.

4.2.5 **Model designed with Karamba**

In the same way as described above, a new model was created, this time with the help of the Karamba plug-in commands. The construction of the model was based on the same process as the previous one: defining the base geometry, assigning properties, boundary conditions and applied forces to finally simulate the deformation process.

The first difference from the previously created model was the construction of the two-dimensional mesh. In this model four points were defined to limit the base mesh. As done in the previous model, slider elements were placed for their easy change (see Figure 4.18).

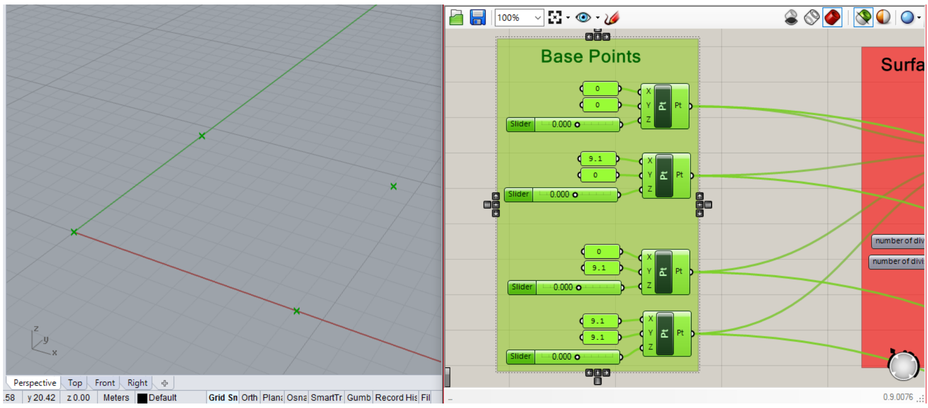


Figure 4.18- Definition of base boundary points

From the four points a surface was defined for the base. On this surface a mesh was defined with thirteen spaces in each direction, that is, fourteen lines in both directions. As in the previous case slider elements were left for the dimensional changes (Figure 4.19).

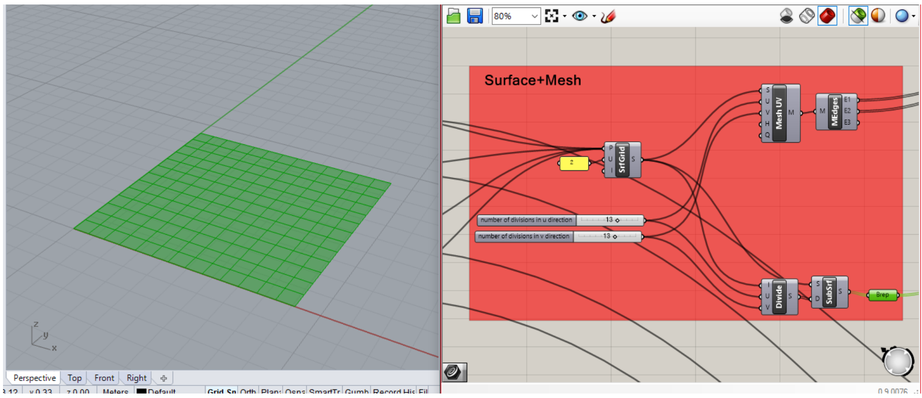


Figure 4.19- Creation of two-dimensional mesh

Then the elements of the base mesh were transformed into elements of the beam type, with the help of Karamba commands. Each of these elements were assigned a material defined by several mechanical properties: modulus of elasticity, modulus of shear and density. The modulus of elasticity assumed at a value of 9GPa (characteristic value of class C18), and the modulus of cut of 0.56GPa (characteristic value of class C18) the density of 416kg / m3, Values calculated previously. Similarly, to the previous model, at this stage, slider components were left so that the material properties could easily be changed. At this stage, the loads applied were further defined so that the mesh deformed in the desired direction (Figure 4.20).

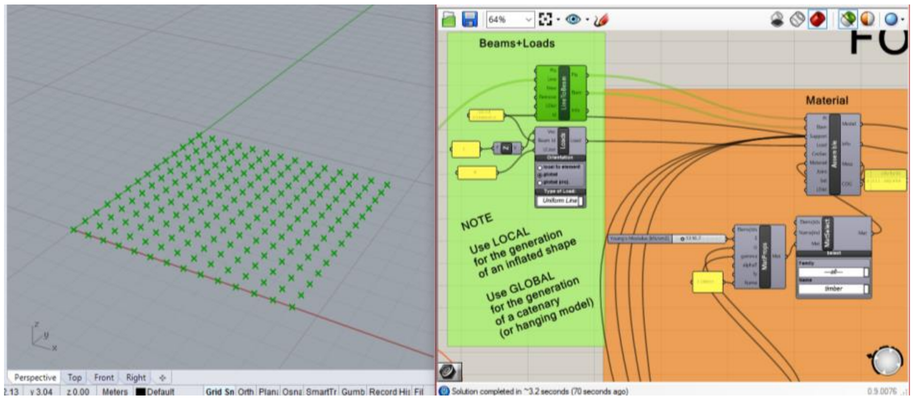


Figure 4.20- Assignment of material properties and direction of strain loads

Prior to the deformation of the mesh, support points were defined; that is, the points that would move in order to allow for the deformation of the structure to occur. These points are the same, created in the first step to limit the mesh. After the points were defined, they were also assigned the conditions of support, allowing them only to rotate in the three directions. For them to move, vectors were associated with the translation directions they would have to take (see Figure 4.21).

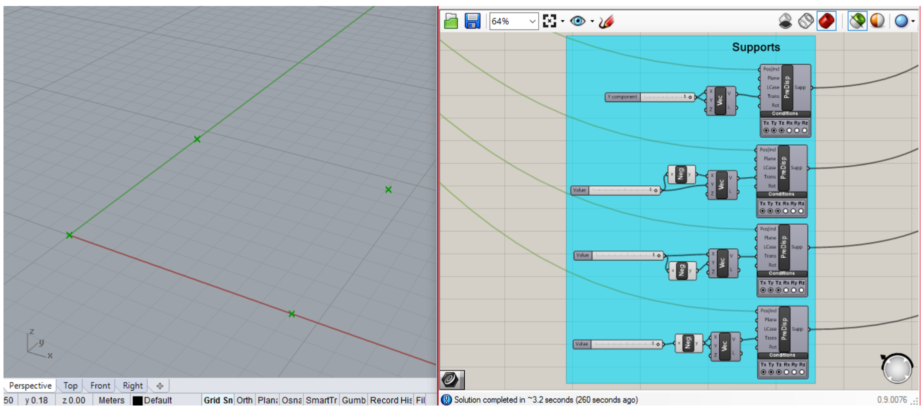


Figure 4.21- Definition of support points

The model had all the necessary elements to begin the deformation process. It was performed by the combination of a series of Karamba commands that allow the deformation forces to be applied until a maximum displacement is achieved. This maximum displacement allows defining the desired dimensions for the main areas of the mesh (Figure 4.22).

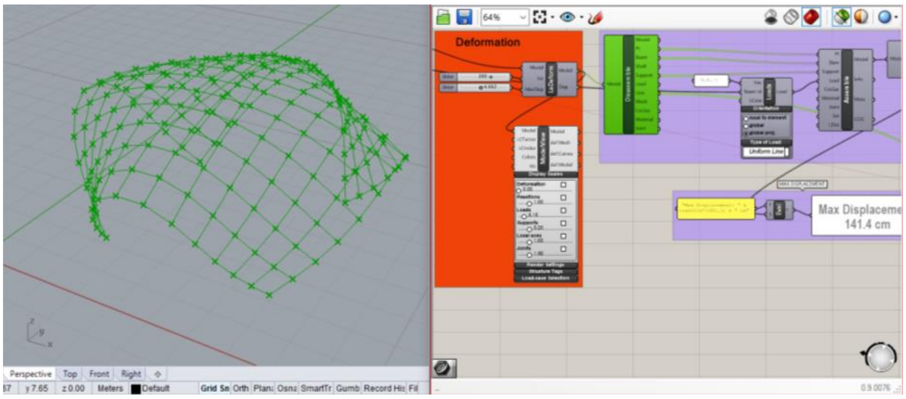


Figure 4.22- Simulation of the deformation process

After the deformation process, some Karamba commands were added to the model, just out of curiosity, allowing to observe some values related to the structure, such as the displacements of each node during the deformation, the values of the axial forces after the deformation, the representation of the applied loads, among others (see Figure 4.23).

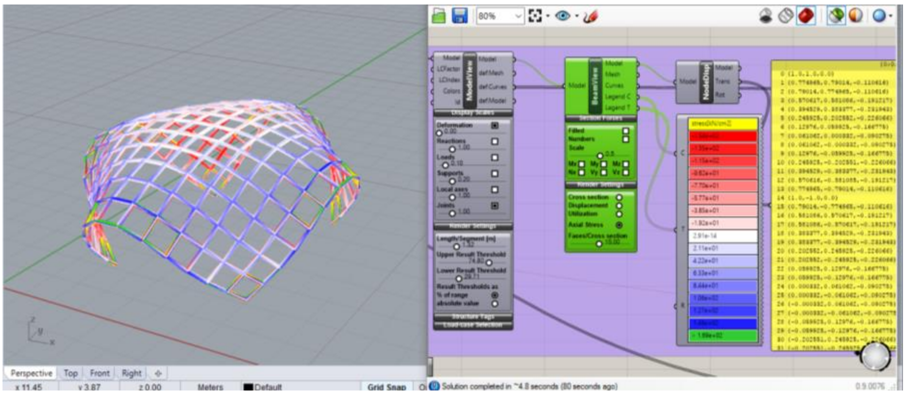


Figure 4.23- Representation of stresses in mesh elements

Due to the way the base mesh was created, unlike the previous model, it was not possible to duly define the geometric limits of the mesh before it was deformed, namely the cuts that would give rise to the support zones of the structure. To do this, it was necessary to eliminate the elements present in these unwanted zones, using a new solid element that intersected them. With this it was possible to eliminate all the elements that intersect with the solid, "cutting" the structure in the desired zone (see Figures 4.24).

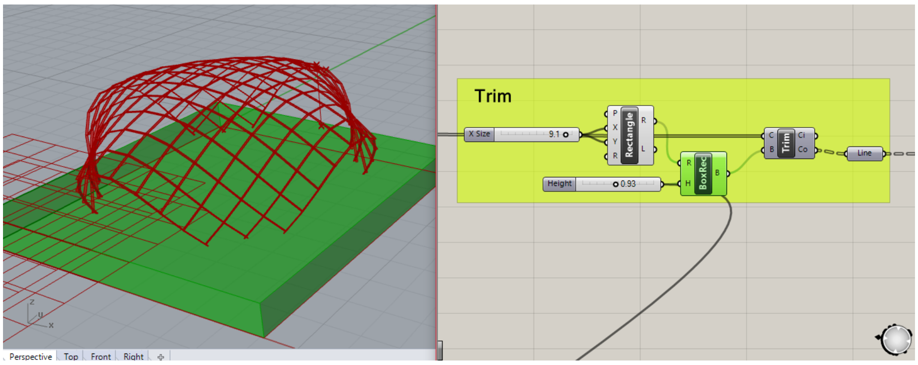


Figure 4.24- Cutting of unwanted elements

When the model was finalized, it was compared with the physical model and with the computational model previously developed. Unlike the model developed with Kangaroo commands, this model presented a shape closer to the physical model, more flattened in the upper zone. Unlike the previous model, the base mesh of this model was not created with individual lines, but rather through a single mesh. This aspect solved the problem of the displacement occurring at the points of intersection between the lines, which in this case no longer occurred by keeping the dimensions of the mesh squares always equal.

Once the models were compared to each other, on the physical model, we noticed that the model developed with the Karamba commands presents better results. Given this, a process of improvement of this model was initiated, so that later the structural calculation could be initiated. The first way to improve this model was to use the Galapagos command.

4.2.6 Use of the Galapagos in the model

In this case the Galapagos was used to improve the mesh model. This improvement was based on the on the interaction with the other commands and assist the form-finding process, so that the dimensions of the final geometry would meet the requirements imposed by the architecture. As previously mentioned, in the entrance areas, the desired height at the center of the arc is 2.1m. This being the main geometric requirement, a system was created that automatically deformed the mesh until the arches of the entrances had a height of 2.1m in the center (see Figure 4.25).

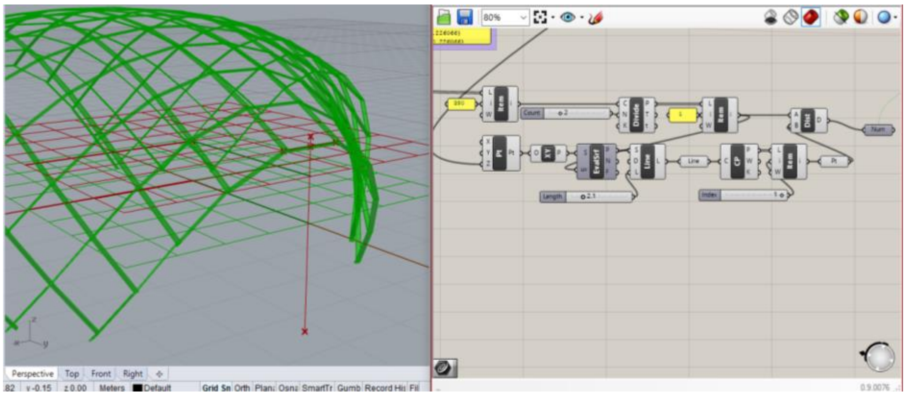


Figure 4.25- Creation of the automatic deformation system

The system created consists of a line with 2.1m in height that is always located at the center point of one of the arcs marked as entry points. The Galapagos is given the objective that the central point of the arc is as far as possible from the upper point of the line previously defined. it is then possible to change the value of the slider referring to the maximum displacement of the supports. With this, the Galapagos changed the displacement value until the centre point of the arc was at the lowest possible distance from the upper point of the line, presenting all possible solutions to the problem that was requested (Figure 4.26).

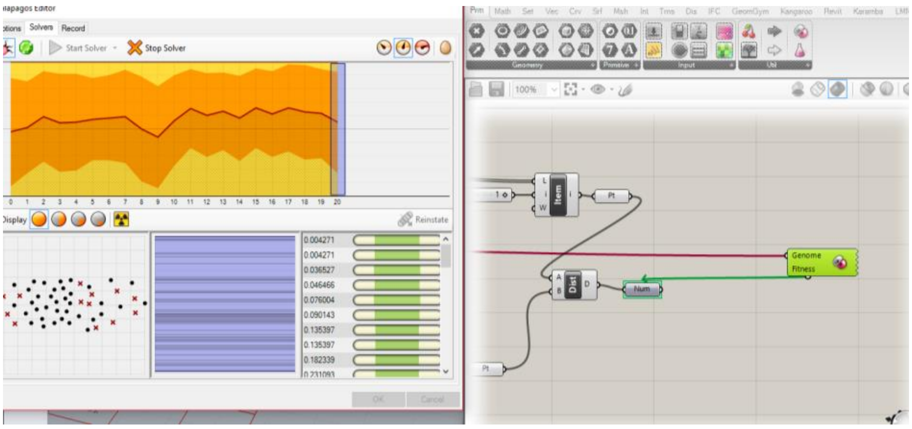


Figure 4.26- Execution process of Galapagos

4.2.7 **Model with double layer**

The second improvement of the model passes through the duplication of the unique layer system of the structure. As previously mentioned, the mesh to be constructed would consist of a double layer system, however the models created had only one layer. To change the model, the base points were duplicated, with the new points placed at a distance of 15mm (thickness of the wood elements to be used in the prototype) (Figure 4.27).

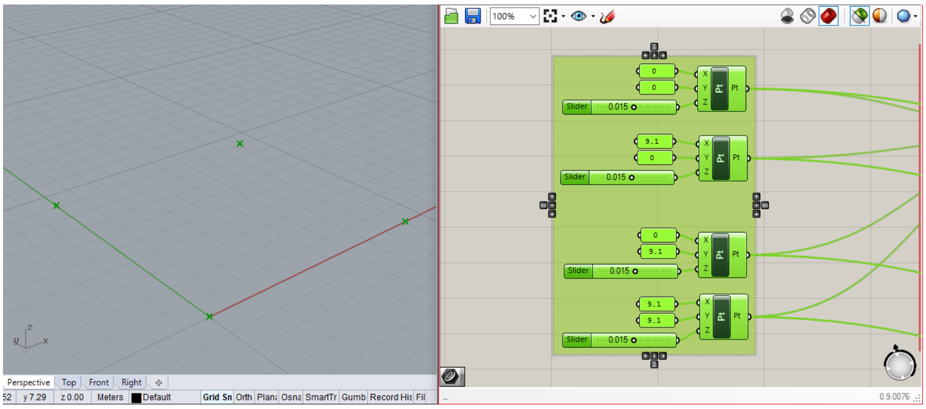


Figure 4.27- Creation of new points at a level of 0.015m

From these points a new surface was created, a new mesh base emerged and defined new support points. This new mesh was attached to the transformation components transforming the lines into existing beam members along with the mesh of the previous model. From this point on, there was no need to add more commands since the existing ones were used. The deformation process was performed again in the same way as it was done on the single layer mesh, until the desired shape was reached again (see Figure 4.28).

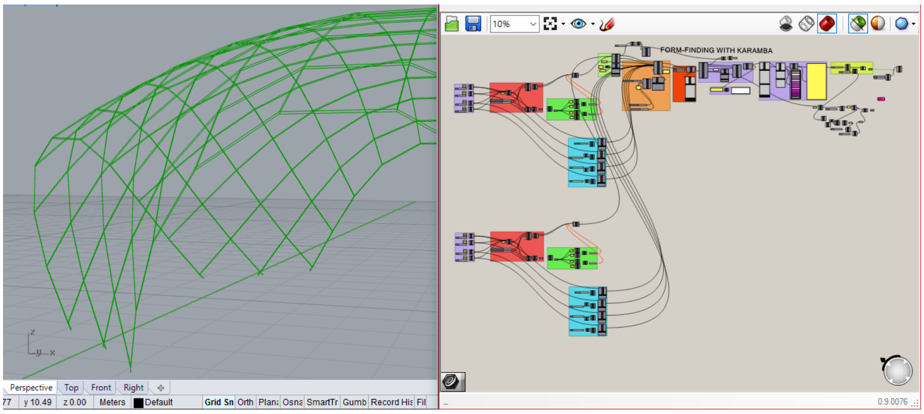


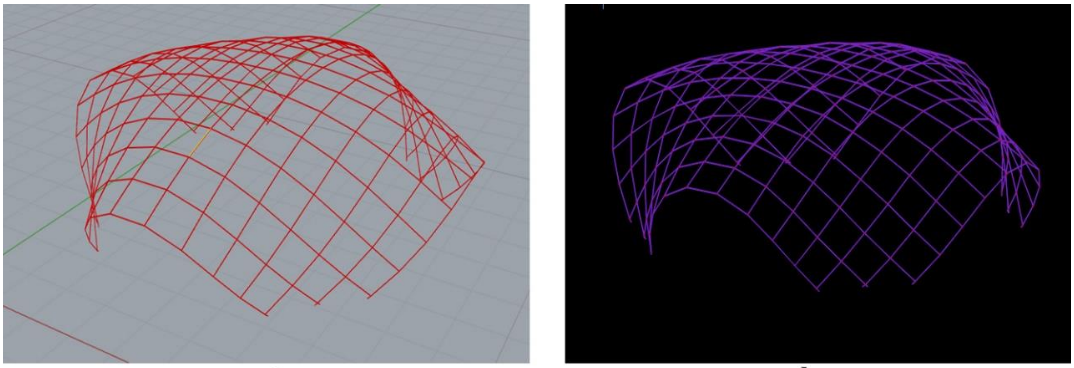
Figure 4.28- Deformation of the double layer gridshell

Considering that in this model two meshes were created separately, linking elements should be created between them. These elements are not created at this stage because they would oblige the creation of a much more complex model, which can be added at a later stage in the Robot, in a simpler way.

4.2.8 **Interoperability**

Since the geometric model of the mesh was complete, it was necessary to find a way to send it to the Robot, to later perform the structural analysis. Although Rhinoceros 5 leverages a direct export for more than 30 different file types, the Robot file, “. “rtd", was not one of the options. This being, a direct export was excluded as an option; it was necessary to look for other alternatives. The first of these alternatives came from another Grasshopper plug-in called GeometryGym (Mirtschin, 2016).

This plug-in was shown to be all-embracing, offering several commands that can be used in Grasshopper, associated to the Robot, that allowed the application of loads, creation of sections of the structural elements, the assignment of properties to these sections and even the creation of finite element meshes, among other functions. In addition to the functions associated with structural analysis, GeometryGym also provided other sets of dedicated Revit components and IFC files (buildingSMART, 2016). Nevertheless, the use of this plug-in in this work did not present good results. The export process, which seemed initially simple, generated constant errors in Rhino, which closed automatically.
This led to a second alternative, which consisted in exporting the Rhino model to an AutoCAD file (Autodesk, 2016a) ,”.dwg”, and consequently importing this new file into the Robot. For this procedure, as a first step, it was necessary to "materialize" the Grasshopper model in Rhino through the "bake" command, making Rhino no longer just a Grasshopper visualization platform. This process automatically divides all elements of the model by their intersection points, turning them into lines with an equal length of 0.7m. Then the model was exported to AutoCAD file, which did not cause any change in it (Figure 4.29).



a b

Figure 4.29-(a) Rhino Model and (b) AutoCAD Model

Finally, the model was imported into the Robot, which caused some changes. At this stage the lines of the model become bar elements, and the points of intersection are presented as nodes, making it possible to associate these elements with the properties of the materials that constitute them (see Figure 4.30). It should be noted that there is a need to evaluate the model whenever it is exported to find out if this export has caused any kind of change that might call into question the structural analysis.

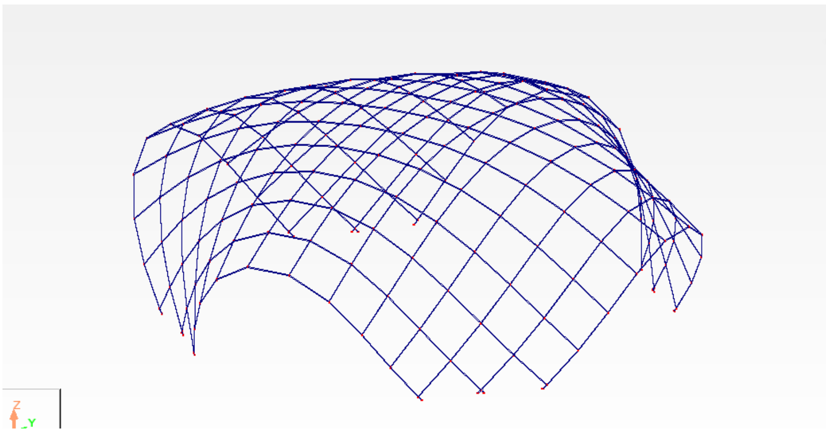


Figure 4.30- Robot Model

4.3 Structural analysis

With the conclusion of three-dimensional parametric models, and the method of model transition between software solved, structural analysis could be started. As already mentioned, several times, the structural calculation tool used was the Autodesk Robot Structural Analysis.

4.3.1 **Material**

The first step executed in the Robot, even before the import of the model, was the definition of the material. As previously defined, it was decided that a C18 strength class would be conventionally used for the properties of the timber to be used in the models. However, also conservatively, the calculated mass in the laboratory was maintained, as it presented a relatively higher value than that associated with the C18 class.

After defining the material, it was possible to create the desired cross sections for the constituent elements of the model. Regarding the section of slats, there was a particularity in the models, due to the double layer structural system. In the previous chapter, it was mentioned that two models were created, one of single layer and one of double layer. In order to compare two types of different models, it was opted to create a simplified model, where the double-layered system was initially represented with a single layer, followed by a more complex model with two layers. In order to represent the double system in the simplified model it was necessary to adopt a section that differed from the original one.

To represent the double-layered system with a single layer it was necessary to create a new section for the elements of this layer. Therefore, the double layered system consisted of two section elements 6x1.5cm^2 in each direction, it was necessary to create a single section with area and inertia equal to two of the original sections.
The new section was calculated, which would have to have an area of 18cm^2 and an inertia of 27cm^4. The result obtained was a section of 4.25x4.25cm^2, as shown in Figure 120.

4.3.2 **Models**

With the material and the defined sections, the single layer model and the double-layered model were imported into Robot, through the previously described process. A first fix needed on both models, was its bar and knot system. The simplified model presented its unique layer consisting of bars distributed in 2 directions (perpendicular) connected by us. In the case of the more complex model, the two layers are represented at different dimensions, consisting of bars in 2 directions (perpendicular), also connected by us but, the nodes of the two layers showed the need to be interconnected by rod elements which represented the actual connectors (steel screws) (see Figure 4.31). As such, in this more complex model representative bars were added as linkers between the points of the two layers. These bars were rigid and had a $5x10^{-8}m^4$.

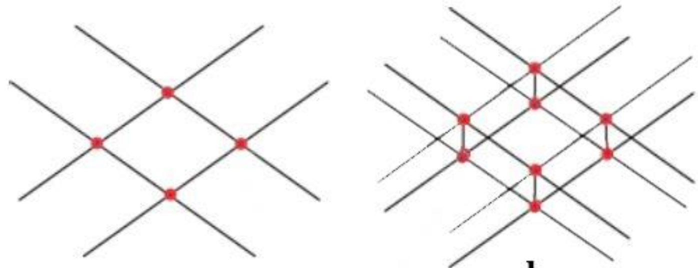


Figure 4.31- (a) Simplified model with only one-layer (b) and two-layer model

After importing the models, the supports were applied. In the present case, it was decided not to put in the model the wooden elements that support the support zones, in the prototype to be built. At a structural level these elements have no influence, serving only as assistance to the supports, to be placed in the structure during construction. In view of this, as supports, it was decided to place 3 fittings in each support location, since the 3 lowest dimension nodes of the model are the points of attachment to the support element of the structure. Structurally, this solution represents well the conditions of support, of the structure to be built (Figure 4.32).

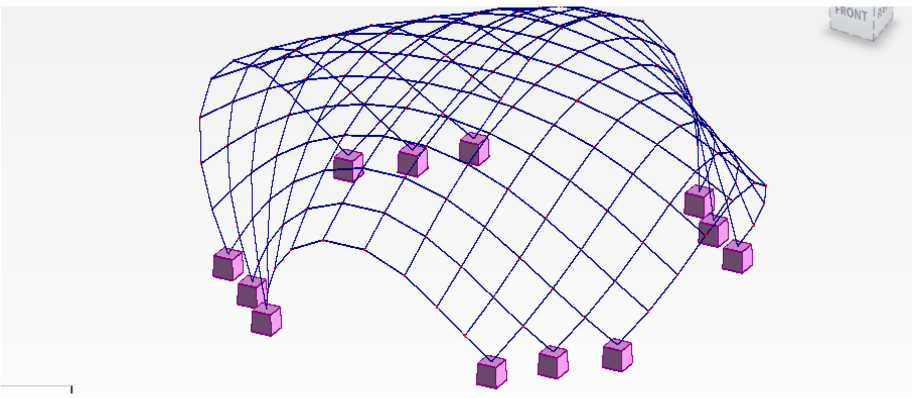


Figure 4.32- Placement of the supports in the model

At this stage, a small comparison can be made between the two models, relative to the quantity of structural elements. It is possible to analyse in Table 4.4 the types and quantities of elements present in each model.

Table 4.4- Comparison of the number of structural elements of the two models

Element Type	Simplified model	Double-layer model
Bar	340	896
Node	184	400
Support	12	24

As it can be seen in the above table, the simplified model has brought some advantages over the number of structural elements. With a smaller number of elements, it allowed to work with a "lighter" model, calculated and verified faster than the twin layered model.

4.3.2.1 Application of loads

In timber structural meshes, uniform loads are usually applied to the slats, bar to bar. This is because, even if a cover was to be applied to the mesh, it would be attached to the slats, and all loads, whether wind, snow, or any other, would be transferred directly to them.
In the present case, the mesh was not designed for the application of any type of cover, and its construction was in the Campus of Azurém of the University of Minho, in Guimarães, factors that justified the non-application of certain loads. Considering the low seismic hazard in the region of Guimarães, with a very low PGA (Peak Ground Acceleration) (CEN, 2010b), and the low weight and height of the structure, the seismic analysis was neglected. The application of snow loads was also neglected for two reasons. Firstly, the slats constituting the mesh have a very small width (6cm) and have a considerable slope in most of the structure, not allowing the snow to be allocated to them. In addition, the probability of snow in the city of Guimarães is very low (CEN, 2010a). Regarding the wind, this analysis was also neglected. This happens because, throughout the whole area of the structure, the empty area is higher than the area filled with structural elements. In addition, as in the case of snow, the elements have very small areas due to the small widths in which the wind has little influence.
Considering the quantity of cargoes that are neglected, there are only two cases of cargo to be considered; one is the weight itself, the load applied automatically by Robot, and the only one that will be considered for this structure. The second case is an accidental

load, derived from the possible rise of individuals onto the structure, which would be represented by a vertical load of 1kN in the centre of an isolated element, the most unfavourable situation.
Once the loads were defined, the models were ready for the structural calculation process.

4.3.2.2 Simplified model

We began by analysing the simplified model. As previously mentioned, the only load case applied to the structure was its own weight, the accidental load being applied later on an isolated element. After the definition of the load case and the calculation, the results were analysed.

In the following Figures and in Table 4.5 are presented the reactions and the maximum stresses caused by the own weight of the structure in its elements.

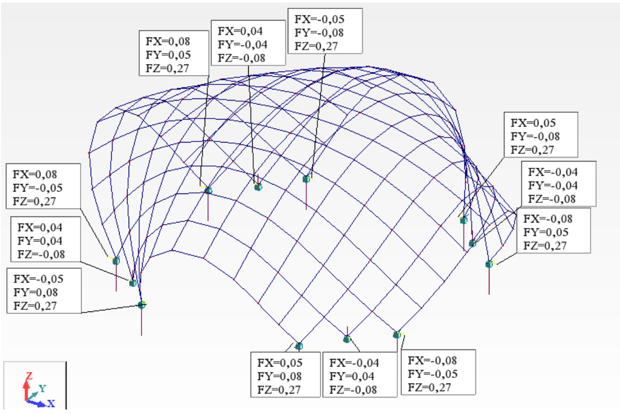


Figure 4.33- Reactions

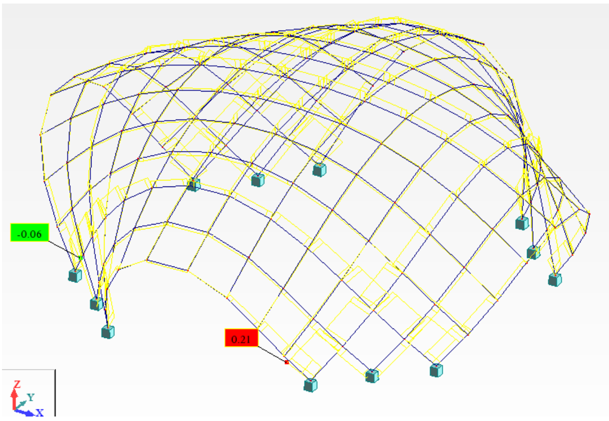


Figure 4.34- Axial stress (Fx)

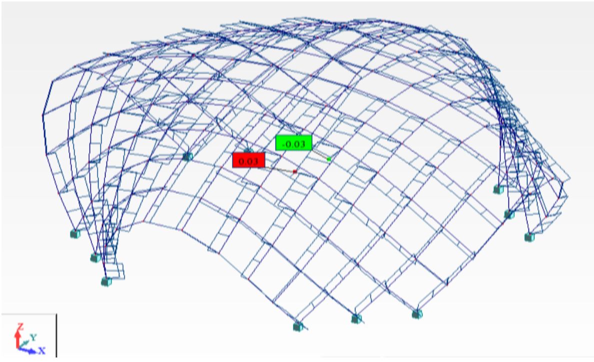


Figure 4.35- Transverse stress (Fy)

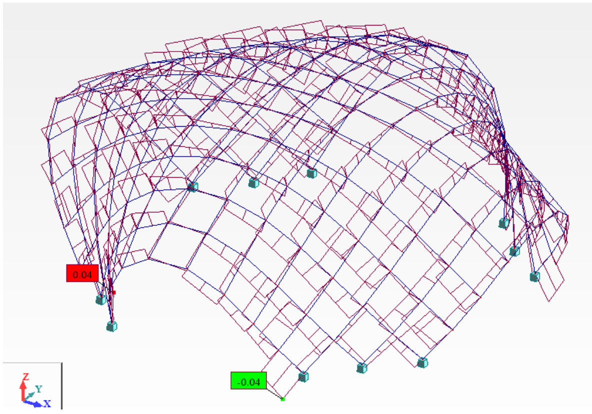


Figure 4.36- Transverse stress (Fz)

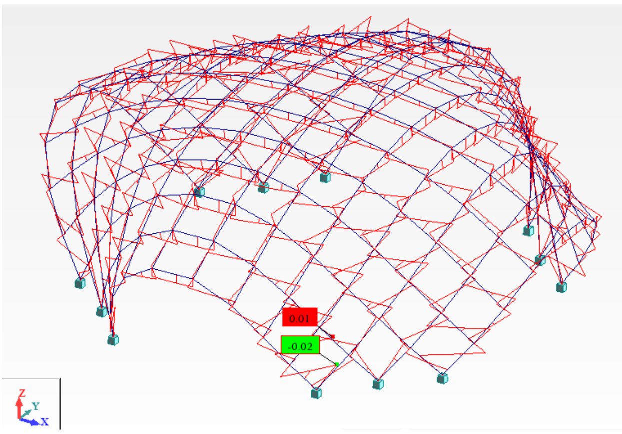


Figure 4.37- Bending moment in y (My)

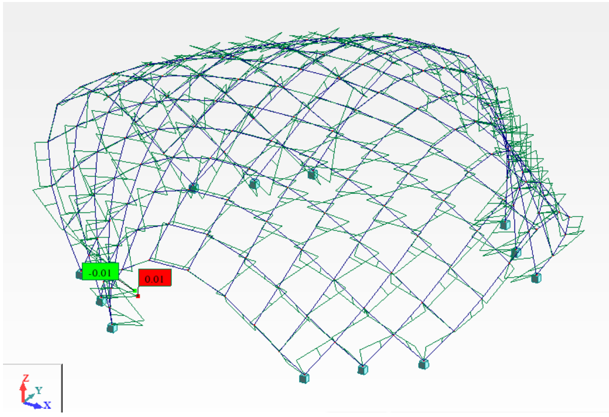


Figure 4.38- Bending moment in z (Mz)

Table 4.5- Maximum effort

	Stresses				
	F_x	F_y	F_z	M_y	M_z
	[kN]	[kN]	[kN]	[kNm]	[kNm]
Max. (MPa) positive value	0,21	0,03	0,04	0,01	0,01
Bar	46	91	331	71	293
Maximum negative value	-0,06	-0,03	-0,04	-0,02	-0,01
Bar	294	88	315	315	294

In order to verify the correct dimension of the structural elements, the "Timber Member Design" menu of Robot was used. This menu allowed to verify that all the elements of the structure had the minimum dimensions necessary to resist the case of load applied, according to Eurocode 5 (CEN, 2004).

To validate the analysis by Robot, the dimensions of the most stressed elements of the structure were verified manually according to the EC5. For these elements, the manual calculation validated the Robot analysis, with small variations in the results.

Regarding the deformation, Robot presented a displacement of 0.9m in the centre of the structure due to its own weight (see Figure 3.39). This displacement had a very high value that could raise several problems.

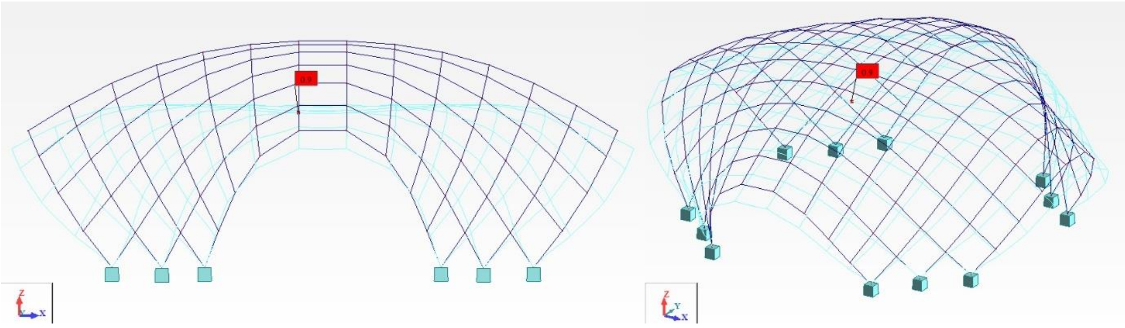


Figure 4.39- Deformation

4.3.2.3 Twin layer Model

Then the 2-layered model was analysed. As in the previous case the only load case applied to the structure was the self-weight. After the definition of the load case and carrying out the calculations the results analysis was initiated, repeating the process of the previous model.

In the following Figures and in Table 4.6 are presented the reactions and the maximum efforts caused by the structures own weight in its elements.

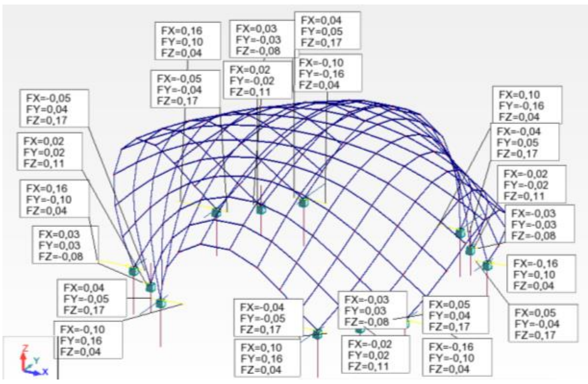


Figure 4.40- Reactions

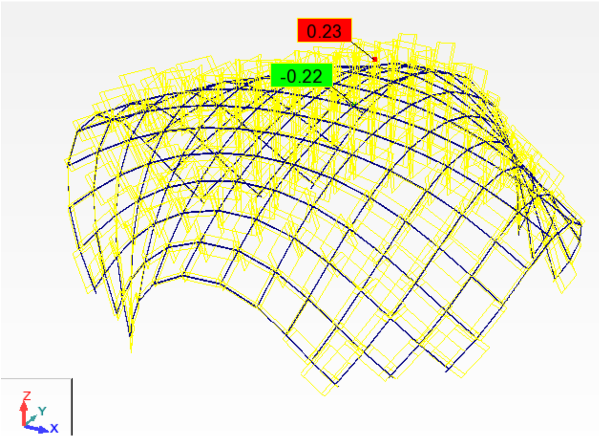


Figure 4.41- Axial stress (Fx)

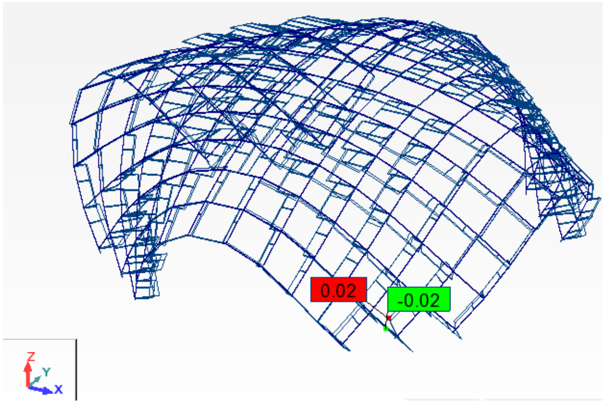


Figure 4.42- Transverse stress (Fy)

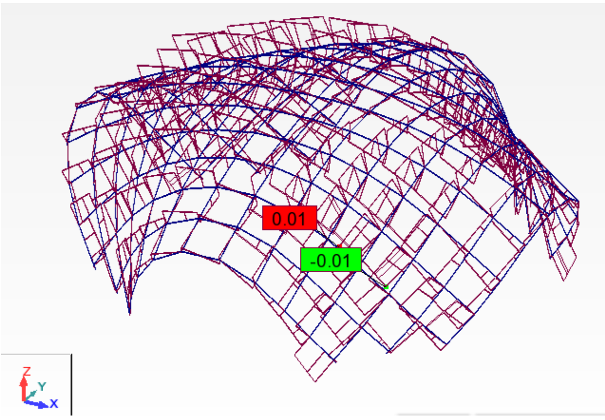


Figure 4.43- Transverse stress (Fz)

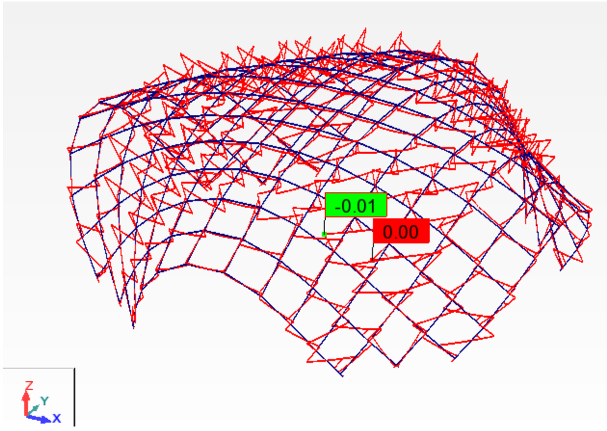


Figure 4.44- Bending moment along y (My) direction

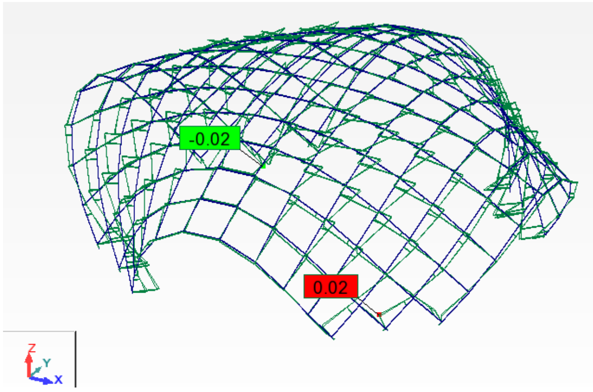


Figure 4.45- Bending moment along z (Mz)direction

Table 4.6- Maximum effort

	Stresses				
	F_x	F_y	F_z	M_y	M_z
	[kN]	[kN]	[kN]	[kNm]	[kNm]
Max. (MPa) positive value	0,23	0,02	0,01	$4x10^{-6}$	0,02
Bar	137	24	428	425	24
Max. negative value	-0,22	-0,02	-0,01	-0,01	-0,02
Bar	513	48	425	453	279

As in the model presented previously, the correct dimensioning of the elements of the structure was verified, using the "Timber Member Design" menu in Robot.

Also, as in the previous model, the Robot analysis was validated through the manual verification, according to EC5, verifying the dimensions of the most stressed elements of the structure. For these elements, the manual calculation validated the Robot analysis, as in the previous model with small variations in the results.

In relation to the deformation, the Robot model presented a displacement of 2m in the center of the structure due to its own weight, similar to the previous model, however with a relatively higher value (Figure 4.46).

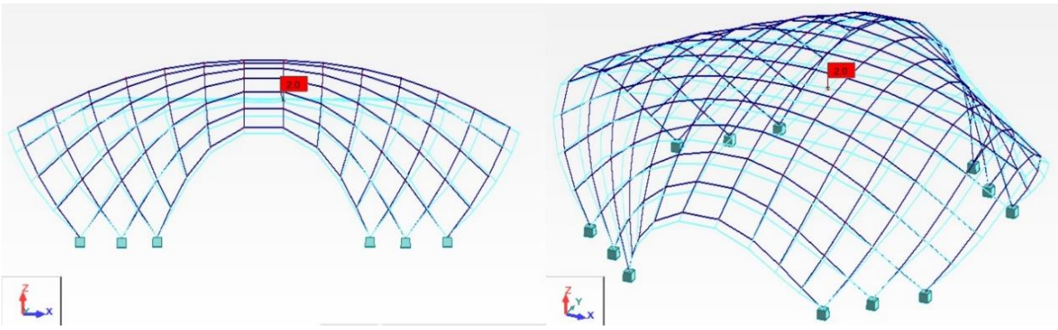


Figure 4.46- Deformation

4.3.2.4 Comparation between models

With the two models completed and analysed it was possible to withdraw several conclusions about the structure. However, it is notorious that there are some differences in the results obtained between the simplified model and the double-layered model. The main differences in the results of the models are associated to both the stresses caused by its own weight, and the deformation of the structure caused by the same load case. These are mainly caused by the total weight of the two models. The simplified model has a relatively lower weight than the double-layered model, caused by the existence of metallic elements that connect the two layers of the mesh in the second model.

With this comparison of results, it is perceptible that the choice of the double-layered model for the analysis of this structure is a more conservative choice, offering more unfavourable results. In addition to this factor, the model also allowed verification of the metallic elements to be used in the connections.

4.3.3 Application of accidental loading

A second load case, related to an accidental load, derived from the possible rise of individuals onto the structure through the wood elements, this would also be applied, which would be represented by a point load of 1kN in the centre of the most unfavourable situation. In order to simplify this application of the load, a model was created with the system of 2 layers, with isolated elements with 0.7m between each, where its own weight and the accidental load were applied, refer to (Figure 4.47).

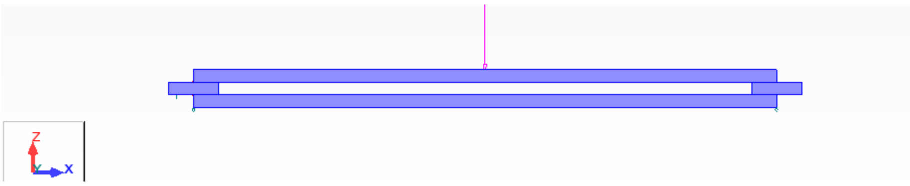


Figure 4.47- Isolated system with accidental live load representation

Considering the low weight of the insulated system, the analysis is focused on accidental loading, which results in the efforts shown in the following Figures and Table 4.7.

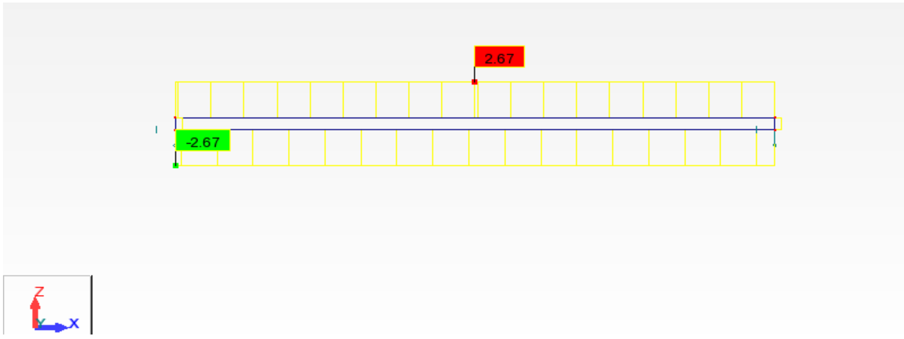


Figure 4.48- Axial stress (Fx)

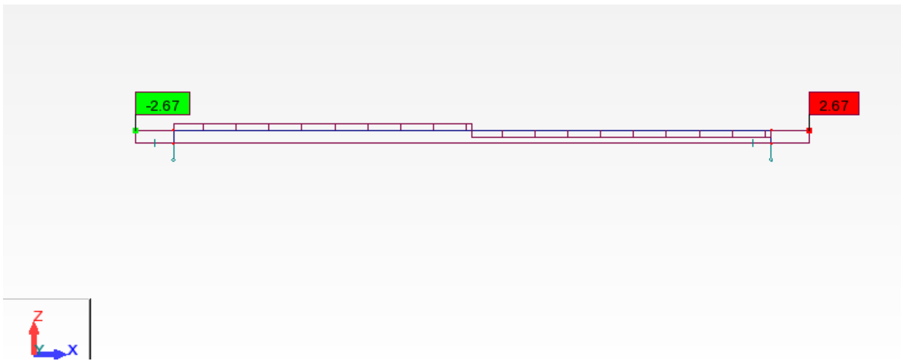


Figure 4.49- Transverse stress (Fz)

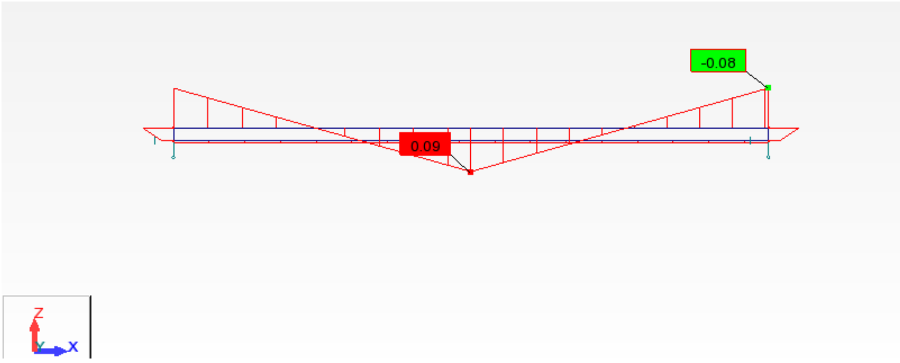


Figure 4.50- Bending moment in y (My)

Table 4.7- Maximum effort

Stresses	**F_x**	**F_z**	**M_y**
	[kN]	[kN]	[kNm]
Max. (MPa) positive value	2,67	2,67	0,09
Bar	2	3	2
Max. negative value	-2,67	-2,67	-0,08
Bar	1	4	2

In the models presented previously, the dimensions of the elements of the structure were verified, using the "Timber Member Design" menu of the Robot. However, the superior element, the harder one, did not verify a correct size, not resisting the applied efforts.
In order to validate the Robot analysis, the dimensions of the upper element of the system, they were manually verified according to the Eurocode 5. As predicted, the Robot analysis is validated, meaning that the element section is not able to withstand the applied load. Despite the non-verification of the dimensioning of the section of the elements of the structure, for this accidental load it was decided to maintain it. This occurs because there is no need to allow the mesh to be "climbed" that is, the structure in question is intended to have the same operation as a cover, and not as an accessible platform. Given this, through the structural analysis performed it is assumed that the structure has the capacity to resist its own weight, the only load that is expected to act on it during its lifetime.

In order to find out the maximum possible load to be applied to the centre of a wooden lath inserted in the mesh system, the previously presented process was repeated several times until the value of the accidental load for which the lath verified the size was reached.

The final value reached for this load was 0.26kN. In the following Figures and in Table 4.8, presents the results obtained from the Robot model for the point load of 0.26kN in the centre of the upper slat of the system.

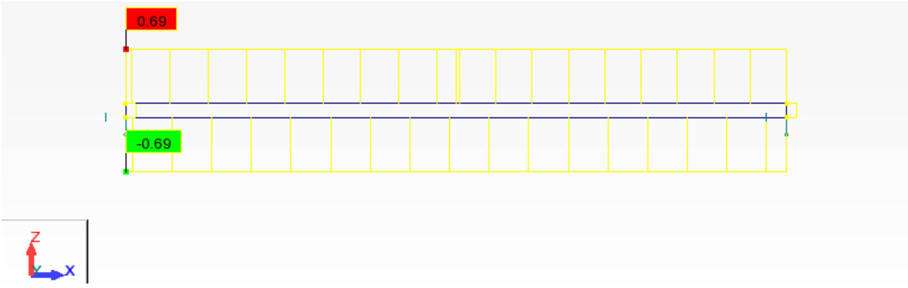


Figure 4.51- Axial stress (Fx)

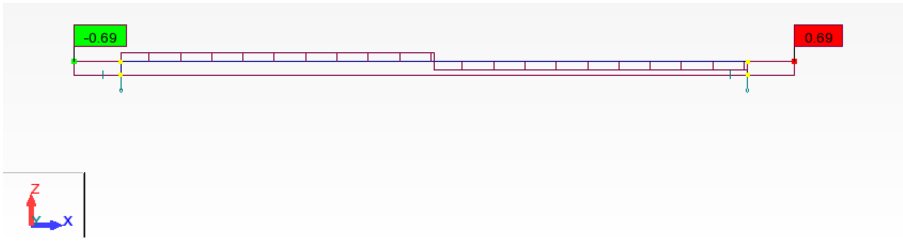


Figure 4.52- Transverse stress (Fz)

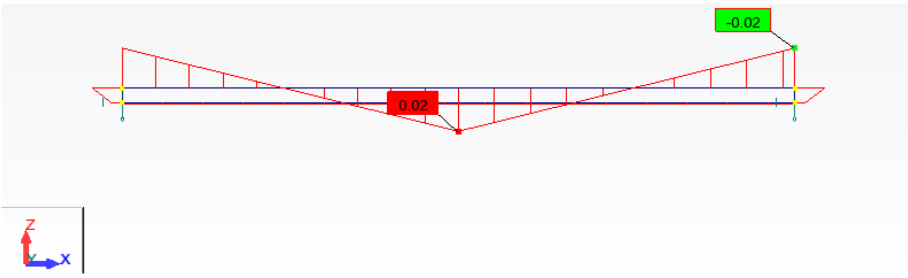


Figure 4.53- Bending moment in y (My)

Table 4.8- Maximum effort

	Stresses		
	F_x	F_z	M_y
	[kN]	[kN]	[kNm]
Max. (MPa) positive value	0,69	0,69	0,02
Bar	2	3	2
Max. negative value	0,69	-0,69	-0,02
Bar	1	4	2

The design of the elements of the structure was verified by using the "Timber Member Design" menu of Robot again, and unlike the previous check, the upper element, verified a correct dimensioning for the new defined load.

4.3.4 **Analysis of the connection elements**

As a solution for the connections, partially threaded M8 steel screws were adopted. The choice of the binders was based essentially on examples of other existing structural meshes, because, due to the need to execute the prototype, it would not be possible to perform the calculations necessary to optimize the metal binder to be used. However, in this type of construction, the strength of the connecting elements is not of considerable importance since its function is essentially to keep the wood elements in their positions.

As mentioned before, the double-layered model is the only one in which the binding elements are present, and the analysis was made through them. Based on the above model, the values of the maximum transverse forces on the bonding elements were removed, the only efforts of considerable values in these elements (Figure 4.54).

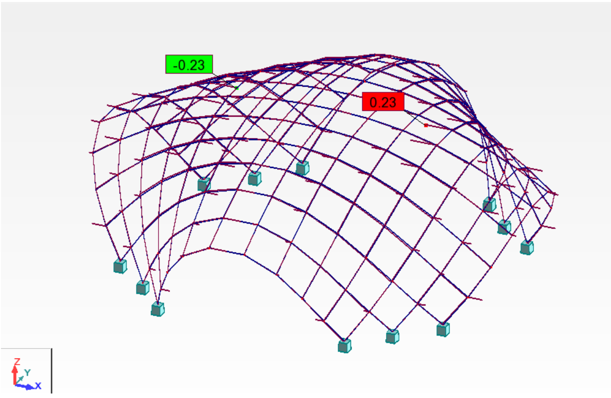


Figure 4.54- Transverse stress (Fz)

Based on the results of the transversal efforts, using the "Steel Design" menu of Robot, the size of the connectors was verified.

The section of the elements has been verified, allowing to assume that the M8 bolt can be used in the structure, nevertheless, it is possible to verify that all the results are far from putting the section of the screw at risk, that is, the structure could be optimized by decreasing the screw section.

4.4 Summary

In this fourth chapter, a case study it was presented and used to test the process of merge the information and characteristics of the material (timber) with a digital model. Were also briefly presented some of the software that can be used as well as the main advantages of using digital tools during the design of a Gridshell, such as the speed of the process, the ease in geometry manageability and the versatility of the model. Also, it was outlining the way they are facilitating the computational process, generating a relationship between structure, material and form based upon the logic of the manufacturing technologies.

To be capable to calculate the structural behaviour of the gridshell, the design model should be a precise approximation of the outcome of the construction, here the structural analyse were made simpler, considering only the geometry of the shape, however, as could be seen, this process manages to bring a great precision to the process of construction of these structures, undoing some uncertainties and fears on the part of the designers.

Chapter 5 continues to use the same case study for the continuation of this experimentation process. Following the construction phase of the structure presented and modelled here.

5 Design and Construction

Case Study

On the previous chapters, the focus will now be addressed at the design and assemblage methods applied during the construction of the case study

The entire construction process is described in detail and accompanied by some comments on each situation that was found during the construction of gridshell. In addition to the description of everything in relation to Gridshell 1.0, based on the conclusions a new mesh that was created will also be presented. Gridshell2.0 is an exercise that comes after Gridshell1.0 to find the best solution that relates optimizes efficiency, cost and feasibility.

5.1 Gridshell 1.0

This test aims to understand the designing approach, the structural behaviour and the construction process of a timber gridshell. Furthermore, it is intended to understand what engineering has to offer in a practical way, the design as a methodology and support (Fernandes & Branco, 2018). The procedure applied is based on a tectonic approach (Hurol, 2016) to the design of the gridshells. It is expected that these results be a summary of general concepts 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.

5.1.1 Workshop

Although it is a structure with reduced-size dimensions, it was necessary to find helpers to assist in the construction of the prototype. A workshop was organized, called "Workshop: Spatial timber gridshells", in partnership with EAUM, which allowed the participation of potential research partners, both in the construction and in the acquisition of knowledge about structural gridshell. During the 13th and 14th of June 2016, this elastic timber gridshell was built in the garden of the Architecture School, at the Azurém Campus of the University of Minho (EAUM).

5.1.1.1 Location

The place chosen for the construction of the prototype was the garden of the School of Architecture of the University of Minho (EAUM) (Figure 5.1). Which it is necessary to mention that it is a space with a rugged topography, having a variety of slopes, had implications on choosing the exact point, once found the implantation point had a slope of approximately 5/6 radian degrees.

Figure 5.1- Universidade do Minho – Escola de Arquitetura (EAUM) Gardens

5.1.2 Design approach phase

To develop such structures and to enable them to be more popular, it is necessary to advance with a useful process of design. There are several requirements that must be considered, starting with the examples to be studied until the modeling of the geometry through drawing, physical models and three-dimensional digital models. These tools have to fill the gap between the aesthetic and functional requirements determined beforehand as well as the shape of the gridshell that can actually be built (Maarten Kuijvenhoven, 2009).

These ideas / general rules to be presented, were followed in the process of designing the case study. Due to the little feedback and know-how available on the practice of 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.

5.1.2.1 Sketches

In the present case study, the method crossed between theory and practice went through several phases. It was not straightforward, it was experimental and trial and error; starting with some handmade sketches looking at a simple geometry that was able to demonstrate different possible situations / problems, as it is possible to see in the Figure 5.2.

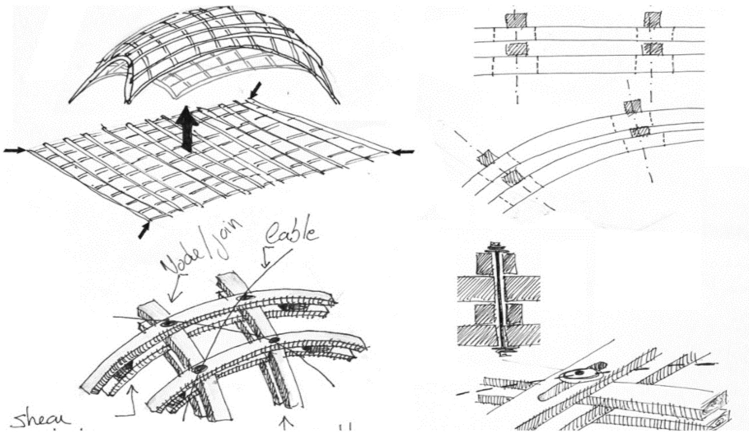


Figure 5.2- Sketch's examples

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

5.1.2.2 Physical Model

After defining the overall dimensions, height, area, grid mesh, it was time to carry out the idea in a model. This model was constructed, at 1:10 scale, as shown in the figure XX. This model was not an exact replica of the gridshell to be constructed, but rather an image of the general concept(Liddell, 2015). Its objective was to demonstrate the behaviour of the different lines and there was no doubt about the forces to torsion, bending and possible collapse movements (Toussaint, 2007).
The importance of this first phase 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 tested previously in the drawing phase, due to the use of the material, the costs involved, and space needed.

This physical approach aimed to provide a view of the final geometry of the mesh, through the process of deformation of a small-scale grid. In addition, it provided a big advantage, the possibility to test the construction sequence, and to perceive the behaviour of the structure when subject to the defined constructive method. The elaboration of this model also allowed the identification of possible problems that could occur during the deformation, so they could be prevented during the assemblage of the real scale prototype.

First, it was defined that the model would be executed with a 1/10 scale compared to the final prototype. Despite the changes to the architectural design of the mesh, the physical model, due to the previous acquisition of the elements to be used, was conceived with the geometry initially foreseen. It was defined that the model was made of timber elements with the properties as close as possible to those of the timber to be used in the prototype of real scale. For this, the elements to be acquired were timber of tola type, with a resistance class of C20, slightly superior to the spruce. These elements would have several lengths, which would be continuous throughout the length of the mesh, differently from the actual prototype. In the case of the section, it would have a correct scale, 10 times smaller than that of the elements that were considered to be used in the prototype. Due to the small dimensions of the timber elements, the opening of slits in the areas of the connections was very complex. It was decided to use a wire of 0.5mm in diameter (usually used in jewellery), because of its ductility, make it easier to simulate the connections. For the execution of the model 40 elements of timber were used, as shown in Table 5.1

Table 5.1- Timber specimens

Specimens	**Length**	**h**	**B**	**Quantity**
	[mm]	[mm]	[mm]	
A	600	2,5	6	4
B	700			4
C	800			4
D	900			24
E	213			4

Starting the process of model construction, holes with a diameter of 2mm were made at the ends of all timber slots, to make these connections fixed, and not allow the elements to exceed the limits of the mesh (Figure 5.3).

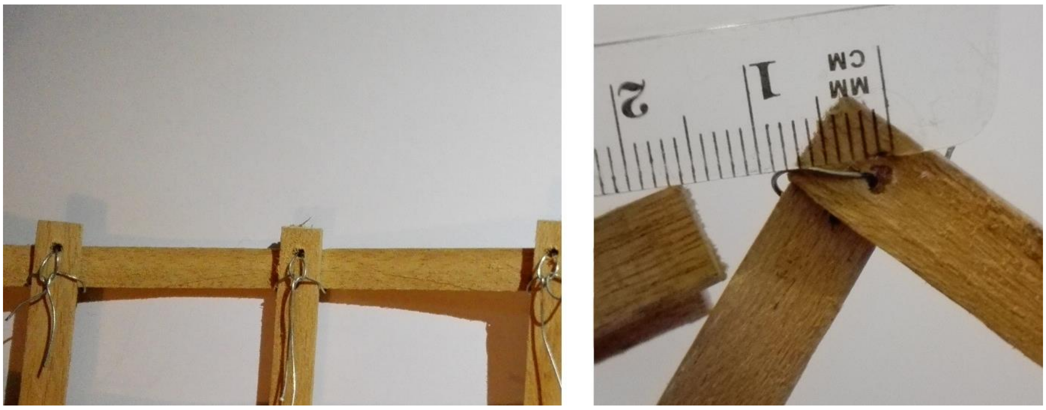


Figure 5.3- Holes in the ends of the elements

Then all the elements were placed in their accurate positions, forming a two-dimensional mesh, in which the inner squares had a dimension of 5cm inside (dimension measured between the edges of each element). The elements were properly joined by the wire in the connecting zones, which is slightly tightened to still allow some freedom of movement to the parts in these connecting zones.

In order to simulate the constructive system, two 3mm diameter steel cables were used to represent the tensions cables, one in each direction, along with two tension adjusters (Figure 5.4). The two stretchers would have the function of replacing the lever winches to be used in the construction of the real prototype. At this stage, before the deformation, the mesh was slightly moistened, so that the timber would be easier to deform. Starting the process of deformation of the two-dimensional mesh, it was first raised manually, and then the tensioners were slowly tightened.

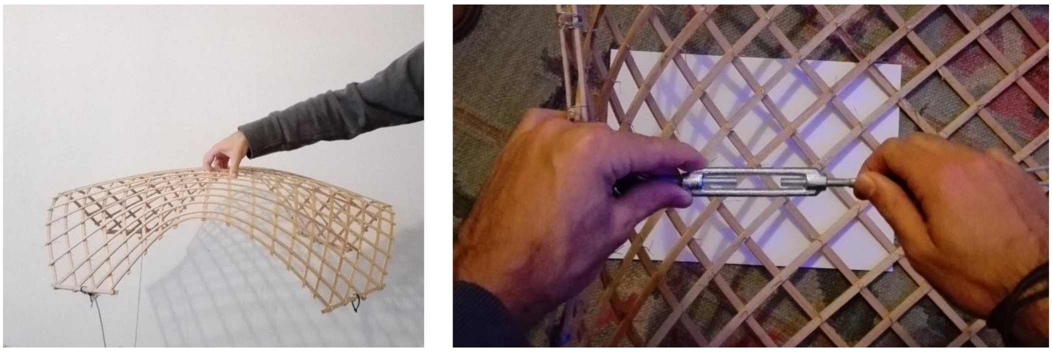


Figure 5.4- Lifting and tightening of the grid stiffeners

The cables, distributed diagonally with respect to the timber elements, had an initial length of 107cm. The objective was to reduce this length so that the distance between the two support zones was 70cm, thus providing a covered area of approximately 490cm2. In addition, as imposed by the architect, the entrance areas of the structure should have the height of 2.1m at the centre of the arches (21cm in the case of this reduced model). During the whole process, the timber had an excellent behaviour, not showing any type of rupture and deforming with relative ease. The connections also showed to function well, because they were not rigid, allowing some displacement to the elements of timber.

To end the process all wires were tightened tightly, simulating the rigid connections that are intended during to exist the life of the structure (see Figure 5.5).

Figure 5.5- Final connection and cable system

The creation of the physical model allowed the development of a good form-finding process, presenting a similar geometry to what was expected, providing an excellent perspective of the mesh to be constructed (Figure 5.6).

Figure 5.6- Final model of the study case

5.1.3 Gridshell 1.0 description

The result of the previous phases was the project of an Elastic timber gridshell with about 80 sq.m.. A flat shell with a regular square grid in the two-dimensional plane with the corner’s cuts, using a double-layered structure with two axes of symmetry. This option of the double-layer was advantageous for the strength of the structure, increasing its rigidity,

but on the other hand it also increased the difficulty of the challenge, because it became a more complex structure, requiring more work during the design and construction phases. There was a line spacing of 0.7m, with 9m lines composed of 3 timber elements each.
This flat grid would be tensioned, making it deform until it gained the new shape. This would result in a tri-dimensional structure with bolted connections in 6cm slitted holes, so it could move during its construction. The arches and the centre of the gridshell respectively had variable heights of 2.1m and 3.4m in the span. To keep the costs controlled, since the timber was offered, the locks were designed with timber elements that are placed.

The mesh would consist of 36 sets of 3 slats of wood, in each direction, making a total of 72 sets. These elements would have a spacing of 0.5m off center, and their total lengths varied slightly throughout the development of the mesh (Figure 5.7).

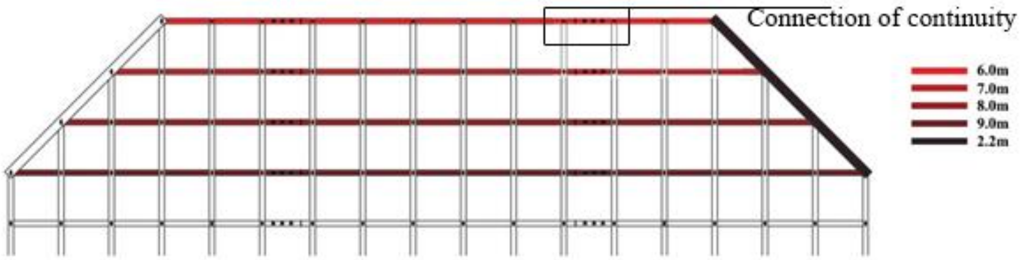


Figure 5.7- Dimensions of the knit element assemblies

The section proposed for these elements had a width of 60mm and a height (thickness) of 25mm. As mentioned, each of these sets consisted of 3 linked elements, as it can be seen in the previous one. The division of slats into sets of 3 is due to the fact that it is not possible to acquire elements with such long lengths, which was from an early stage a limitation, the use of elements smaller than 4m in length. Therefore, it was necessary to develop a solution to bind the elements making them a single element.

5.1.3.1 Change of the basic design

Through the execution of the buckling tests, it was noticed that the dimensions initially foreseen for the projected mesh would not be the most adequate. Thus, new dimensions were defined, both for the spacing of the slats of the mesh, and for the section of the same. Considering the difficulty of bending the specimens with l = 500mm, it was decided to reduce the section of the slat to a section of 60mmx15mm, thus reducing the inertia of the

section and making it slimmer. In addition to the section, the spacing of the slat assemblies was also redefined, increasing to a value of 0.7m, increasing the free span of the elements, and facilitating their buckling.
With these changes it was necessary to redefine the architectural design, starting with the dimensions of the mesh (see Figure 5.8).

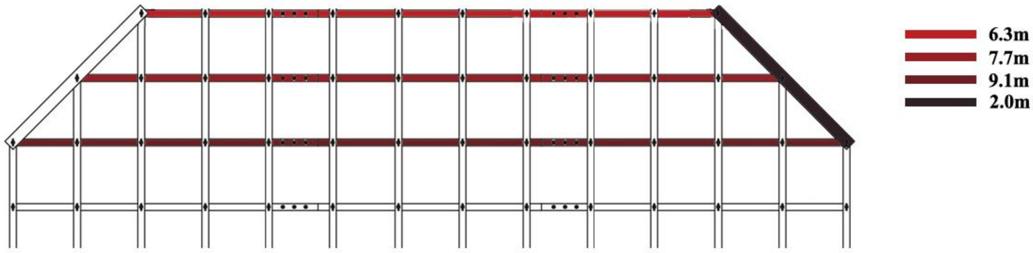


Figure 5.8- Dimensions of sets of mesh elements

After the changes were made, the number of elements to be used in the mesh was reduced. The mesh was constituted by 28 sets of 3 slats of wood, in each direction, making a total of 56 sets. This reduction in the number of elements became an advantage, in terms of the reduction of material used in both, the connections and wood timber members, reducing the overall cost of the structure.

5.1.4 **Preparation**

5.1.4.1 Assembly method

There are several construction methods and it was necessary to choose the best one to this case. Among some of the methods described in this study, the "pneumatic framework" method was out of the question, since a pneumatic cushion would not be available, and it would be very expensive to acquire one. The "ease down" method was a possibility, but after analysing the cost and difficulty of transporting the equipment (scaffolding), it was also considered unfeasible. Like the previous two methods, the "push up" method was, at this initial stage, withdrawn from the possibilities because there would be no equipment to carry out the lifting of the mesh. With the available means, there were two options, the "pull up" and the "by recessing / constraining".

Despite the possibility of using the two remaining methods, it was necessary to understand which would be the most suitable for future uses, in order to help fulfil the objective of creating a standard mesh that could be commercialized, and also to be able to offer construction know-how. Given. The "by recessing / constraining" method might not be a good solution, since it requires the existence of two support zones before the application of tension, which creates a dependence on the construction site. In addition, the equipment that was available for the application of loads in the construction, were hydraulic jacks that only allowed a displacement of 0.2m, which would imply a very slow construction process. Therefore, it was decided to go with the "pull up", with a small adaption with the addition of a new component. This new component consisted in the use of steel cables, distributed in two directions (see Figure 5.9), to aid the deformation of the mesh by displacement of the future support zones, as used in the construction of the "Toledo 2.0" structural mesh, in Naples (D'Amico et al., 2015).

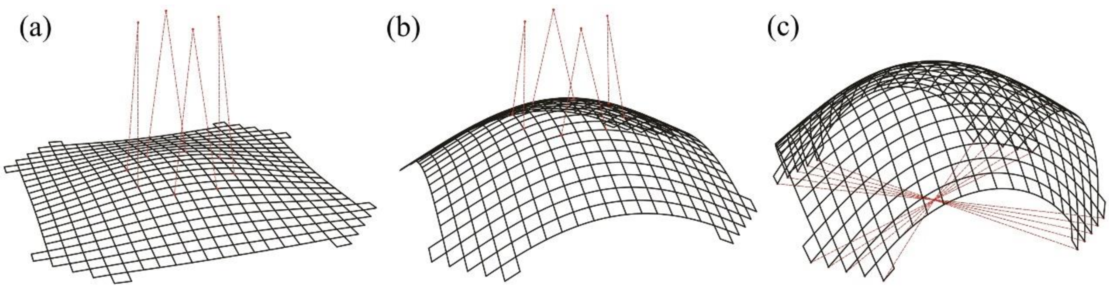


Figure 5.9- Scheme of the constructive process. a) Pull-up method with the help of a crane; b) Elevation of the mesh until the corners stop moving by gravity; c) Application of steel cables to aid deformation

A solution for the connections of continuity was thought based on the design chosen for the Pavilion ZA (Figure 5.10) (Dragos Naicu et al., 2014). This detail consisted of an overlap of pieces, 40cm, so that the loads would transfer between the elements.

Figure 5.10- (a)Pavilion ZA solution (b) solution chosen (Dragos Naicu et al., 2014)

As it can be seen in Figure 5.10 b, the elements of the two layers were overlapped together, thus allowing the bond to be unique for both, as it happened for the remaining bonds, making the mesh more homogeneous, facilitating its construction and reducing the cost of the connections.

As for the connections at the points of intersection of the mesh, the option chosen was a simple screw-threaded connection inserted into the elements (Figure 5.11). The choice of this connection was primarily due to its low cost and ease of assembly compared to metal sheet connections. The reason for the existence of tears was due to the necessity to allow the displacement of the wood elements. This need arose from elastic typology of this mesh, that is, from its deformation during construction.

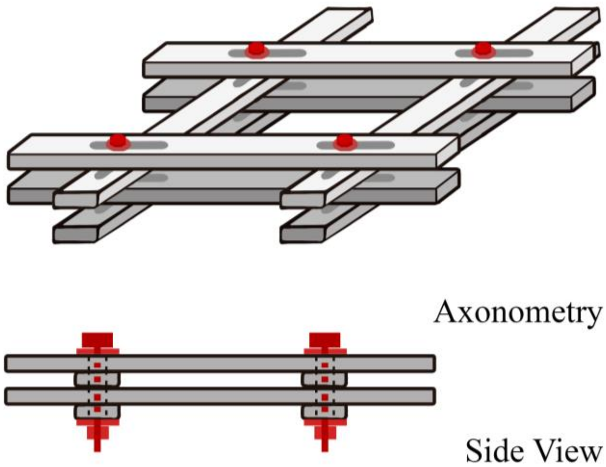


Figure 5.11- Adopted connection solution

5.1.4.2 Timber Elements

For everything to be prepared and built during the two-day workshop, it was necessary to consider some preparation work beforehand. At the design stage, the size of the items to be transported still needed 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). Therefore, the structure was divided into 9 quadrants, 1 central, 4 lateral and 4 at the extremities. Each type of quadrant consisted of different types of elements. For the construction of this structural gridshell it was necessary to design an inventory with the different types of pieces. So, we designed 8 different types of elements that are presented in the table below. Finally, in addition to the dimension of the pieces, the idea of only receiving the pieces already cut and making all the tears on the same day, would make it impossible to construct within the two days schedule. Therefore, the cutting tickets of all the different type of pieces (Table 5.2) were sent to the timber company with the location and dimension of all the tears so that they would come ready to be used.

Table 5.2 - Number of elements

Elements	Quantity	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

5.1.4.3 Steel elements

It was defined that the screws to be used in the connections of this prototype are M8 screws, which would have 2 different lengths in different connections. For the use of the bolts in the connections, were also purchased to tighten them, and 2 washers for each connection. Threaded rods were used as the bearing elements, due to the absence of screws of enough length. The number of metallic elements acquired for the construction of the prototype can be found in Table 5.9.

5.1.4.4 Quadrants

For an easier organization of the construction, the mesh was divided into 9 quadrants, with 3 different constitutions. In Figure 5.12 it is possible to visualize the division of the mesh by quadrants and each of the elements.

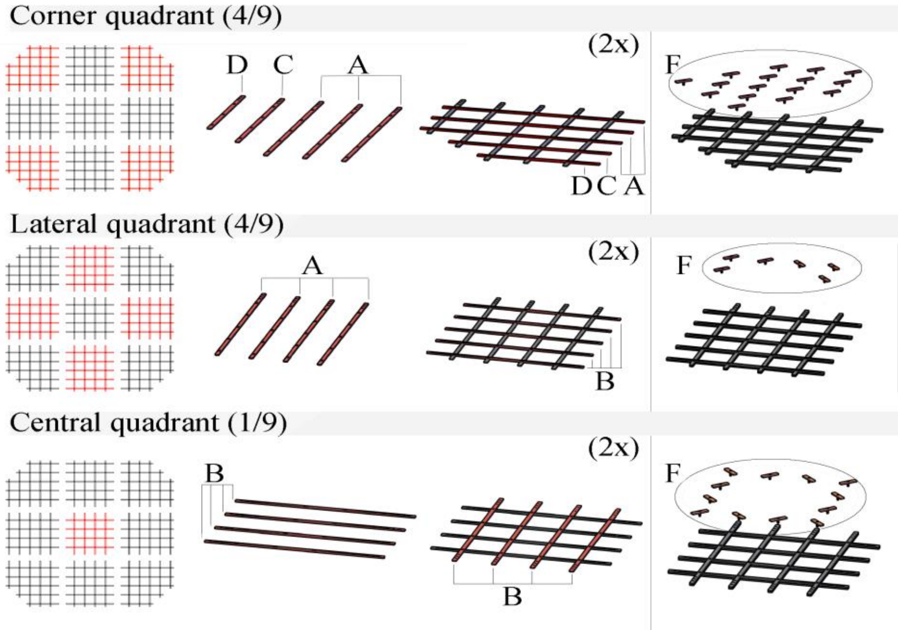


Figure 5.12-Grid division by quadrants

5.1.4.5 Tests of the most bent arcs

With all the uncertainties generated around the constructive process, due to the lack of knowledge, and assuming it was an experimental process, a final test was defined that allowed to verify the deformation capacity of the elements to be used. This test consisted in the simulation of the prototype construction process but applied only to the set of slats that would undergo extensive deformation in the construction process, hereby certifying if the elements would have the capacity to achieve the desired deformation, through the defined process. As a set of most requested elements, the lowest total length set, 6.3m, is identified, which will have the most "closed" arch of the structure (Figure 5.13).

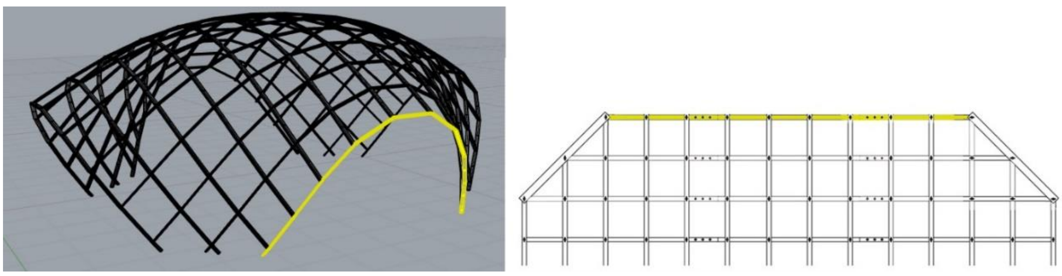


Figure 5.13- Elements to test

After deforming, this set of slats would form an arch, which was required to reach a minimum height of 2.1m, from its centre to the ground. The value of this height could be obtained, as previously mentioned, represents the minimum value intended by the architect for the entrance zones of the structural mesh, zones represented by the set of slats to be tested. To know the displacement necessary to apply at the ends of the set, so that the desired height, a simple model was created in Grasshopper that allowed obtaining this value.

5.1.4.5.1 Arch model

The developed model was a simple model, composed of a single line with the properties of a catenary, that is, a flat curve, similar to the one that would be generated by a rope suspended by its extremities and subjected to the action of gravity. In this case, the catenary would have the length of the set of slats to be tested and would be deformed in the opposite direction of gravity, causing it to have a behaviour equal to the set of slats to be tested, when its distance between the ends is reduced.

For the model to offer a value as accurate as possible, it was only possible using Galapagos in a similar way to that already executed in the mesh model. Thus, a 2.1m line was created, which was always located in the centre of the catenary along its deformation, so that the Galapagos could find the position for which the centre point of the catenary was as close as possible to the upper end of this line (Figure 5.14).

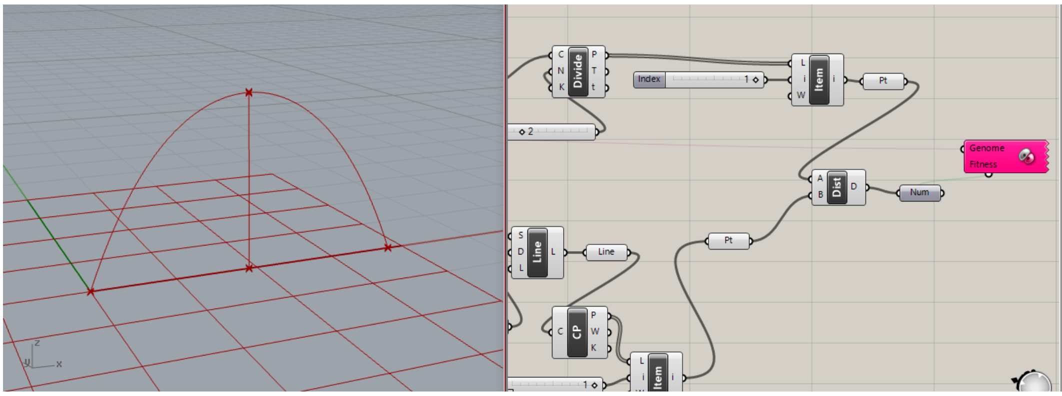


Figure 5.14- Catenary model

With the aid of Galapagos, it was possible to define that for a 6.3m long element to reach a height of 2.1m, it was necessary to bring the ends closer together until they were 4.2m apart.

5.1.4.5.2 Methodology

For security and for clarification of some doubts, some days before the workshop, two arches were tested until the collapse occurred, as it is possible to see in Figure 5.15 a, b. These experiments aimed to perceive the reaction of the timber when folded quickly.

Thus, a line was tested that would simulate the most tensioned arch of the case study, ensuring that in no case could be "worse" (J. Barroso, Fernandes, & Branco, 2016).

Figure 5.15 – a) and b): Arch test

To run these tests, a partner company of the project was needed, as the necessary elements for the construction of some examples of the sets of slats were required to be able to test. The assemblies were properly joined in a 2-layer system, elevated from the ground and a steel cable system was installed, identical to the one intended for the prototype construction process. This system was composed of two cables, each with one end tied to the end of the element to be tested, and the other to a winch, which would have the function of pulling the cables causing the ends to move (see Figure 5.16).

Figure 5.16- Line to be tested

5.1.4.5.3 First test

In a first run the results were not positive. After some displacement at the ends of the set to be deformed, some cracks began to appear on its upper layer. The upper layer element eventually broke before reaching the desired minimum height. This break occurred at a height of 1.5m, with the ends of the set at a distance of 5.5m between them. However, after a brief analysis of the possible causes that led to the rupture, the test continued until the rupture of the lower layer element occurred. This second break occurred at a height of 2m with a distance of 5m apart between them (see Figure 5.17).

Figure 5.17- Breakage of the upper layer of the set

As previously mentioned, the slat set was analysed in order to understand the reason for the occurrence of a rupture, considered to be early. It was easily understood that the rupture was due to the connection of lack of between the elements. This connection was too rigid and did not allow shifting to occur on the elements of the 2 layers. Considering the difference of dimensions between the layers, the upper layer had to move so that it had the ability to deform in conjunction with the lower layer without being broken (Figure 5.18). Therefore, it was necessary to find a solution to the problem.

Figure 5.18- To rigid connection

To solve the problem, it was decided to replace the holes of the wooden elements by slits, thus allowing the displacement of the elements towards their central axis. In order to define the length of the tears, the displacement of the upper layer element relative to the lower layer was measured in the parametric model, obtaining a value of 5cm.

5.1.4.5.4 Second test

After opening the slits on the elements, the second test was started. As predicted, by allowing the displacement of the elements on both layers, the behaviour of the set was much closer to the expected, and the results obtained were positive. For this second test, the assembly reached a height of 2.1m without breaking or any kind of cracking, which allowed the mesh elements to behave acceptably when deformed through the defined process.

Although the desired height was reached, the value of the distance between the ends did not correspond to the value calculated in the model, occurring at a distance of 4.8m. Even if the desired height was reached, it was decided to continue to flex the elements to collect the values at which the first break would occur. After some more displacement, applied at the ends of the set, when these reached a distance of 4.7m, some cracks began to appear on its upper layer, at this point the set reached a height of 2.15m. These cracks appeared around a wood knot in the centre of the upper layer element, being interpreted as the main cause of element breakage (Figure 5.19). The element collapse occurred at a height of 2.25m with a span of 4.5m between the ends.

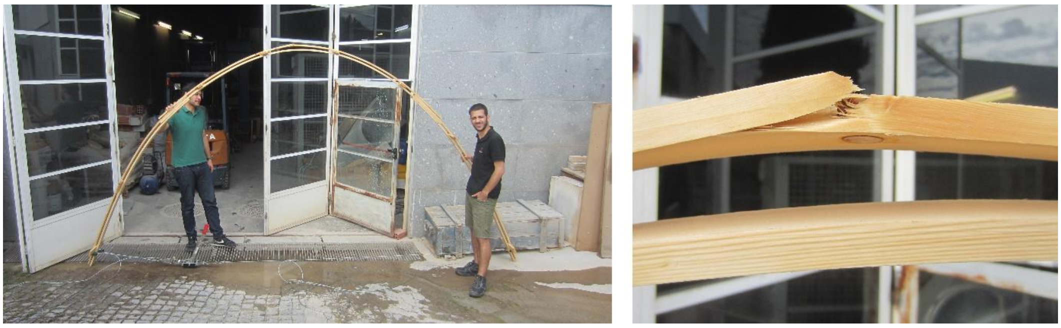


Figure 5.19- Upper layer element break

After these tests, it was easy to see that there were two main problems. First, it was defined that during the construction of the gridshell the timber elements had to be be constantly watered to increase the moisture content, 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 the equipment available would not manage to soak all the elements at once. In addition, a visual check of the elements was done to leave out those with larger knots. In relation to the stiffness of the connections, long screws were chosen enabling to hold together the elements but also to keep them loose to the point where movement of the gridshell elements was allowed of the during the deformation.

5.1.4.6 Increase in moisture content

After analysing the constructive process of several existing elastic structural meshes, it was noticed that in most of them, the wood elements were wetted. Hence, for the case of mesh being constructed, before and during the entire deformation process, the elements of the structure were "watered", almost constantly, to be easier to bend the timber elements (Figure 5.20).

Figure 5.20- Moisturing of the timber elements

5.1.5 Assembly process

5.1.5.1 June 13th – Day one

In order to facilitate the whole process, the participants were divided into groups, and different tasks were defined for each one of the groups. Two groups were responsible for the drilling of the parts that were not properly drilled, and for the opening of tears in the continuous connections of the elements, since it was necessary to increase these tears. The remaining groups were responsible for the organization and division of the timber elements into different quadrants.

To begin constructing, the pieces were separated and organized by quadrants (see Figure 5.21a) 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 support were placed in the quadrants to the subsequent application of locks, as shown in Figure 5.21b. It was necessary to place these pieces in this first phase combining the structure through the existing connections in the quadrants.

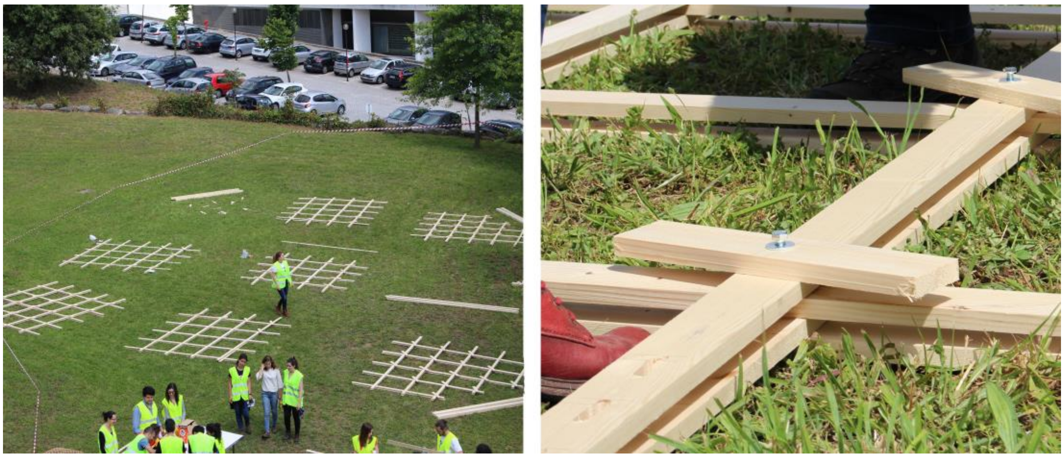


Figure 5.21 a, b- Gridshell Construction

To allow the support system designed for the structure to function it was necessary to place two elements that "embraced", on in each side, 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 completely tightened, allowing the structure to move without becoming too rigid during the lifting process (see Figure 5.22a).

In order to finish the first day of the Workshop, the different quadrants were connected, as it is visible in Figure 5.22b, 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.

Figure 5.22 a, b- Gridshell Construction

5.1.5.2 June 14th - Day two

Since the structure is quite light, the use of a crane, or other mechanical equipment, was not required for the lifting process. Therefore, the expected "pull up" method was changed to the "push up" method. Without the aid of scaffolding or any type of mechanical equipment, the participants manually raised the two-dimensional mesh to the desired height.

Two hours before the beginning of the deformation of the shell, we began to irrigate the pieces to ease their deformation (see Figure 5.23a). At the same time, several pieces were built with timber elements to serve as anchors and assist during the process of erecting the gridshell. Moments before beginning this process, the grate was transported to the place where it would be the final position (see Figure 5.23b).

Figure 5.23 a, b- Gridshell Construction

The centre of the shell was erected manually, and the props constructed were placed in the inner zone of the grid, as it can be seen in Figure 5.24a. The next phase was to mount the tension application system on the flat gridshell. The system used was a set of 6mm steel cables that would then be pulled with the aid of two lever winches, one in each direction.

During the application of tension, the supports could be moved horizontally, the grid was lifted and placed on elements of timber, allowing the supports to be shifted, presented in Figure 5.24b.

Figure 5.24 a, b- Gridshell Construction

The application of tension started through the winch lever; safety cables were placed parallel to the tensioning cables (see Figure 5.25a). After a first application of a tension force, the timber was given some time 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, since these are the main 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, see Figure 5.25b.

Figure 5.25 a, b- Gridshell Construction

With all these processes completed, a new phase of tension force to be applied began. The processes described above were repeated until reaching the desired form of the structure (see Figure 5.26a).

Once attained the desired geometry (see Figure 5.26b and 5.27), it was time to fix the structure. For this, the locks were placed in the previously chosen locations, 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.

Figure 5.26 a, b- Gridshell Construction

Figure 5.27- Final geometry

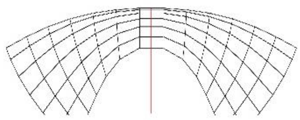
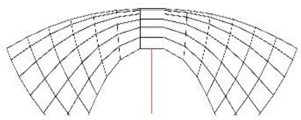
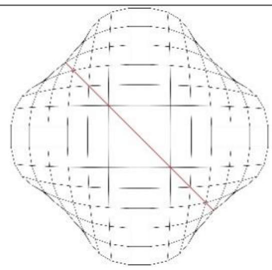
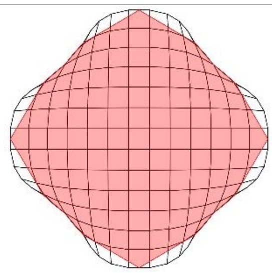
Finally, the locking was applied. This consisted in the placement of slats on the diagonals of the mesh squares, in certain areas, that would help maintain the geometry of the structural meshwork. These elements were connected with the aid of metallic bonds, stopping the mesh squares from deforming; in addition, it helped to make the structure more rigid. The elements were nailed to existing slats, placed simultaneously with the metal connections, with the aid of a nail gun (see Figure 5.28).

Figure 5.28- Application of locking with nail gun

5.1.5.3 Desired Geometry

The constructed gridshell presented very positive results, with a few numbers of shortcomings that came up, as described before. Comparing the constructed gridshell with the computational model developed it could be concluded that the geometric differences between them were very small. On Table 5.3, the main dimensions of the three-dimensional model and the constructed gridshell are compared.

Table 5.3 - Comparation between Three-dimensional Model and Constructed Gridshell dimensions (J. M. P. Barroso, 2016)

	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	

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.

5.1.6 **Disassembly**

The gridshell was designed to remain in place for six months. After this time, the shell would be dismantled, proving its short life span, and in a way that does not endanger the safety of its users. Taking into account that the timber used was treated, that gave a few guarantees of its structural capacity and also the fact that Guimarães is a city with a temperature between a maximum and minimum around 40º Celsius (Fisiogr, 1995) which accelerated the aging process of the timber. In January 2017, seven months later, the gridshell was cracked and broken, with the central quadrant already visibly distressed 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 gridshell rises again.
The dismantling process was relatively fast, unlike its construction. During this stage, only two people were working, and the process lasted for about 5 hours.

5.1.7 **Problems**

Although the objective was successfully completed, some problems were encountered during the deformation process and after the construction of the prototype.
During the deformation process, the collapse of two wooden slats occurred, both belonging to the same arch, one of them concerning the lower layer and another one of the upper one. The rupture of the lower layer slat occurred due to the existence of a knot in the central zone of the element. The upper layer lath was eventually ruptured, caused by the rupture of the lower layer lath (see Figure 5.29). The cause of these cracks were associated not only with the existence of the knots referred to above, but also with the speed of execution of the deformation process. This process was carried out in about six hours, which was not enough time for the wood elements to adapt to their new positions and lose some tension accumulated during this process. Nevertheless, this problem became an added value for the project, since it allowed to demonstrate that, in the

construction of structural elastic wooden meshes, it is possible to replace elements during the deformation process.

Figure 5.29- Breaking of two timber elements

To solve the problem, it was chosen to replace the damaged elements, as previously mentioned. To do this, two straight elements were dampened and flexed manually until they reached the desired shape. Then the damaged elements were removed, and the new elements already bent were installed into place (Figure 5.30).

Figure 5.30- Replacement of damaged elements

Another problem that raised regarding the application of the locking was that the locks were placed in a vertical position, perpendicular to the ground, which forced them to be nailed in curved elements, being constituted by rectilinear elements. This application generated several difficulties in the nailing of the elements, and aesthetically influenced the difference between the curved surface of the mesh and the straight locks. In order to solve this problem, the locks were removed and replaced in a horizontal position, parallel to the ground. With this solution the locks were easily placed and improved the aesthetic aspect of the structure (Figure 5.31).

Figure 5.31- Changing the position of the locks

To conclude, another limitation that came up; through the results of the Robot models, it was anticipated that after the construction, the structure would deform in the central zone, due to its own weight. As predicted, this deformation occurred, after about eight days, the central zone of the mesh deformed about 0.7m, because of the creep (Figure 5.32).

Figure 5.32- Crown (central) displacement

As an attempt to solve this problem, and not allowing the structure to continue to deform, based on the study of Gridshell 1.0 (Gridshell.it, 2016), a system was developed that allowed to move the upper zone of the mesh again. This system consisted in the application of a steel cable around the mesh, forcing it to maintain its position. The central zone of the mesh was raised, with the aid of the previously used struts, until reaching the height initially achieved. After this elevation, some hooks were applied, in certain connections, immediately above the entrances clearance height (2.1m). A steel cable of 6 mm was placed inside the hooks, which was drawn with the aid of a winch-lever (Figure 5.33).

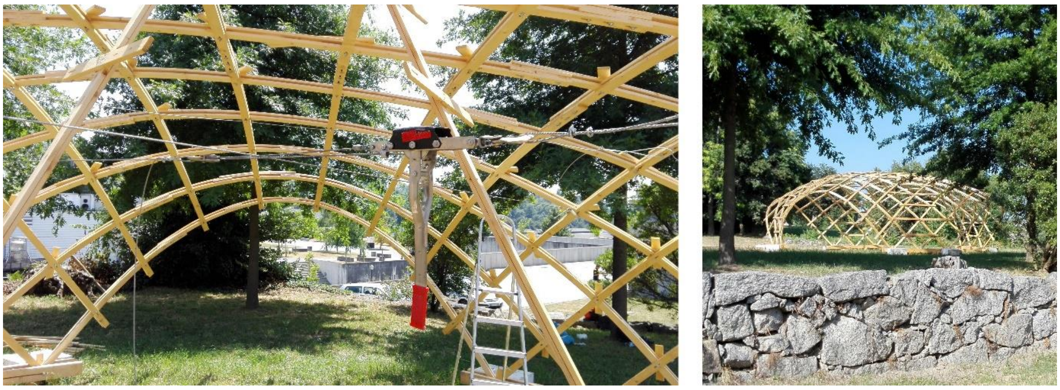


Figure 5.33- Application of cable inside the structure

5.1.8 **First elastic timber gridshell - conclusion**

Once the prototype construction process was completed, it was possible to state that the first elastic timber gridshell was built. This type of structure was the first one to be recorded in Portugal (Antunes, 2016), thus demonstrating the innovation of the work developed in this thesis (Figure 5.34).

With this construction prototype it was possible to demonstrate the innumerable advantages of structural meshwork in timber. As it was foreseen, the lightness of the structure was notorious and it ended up facilitating the execution of the constructive process, with the need to use mechanical equipment for its elevation. This same process demonstrated another advantageous characteristic, its speed. The prototype was entirely built during the workshop, which lasted two days, of which only 12 hours were dedicated to its construction. Another advantage was the small amount of material used in the construction of this structure. Since sustainability is a very important topic today, this small amount of raw material used is a great advantage for elastic timber gridshell.

However, not everything were good news and during this process there were several problems. The problems were all noticed in the construction phase which demonstrates the importance of this phase and how it is the face of the whole process. There were problems of design, detail, sequential process and structure life, such as: mesh stiffness in the connections, weak element resistance, grid direction, and decay of the central quadrant. All these details give hints to improve the design and to know what should be addressed by the builder.

Figure *5.34*- First structural mesh in wood, recorded in Portugal. Campus of Azurém, University of Minho, Guimarães

5.2 Gridshell 2.0

After the workshop, some conclusions were drawn, by the problems met, from the design and construction process. In this work, as result of these problems, some changes were adopted, for a parametric analysis that will result in the case study Gridshell 2.0.

5.2.1 Base case study

The same general configuration and geometry is initially considered as a framework base. Gridshell 1.0 was an elastic timber gridshell with about 80 m^2 open area. This structure had a variable height between 2.1 m and 3.4 m on the span arches and on the centre of the gridshell, respectively, as shown in Figure 5.35.

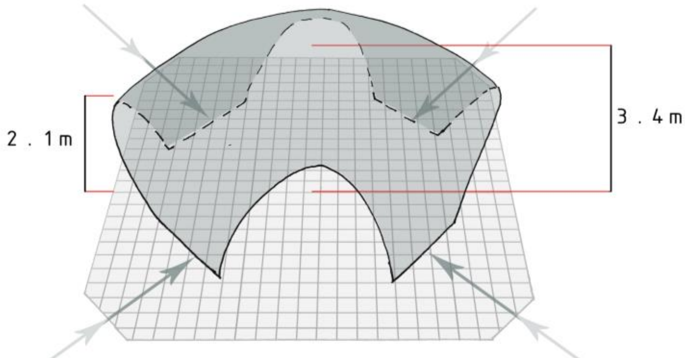


Figure 5.35- Illustration of the final geometry

During the design phase, in the Gridshell 1.0, the maximum length of the elements was limited to 5 meters due to common conditions of manufacturing and transportation. For this reason, all the Gridshell 1.0 lines were divided into a maximum of 3 pieces each. The grid was divided into 9 parts, 1 central, 4 lateral and 4 at the extremities, as detailed in Figure 5.36.

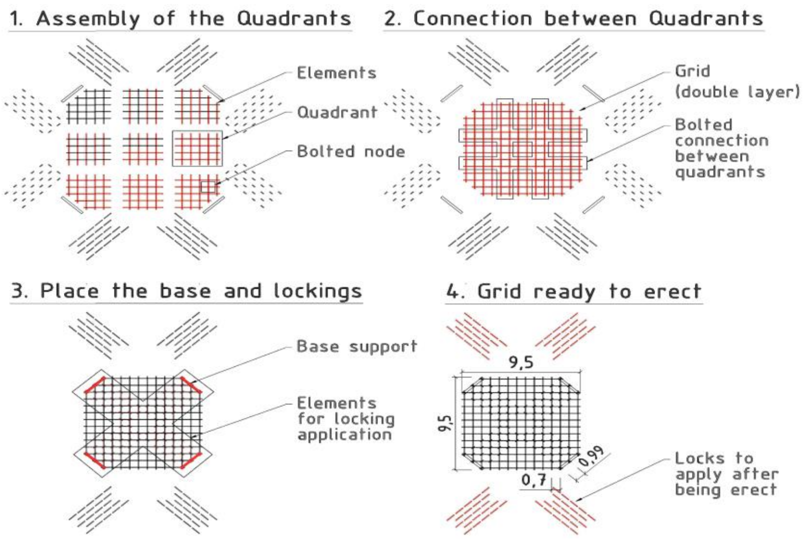


Figure 5.36 - Mounting process, scheme Gridshell 1.0

It was easily concluded that the most striking problems were weaknesses resulting from decisions made during the design phase, noticeable during the time of assembly. The more relevant difficulties and problems encountered were: (1) the elements used had a substantial number of defects (knots); (2) decay of the central part of the gridshell; (3) the number of very tight / tensioned arches at the entrances; (4) problems in the application and malfunctioning of the locking elements.

In this exercise, some different steps will be taken during the conceptual and constructive process of the gridshell. These will be clearly identified and for each one of them some solutions will be proposed to solve the problems.

5.2.2 **Digital Model**

Repeatedly, the software used for the visualization was Rhinoceros 5 (Robert McNeel & Associates, 2016) and for the creation of the model, the Grasshopper (M. Mingallon, 2012) was used. Before starting to program, some preliminary considerations were established, which helped to define and choose the best way to (re)build the 3D model

(Toussaint, 2007). The priorities were: (i) the definition of the shell like final image; (ii) to obtain the greater number of workable parameters (features that can be changed without creating a new template as, for example, the distance between lines or section of lines); (iii) to make models with the same base parameters; (iv) to create an easily updated model; and, (v) to create an interactive and educational model which would allow for other designers to analyse the results. The software Karamba (Preisinger, 2016b) was also used to simulate the constructive process of the gridshell.

The design process began with the characterisation of a flat geometry, to which elements with properties of the material to be used were associated. Then, the boundary conditions were fixed and the forces of deformation of the structure defined. Subsequently, a simulation was carried out until the point of equilibrium was reached and a new geometry was obtained. The described process was repeated in an iterative procedure, changing the applied forces and following three factors: (i) material model; (ii) approximation of the target shape; (iii) equilibrium form finding procedure (Maarten Kuijvenhoven, 2009). It was concluded when the desired shape was attained.

5.2.3 **Gridshell 1.0 to 2.0**

In this validation section, the objective is to present the results derived from all the improvements implemented in the gridshell, with the help of a three-dimensional model and after it was tested in the lab. The new model will be compared with the original gridshell model to verify if the proposed alterations led to any improvements in the structural system of the timber gridshell, thus validating each change. At the end of this section, a direct comparison is made between the characteristics of Gridshell 1.0 and the resulting Gridshell 2.0.

5.2.4 **Wood**

It should be noted that the material for the first gridshell (Gridshell 1.0), spruce (*Picea abies)*, was chosen from low-grade timber commonly available in local lumberyards. In the parametric analysis, conducted after the construction of Gridshell 1.0, it was identified the need to use a timber with higher mechanical properties. Therefore, between the possible timber species used in local carpentry, it was decided to use the Eucalyptus (*Eucalyptus globulus*). The Eucalyptus is a hardwood, characterized by a great strength, stiffness, high density and good natural durability (Hiwale, 2015). Moreover, this wood species presents a lower number of knots making easier the selection process of the ribs to avoid premature failures. As curiosity, in the last World Conference of Timber Construction that took place in Seoul, South Korea, a timber gridshell made of Eucalyptus was awarded a prize of best new structure (Ciencia Galega I.Creativas, 2018).

In this context, and to collect the same information previously obtained in the case of Spruce, some tests to assess mechanical properties of Eucalyptus were performed. For that, a sample composed by 15 specimens of 20x20x340 mm^3 made of Eucalyptus was considered. The first characteristics obtained were its moisture content and its density, by using Standards NP 614:1973 and NP 616:1973, respectively. Following NP 614:1973, the specimens were weighed and measured before and after undergoing a drying process. From the values obtained during this procedure, the moisture content was calculated, being the average value equal to 8.93% ($W \approx 9\%$). Following NP 616:1973, by using the values obtained before, it was possible to calculate the density, the average value for this property being equal to 978.12kg/m^3 for $W \approx 9\%$. Table 5.4 summarizes the tests results obtained for the density and moisture content of the Eucalyptus specimens.

Table 5.4 – Moisture content and density presented by the Eucalyptus specimens

No. of Specimens	***Moisture Content (W)***		***Density (W=12%)***	
	Average [%]	**CoV [%]**	**Average [kg/m³]**	**CoV [%]**
15	8,93	2,66	987,12	7,26

EN 338:2003 classifies Eucalyptus as being a D40 timber. To assess if this strength class could be addressed to the timber elements, it was decided to quantify the modulus of elasticity in bending of the Eucalyptus used. For that, 15 specimens were tested according to NP 619:1973, under a three-point bending. The test setup used is presented in Figure 5.37.

Figure 5.37- Bending test setup

From bending tests, it was possible to obtain the values of the maximum load applied to each element and maximum displacement before failure. Following the standard recommendations, the maximum bending strength was calculated, for every element, by applying the Equation [1].

$$\sigma_{fH} = \frac{3Fl}{2bh^2} \qquad [1]$$

Where *F* is the maximum force, *l* is the element span between supports, *b* is the width of the element, and *h* the height of the element.

Applying the Equation [2] an average value of 16980N/mm^2 as obtained for the modulus of elasticity in bending (see table 5.5).

$$E = \frac{K}{bh^3} \qquad [2]$$

Where E is the modulus of elasticity, *K* is the stiffness (corresponds to the slope of the force-displacement curve at the elastic area, obtained during the test), *b* is the width of the element, and *h* the height of the element.

Table 5.5 – Modulus of elasticity in bending

Number of Specimens	Load $_{max}$ (F)	Displacement	Bending strength (σ_m)		Stiffness (K)	Modulus of Elasticity in bending (E)	
	Average	**Average**	**Average**	**CoV**	**Average**	**Average**	**CoV**
	[kN]	**[mm]**	**[N/mm^2]**	**[%]**	**[kN]**	**[N/mm^2]**	**[%]**
15	2,53	9,25	140,32	13,84	2165477,87	16980	17,03

Despite the small number of specimens tested, and because of their dimensions they can be assumed as clear specimens, the tests performed helped to confirm that the Eucalyptus timber used is at least from a D40 class strength, based on the value obtained for the modulus of elasticity in bending (16980 N/mm^2) and bending strength (140,32 N/mm^2).

5.2.5 **Design**

Several improvements were introduced into Gridshell 2.0. After the change of the wood species, from a softwood (Spruce) to a hardwood (Eucalyptus), other enhancements were analysed, namely: (a) to modify the grid direction; (b) the number of layers; (c) the lightness of the gridshell; (d) the connectors; and, (e) the elements cross-section. Regarding the possibility of changing the cross-section of the elements and the connections between them, it was decided to perform bending tests to understand the behaviour of four different types of grid elements. As far as it is concerned with the elements cross-section, two possibilities were analysed: a rectangular section with 50x15 mm^2 and a square section of 20x20 mm^2. As connections, a tear hole was provided in the centre of the connection to allow the use of a bolt.

The setup adopted for the bending test was like the one suggested by NP 619:1973: a single element, simply supported, but this time with a span of 1.3m. In the middle point of the element, at the bottom, a LVDT was placed to measure the displacement, thereafter a load was applied at the same middle point, on the top of the sample. With this test, the maximum due to bending was obtained.

Table 5.6 presents the mean values, and corresponding coefficient of variation (CoV), obtained from the tests.

Table 5.6 – Bending tests on the grid elements

Sample	$Load_{max}$	Displacement	σ_{max}
	Mean	**Mean**	**Mean**
	[N]	**[mm]**	**[N/mm^2]**
A (Tear Hole)	599,00	158,77	120,73
B (Tear Hole)	400,33	159,27	142,89
A (Solid)	649,00	165,44	112,49
B (Solid)	318,00	109,95	73,78

By comparing the mean experimental values obtained for each sample, it can be pointed out that elements from samples A have more capacity to bend than the ones of samples B, when the element is not stuck, but the opposite happens when the element has the tear hole to perform a bolted connection.

Regarding the connection, two types were considered: one bolted and another one using two external metal plates. For the bolted connections it is also necessary to provide a tear hole which weakens the element at the pierced point. However, even with this disadvantage, the bolted solution presented several advantages when compared with the use of two external metal plates. One of the advantages of this last solution is related to the cost, since the use of metal plates and screws (at least 4) needed for each joint/intersection. Also, the construction time increases and it can impose limitations in the number of spatial orientations adopted by the members. The connection solutions evaluated are presented in Figure 5.38.

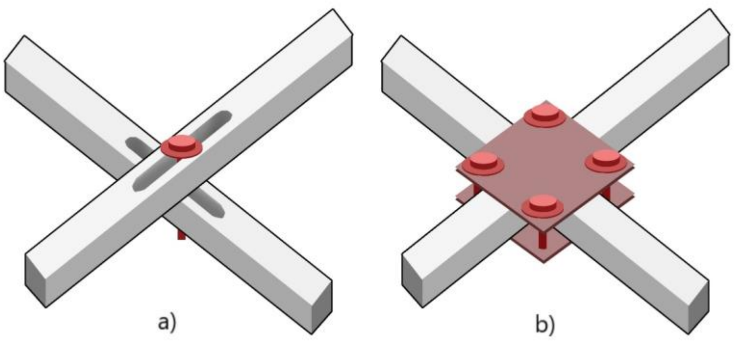


Figure 5.38- (a) Connections evaluated: Bolted (b) and External metal plates

To validate the choice of the new wood species and the new cross-section as improvements to the gridshell, a three-dimensional model of the Gridshell 1.0 was developed with Grasshopper software. This model was exported to Robot Structural Analysis (Autodesk, 2009) software to compare the behaviour of the gridshell when subjected to its self-weight, for both wood species with all cross-sections evaluated. From the structural analysis point-of-view, the model with the new cross-section (50x15mm^2) and made of Eucalyptus, behaved similarly to the initial one, with a section of 60x15mm^2 made with Spruce, as can be seen in the Figure 5.39.

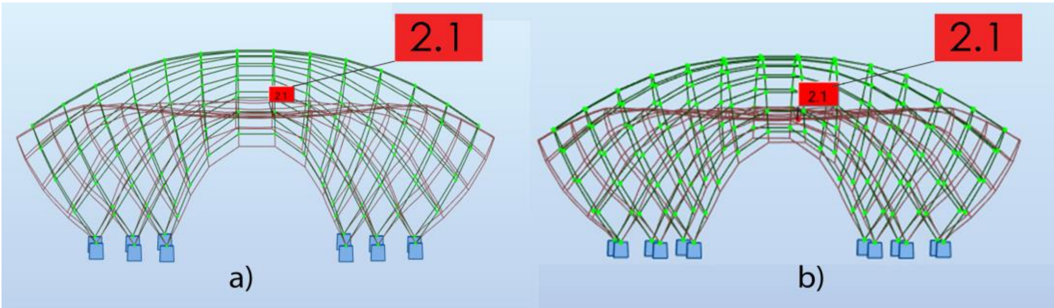


Figure 5.39- (a)Maximum deformation (in meters) cross-section 50x15mm^2 made of Eucalyptus (b) and cross-section 60x15mm^2 made of Spruce

This result comes from the combination of several factors such as weight increase, the resistance of the material, the area of the section, among others. Since the results obtained with the two samples were similar, the change was considered as viable.

Another intended improvement at the design level of the gridshell, concerns the number of layers (Richard Harris et al., 2003). The use of a single layer would improve the system, turning it into a lighter structure. However, the structure becomes less redundant. This hypothesis was already taken into consideration during the design stage of Gridshell 1.0 and it was found that the use of a single layer reduces the performance of the system. However, the use of a double layer gridshell could offer a more rigid structure, even though the increase of the weight will be prejudicial to the system. The previous three-dimensional model created with the new variables (change of the cross-section and wood species) was compared with another one, with a single layer system to understand if the reduction of layers would be an improvement. The model with a double-layered system showed a much better performance when subjected to his self-weight load in comparison to the single layer model (Figure 5.40). Thus, the conclusion was that the reduction of layers does not optimize the gridshell.

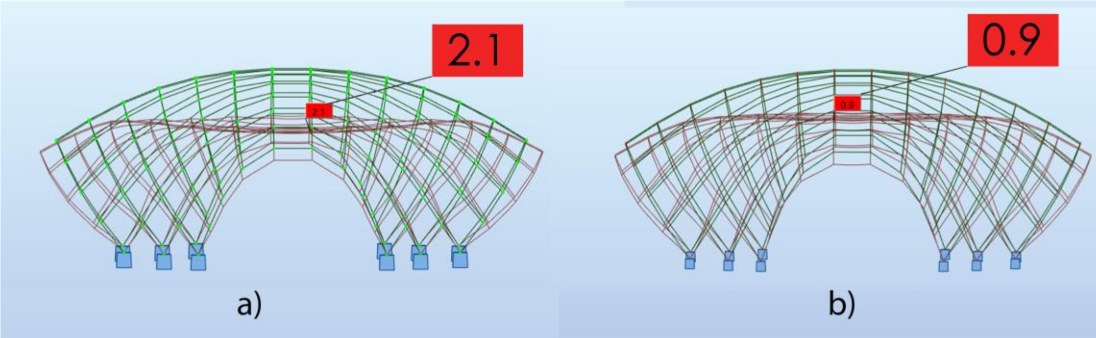


Figure 5.40- (a) Maximum deformation (in meters) single layer (b) and double layer

The possibility of using less layers to reduce weight creates other problems in terms of stiffness of the structure. This being the case, another possible solution consists in removing the second layer from specific areas of the gridshell, maintaining its stiffness and decreasing the weight. This solution will be tested with the three-dimensional model. The final proposed improvement on the design of the gridshell concerns the grid direction. The rotation of the layers, help make the structure more stable. Like the previous tests, this one was also developed by using Robot Structural Analysis software for the three-dimensional model, by subjecting the structures to a self-weight load test. The structural analysis proved that the rotation of the grid hinders the behaviour of the structure, increasing in 45% the maximum value of deformation of the gridshell. With these results, it was possible to ascertain that the rotation of the grid does not improve the structure. One justification for this is that the elements placed in one direction stay parallel to the ground, meaning that they do not bring any advantage to the system; on the contrary, they only contribute to the increase of the weight of the structure, which is an obvious disadvantage (Figure 5.41).

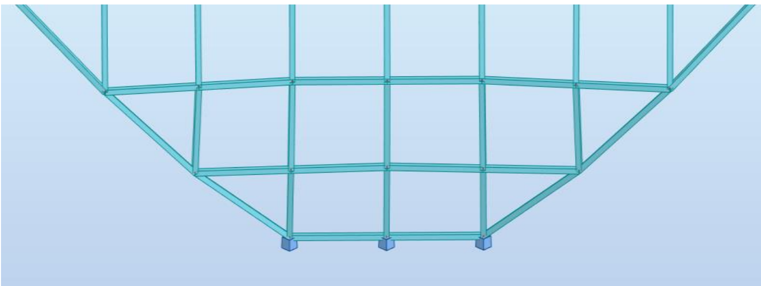


Figure 5.41– Elements in one direction (horizontal) parallel to the ground

5.2.6 **Construction**

For this type of timber structures, the execution stage (construction) is the most important. During construction, the gridshell will be subjected to loading and deformation processes before achieving its final geometrical configuration. To prevent problems during this stage, there are various elements to be considered, and the experience of the first gridshell was quite valuable.

Regarding timber deformation, after analysing the construction processes of different timber gridshells around the world, it was possible to verify that, in most of them, the elements of the timber structures were moistened to help its deformation. During the construction of the first gridshell, the use of water to make the deformation of the elements easier was adopted and the result considered positive. To wet the elements, it is possible to leave them immersed in a water tank, during a certain period, before construction, to allow the timber to absorb the water and increase its moisture content.

During the construction stage, the structure is subjected to the application of loads to create the desired deformed shape. There are several ways by which loads can be applied, depending on the desired final form and on the resources chosen for this purpose (G. Quinn & Gengnagel, 2014). For Gridshell 1.0, in an initial stage the chosen method was a manual application of loads, without using any mechanical tools, only timber struts to sustain the gridshell at the central area. Nevertheless, a manual application of load is neither safe nor easy as the elements present resistance to bending. As such, the load started to be applied with the help of steel cables. These cables where fixed in each corner of the gridshell and pulled, placing the corners closer to each other until the final form was obtained. This method proved to be efficient and, therefore, it was decided to apply it during the execution of Gridshell 2.0.

The internal tension created by the applied loads gave stability to the structure, making it static when it came to the displacement of the system, as well as rigid, thus creating a structure resistant to the external factors/loads. However, in the timber elements tension vanishes with time, giving way to the deformation of the structure and altering its intended form. However, there are several methods through which this change of form can be prevented. On Gridshell 1.0, timber slats were applied in the centre of the dome squares of the gridshell. This helped to maintain the gridshell form but only for a short period, proving the inadequacy of the solution. In addition, the application of the slats was rather complicated, demonstrating that the application of straight slats after the deformation takes place is not the best approach. The problem described can be analysed in Figure 5.42.

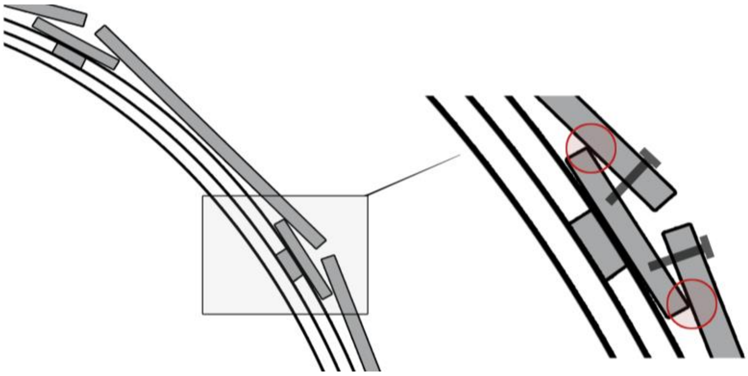


Figure 5.42- Problems with the application of straight slats after grid deformation

For Gridshell 2.0 another solution was planned based on an upgrade of the one used on the previous grid. This new solution consists on the application of complete lines of timber slats, within specific areas of the gridshell, placed at 45º from the grid lines instead of the isolated small pieces. These were applied before the grid deformation, giving more stiffness to the system. This solution brings the subject back to the design stage. The three-dimensional model was then used to validate this update. For this test, the model, with all the changes introduced until this point (except the rotation, that did not improve the structure), was considered, including the extra timber slats. The results from this test showed a much better behaviour of the structure with the new slats, decreasing the maximum value of displacement in the appex of the grid, from 0.9m to 0.4m, as shown in Figure 5.43.

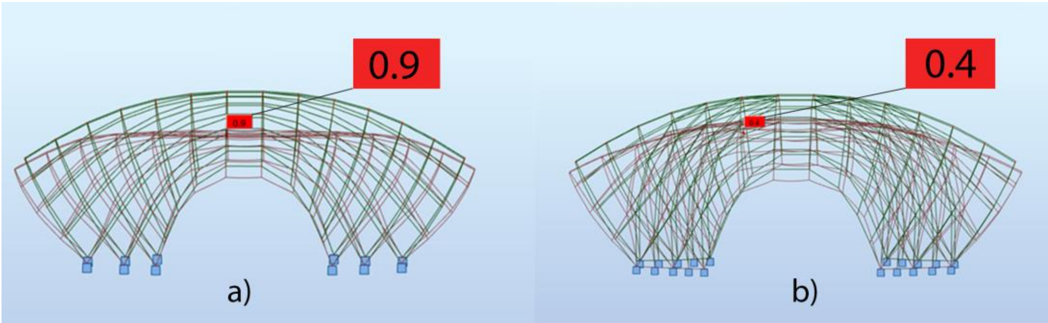


Figure 5.43– (a) Maximum deformation (in meters) without extra stabs (b) and with extra slats

After adding extra slats to the gridshell, which was a clear improvement, another possibility emerged from this solution: combining the gridshell rotation with extra slats. As previously described, the rotation of the gridshell reduces the capacity of the structure, by turning some slats parallel to the ground. However, the addition of extra slats, rotated at 45º, may increase the performance of the system. Another test was conducted, comparing the gridshell with the initial gridshell and the gridshell with the rotated gridshell, both including the extra slats. From this test, it was concluded that the rotated gridshell had a better behaviour than the original one, after the extra slats were added. The maximum displacement of the original gridshell was 0.7m, higher than the rotated gridshell, with a maximum displacement of 0.4m, as presented in Figure 5.44.

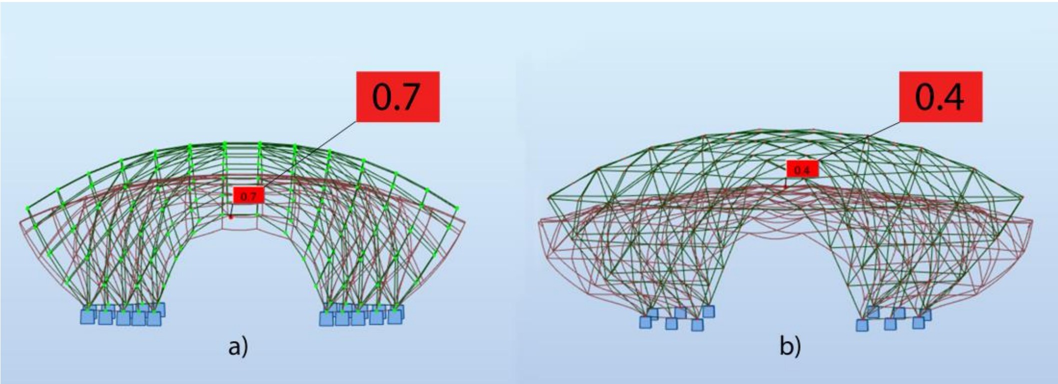


Figure 5.44 – (a) Maximum deformation (in meters) for the original gridshell (b) and for the rotated gridshell

Regarding the loss of tension of the timber due to creep, the central area of the gridshell appears to be the most affected and compromised section resulting from this effect. The self-weight of the structure is also a factor. It is usual for the central area of the gridshell to have long-term deformations. To prevent this, a possible solution is to apply tensioned cables (Kelly, Harris, Dickson, & Rowe, 2003) through the structure, in the critical area, helping the structure to keep its form (Figure 5.45). This solution was applied successfully in Gridshell 1.0.

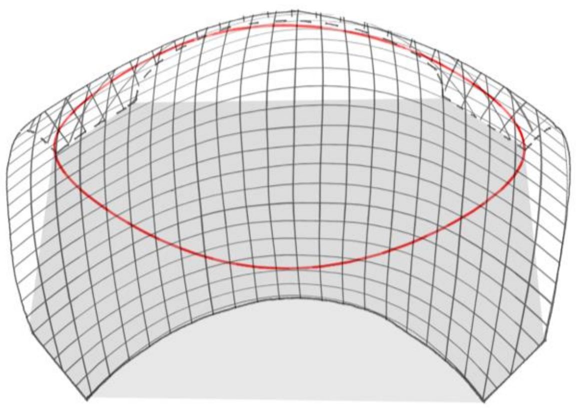


Figure 5.45 - Tensioned cable to prevent gridshell deformation

5.2.7 **Final Description**

Following the analysis of the different proposed changes in terms of configuration and construction and after obtaining a more substantiated knowledge of the gridshell behaviour, Gridshell 2.0 is proposed. This is an elastic timber gridshell with an open space of about 87 m^2, a flat grid with a regular metric in the two-dimensional planes, with the cropped corners and using a double layer. This flat grid is divided into 3 parts, 1 central and 2 laterals. After connecting the quadrants, a layer of locking elements will be applied, as presented in Figure 5.46. This is followed by a gridshell structure composed of a double layer of mats comprised of four layers of thin timber laths, with a line spacing of 0.7m. This flat grid will be bent, deforming it until it acquires a new shape, with a variable height between 2.1m and 3.48m, respectively, in the span arches and the centre apex of the gridshell.

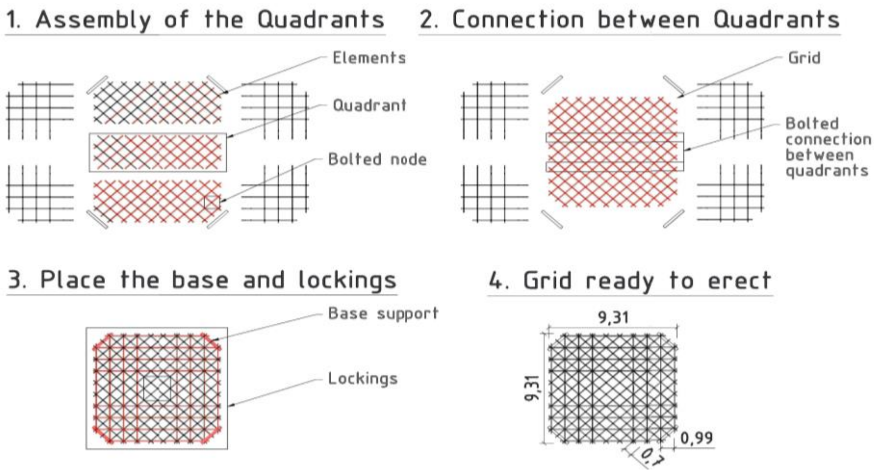


Figure 5.46- Mounting process scheme of the Gridshell 2.0

Both Gridshell 1.0 and 2.0 were aesthetically similar. However, in terms of general characteristics there are several differences, from the detail of the section to the direction of the whole grid, see table 5.7.

Table 5.7- Case studies 1.0 and 2.0

Gridshell 1.0	***Gridshell 2.0***
Elements cross-section 60mm x 15mm	Elements cross-section 50mm x 15mm
Double layers	Double layers
Spruce (Picea abies)	Eucalyptus (*Eucalyptus globulus*)
Locking elements applied afterwards	Locking elements built into the grid
Grid of 45 ° relative to supports	Grid perpendicular / parallel to supports
Simple bolted connections	Simple bolted connections

5.2.8 **Budget**

In construction, every change or different solution leads to different values and costs. In almost all situations, the cost is the prevailing decision factor (Cosgrove & Collins, 2016). On this subject, cost estimate of the tested gridshells will be shown by comparing the cost of Gridshell 1.0 with Gridshell 2.0. This calculation was based only on the initial costs, material and labour needed for the construction.

The price of timber per cubic meter varies depending on the section. This is an advantage for elastic timber gridshells, since the raw material can be obtained at a lower price, and the sections being used are always smaller than normal structural elements. In this sense, sub product pieces were cut from other elements of larger sections. Consequently, based on the average value of the cubic meter presented by sawmills and carpenters, in the North of Portugal, the average price of the cubic meter, for pieces with a section less than 10 x 10 cm^2 is 400 €. The average price of the cubic meter of Eucalyptus, green or dry, varies between 320 € and 350 €, considering the sections previously presented (Table 5.8). This reference is for sawing with automatic cut. Otherwise, the labour must be added to the cost of the elements, which would increase the final cost.

Table 5.8- Timber Quantity and cost

Timber Quantity	Gridshell 1.0	Gridshell 2.0
Number of layers	2	2
Vol. of timber Grid (m^3)	0,48	0,37
Vol. of timber Locking (m^3)	0,091	0,11
Vol. of timber Bases (m^3)	0,36	0,32
Total (m^3)	0,94	0,80
Spruce Price fir 400=m^3	420,00 €	
	398,12 €	337,26 €
Eucalyptus price 300=m^3	350,00 €	
	331,77 €	281,05 €
Total Cost	398,12 €	281,05 €

By analysing Table 5.8, timber Eucalyptus appears to be cheaper and, in this case, it presents the best behaviour. Therefore, Eucalyptus has a greater potential path of applicability.

As for the connections, two types were presented: the bolted connections and the connection with plates. Although the solution of the simply bolted connections was the one applied, it is important to note that opting for the use of plate connections would imply extra costs. For each bolted connection, a bolt is used together with a nut and two washers. Whereas with plate connections, the material used is two plates, eight washers and four screws and the respective nuts.

Even without the price of the plates, it is possible to understand that each connection would take four times more screws. The bolted connection will cost 0,16 €, on average, as it can be seen in Table 5.9.

Table 5.9- Connectors quantity and cost

Connections Quantity	**Gridshell 1.0**	**Gridshell 2.0**
Bolted nodes	184	177
Link between lines (3 bolts)	56	52
	168	156
Total (Links)	352	333
Connection price (Bolt 10cm)	0,16 €	
1 screw / 1 nut / 2 washers	56,32 €	53,28 €
Total Cost	56,32 €	53,28 €

Despite the extra time needed for the simple connection solution (cutting and preparation of the tears in the pieces), it can be observed that the use of the plates would also increase four times the time necessary to assemble and lock the gridshell, due to the time spent on tightening more screws.

In addition, there is also the labour cost required during the assembly of the grid, the laying of connections, the preparation of the bases, the erection of the grid, application and tightening of the knots, with an average payment of 15 € /hour with the equipment. The same hours and number of workers will be considered for the two cases: two days of work for four people. Below, it is possible to see clearly the cost value of each proposal, resulting in an estimated cost of 960€.

In Table 5.10, it can be observed that the cost difference it is about 8,5%. An extrapolation of this margin, in the case of constructing large areas, can influence greatly the final budget. The intention of introducing the changes to the building of the structure was merely to improve the gridshell, not to lower the price. Nevertheless, the change of timber, the optimization of the section and the better use of the material have made Gridshell 2.0 more efficient and cheaper. These are probably the two most important factors, cost and structural behaviour; both were improved, and did not affect the aesthetics.

Table 5.10- Final Budget

Budget	Gridshell 1.0 (42m2)	€/m²	Gridshell 2.0 (42m2)	€/m²
Timber elements	398,12 €	9,48 €	281,05 €	6,69 €
Connections	56,32 €	1,34 €	53,28 €	1,27 €
Workmanship	960,00 €	22,86 €	960,00 €	22,86 €
Total Cost	1.414,44 €	33,68 €	1.294,33 €	30,82 €

5.2.9 Second elastic timber gridshell - conclusion

Based on the conclusions of the first gridshells tested some changes resulted in the second structure. It is important to admit that not all changes presented were expected to improve the mesh would give better results, such as the number of layers. However, most of these changes did, and in the end the structure ended up with better behaviour. This management between what the wills are and what happens highlights the importance of the monitoring and supporting of the engineering knowledge. The whole process was aided and validated by a teamwork that reinforces its need.

5.3 Outcome of the Gridshell 1.0 & Gridshell 2.0 projects

Regarding all the improvements made on the original structure Gridshell 1.0, the change of cross section decreased the weight of the structure but, on the other hand, reduced the strength of the timber slats. Moreover, the change of material also increased the weight and the strength of the elements. To improve the performance of the gridshell, another aspect was subjected to testing: the quantity of layers. Diminishing it was inefficient when the grid was rotated. This rotation, when it was evaluated separately, proved that it alone would not be any improvement. However, by adding the locking, also rotated at 45º, the behaviour of the rotated grid changed positively. By analysing the results of Gridshell 2.0, it is possible to observe that some progress was achieved and that solutions to several problems were found. The quantity of the material used decreased, and along with it, the cost of the gridshell. On the new gridshell, the number of arches with high deformation decreased as compared with the Gridshell 1.0, offering a more uniform structure and preventing the failure of some elements during construction.

5.4 Summary

This final chapter, based on the case study, has experienced the actual construction of an elastic timber gridshell raised various problems. Problems that appeared in the final built solution, but which showed flaws in previous processes as well. Also, based on this case study, a new structure was recreated, for which some changes were proposed and tested.
It was possible to realize that this is not a straightforward process, as was mentioned in chapter 3.7, there is a constant dialogue and help of both areas. engineers and architects which have to work together to test design and construction issues.
The result of this teamwork ended up being expressed in a structure with better structural behaviour, better use of material, better efficiency rate and cost.

6 Conclusions and Future Work

This study starts with a contextualization and an explanation regarding the history and techniques of elastic timber gridshells, by considering the main contributions even if they are not about elastic materials or even timber structures.

It was addressed what should be taken into consideration during the conception, design and construction of an elastic timber gridshell. All the methods to assemble these structures are presented, with the constructive details and its great importance in the global behaviour are explained.

Followed by a case study used to test the process of merging the information and characteristics of the material (timber) with a digital model. Some relevant software tools and the main advantages of using digital tools during the design of a Gridshell are also discussed.

Finally, the pratical experience of the construction of an elastic timber gridshell is obtained during the process where some difficulties arose. Based on this case study, a new structure is conceived, where some changes were proposed and tested.

It was possible to realize that the process of create an elastic gridshells is not straightforward it is a constant discussion and help of both architectural and civil engineering areas. Engineers and architects have to work together to test design and construction issues and architectural goals must be defined within a technical space of possibilities. Engineering research and its development expands the universe of possibilities that constrains architectural invention. However, it cannot be taken for granted that engineering research, is alone development technical expands the universe of possibilities in relevant, desired directions being prompted and inspired by architectural goals. To sum up, architectural goals and inventions have be related and inspired by recent engineering advances. The two disciplines co-evolve in mutual adaptation. Governed by different priorities, knowledge and its understanding are critical to the harmony of the work and the tectonic success. Even though there can be no doubts that architecture remains a discourse that is distinct from engineering, a close collaboration with the engineering discipline, as well as, the architect's acquisition of reliable intuitions with their respective thinking approaches, are increasingly important conditions for the design of contemporary high-performance built environments. This reflection is evident in this work where the elastic timber gridshells have proofed that this teamwork is the future of this field.

6.1 Outcome

The aim of this work is to answer to most of the research questions which have been presented in the initial state of this study. These answers are intended to explain all the steps involving the design of elastic timber gridshells and to suggest improvements that would affect its structural behaviour, by reforming the construction stage.

In the search for these responses it was possible to conceive elastic timber gridshells from their material and shape. It was even possible to define and divide them into three smaller groups, regular in compression, regular in tension and irregular, based on their geometry and structural behaviour. Some notions have been explored regarding the characteristics of the construction, details and finishes of gridshell structures. These notions are of great importance because they must increase their qualities and minimize their defects considering the situation in which they are included.

Furthermore, some structural analyses have been made, considering only the geometry of the shape. However, as could be seen, this procedure gives great precision to the process of construction of these structures, eliminating some uncertainties and fears on the part of the designer, accelerating the process of demand and experimentation, and giving a broad panoply of different choices.

It is important to finalize this search with the enhancement of the support that the engineering knowledge can inform into the architectural process. The result of this team work ended up being very useful. The engineering has much to offer to the architectural process and, in this case, the importance of the two areas is so great and so intrinsic that the process, like the structure, is tectonic, method that would work as a conceptual design tool.

All this process allowed different options to be tested, as well as, to find possible changes and deny some assured options. Accordingly, it has been possible to recognise that the construction of these type of structures requires that attention be paid to the details, which are not always obvious but it can influence the result. Several moments of the process deserve to be referred, as the choice of the connections, the direction of the grid or the locking of the elements. It is important to understand the need for these steps to be adopted correctly and at the right time.

In a theoretical way, this work was intended to be a tool, a more transversal example, with improvements and notions, in the different phases of the conceptions that can be re-used for other cases. From a pragmatic and critical reflection view point, some more ideas were registered to reach the goal of sharing theoretical and practical information in elastic timber gridshells field of design, such as:

a) The Form Finding:

- The shell shape should be defined geometrically or digitally for making their construction possible;
- The architect has at her/his disposal tools that allow her/him 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;

- The locking procedure should be balanced between weight / efficiency so that the use of excessive force does not become a problem.
- The gridshells with two layers must be optimized and the grid metrics can change;
- Only one layer can also be used in the areas where less load is desired;

b) The Approach Concept:

- The span must be proportional to the height;
- A gridshell can work in tension or compression or both depending on the approach;
- Curvature and height of the timber gridshell should be enough 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 columns always give it a unique tectonic characteristic;
- Each work must be understood as a single case, but the Approach Concept should be perceived as a tool applicable to various circumstances;
- The monitoring of these structures and the categorization of the timber, considering the movement and stiffness given to the gridshells, is of the utmost importance for the design process.
-

c) Assembly Process:

- The surface should be bendable;
- Localized forces must be avoided;
- Besides the obligatory projects, an assemblage project should always be prepared;
- Cost 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 lifting process combined;
- The flexibility of timber and its ability to adapt to new shapes is a huge quality. However, over time it loses tension, because of the material relaxation. The fact that the time factor is not present in the parameterized model brings some uncertainty about the long-term movements in the structure;

- Tension forces give stability to the structure. The more tensioned it is, the less influence the outer forces have on the geometry.

(d) In the Constructions Details:

- 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 on the adapting properties of the timber;
- Joints and the locking elements should allow rotation of members before fixing.
- The links should be chosen considering the assemblage process, the behaviour after that and the Architectural image;
- The Architect must be skilful in handling all the phases of this process;
- Locking with timber 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;
- Elastic gridshell cover material should provide rigidity to the structure or must have the capacity to adapt to its deformation;
- The design process lacks rules of geometry and effective proportions as a complement to the structural analysis and they can never be created as a rule since it depends on the characteristics of the type of timber used.

To create this compendium assumptions genuine knowledge about elastic timber gridshells, several theoretical extrapolations and reflections about their definition as a structure were made. Here, it was clearly intended to leave its categorization in relation to the structural behaviour, its programmatic purpose, as well as the construction processes.

Laboratory tests were carried out to study the mechanical properties of the timber, and to obtain values of the same, to be used in the testing models. The dimensions for the elements of the mesh in the initial architectural design were also revised. With the data obtained in the laboratory tests, physical and computational models of the architectural design of the mesh was designed to simulate the complex construction process. Moreover, these models allowed to find the exact geometry that elastic mesh would obtain after being deformed during the construction process. Throughout this design and analysis process a prototype of a structural elastic mesh of wood was built, which validated the developed models, both parametric and numerical ones. In addition, the construction of the prototype allowed testing the constructive method developed and demonstrating the various advantages of an elastic structural meshwork.

Besides all the advantages obtained with the construction and design of a real elastic timber gridshell, another objective was reached. The separation of the image, the structure and the assumption that everything has an option. In the end, this is what is that all about, making it known so that its potential is harnessed and it can be well conceived. Making people more aware and explaining something 'new' to people is always the best way to make it more attractive. In this case it is not just the good feedback that was received from the workshop, and from those who passed through the built gridshell. It was the successful repercussion that resulted from it; it increased curiosity about these structures, which mirrored new workshops with new timber gridshells being built (Figures 6.1 and 6.2). It should be made clear that the structures mentioned here have not been created on the initiative of this investigation; they were only inspired on this project. One of the structures is a reciprocal gridshell and the other is an elastic gridshell, as shown in the images below with the original mesh and the two meshes that followed. These were also built in Guimarães with an academic and educational prurpose

Figure 6.1- Reciproc Gridshell (July 2016)(Ciencia Galega I.Creativas, 2018)

Figure 6.2- Gridshell (June 2016)

It was from this project that the first structural elastic timber gridshell was built, and recorded, in Portugal (Figure 6.3).

While significant progress has been made on this subject, which has not been studied and developed at a global level, which is new in Portugal, there is still work to be done, with the help of this tool.

Figure 6.3-First elastic timber gridshell in Portugal

As elastic timber gridshells are entering the new cycle of thinking and design process, their characteristics will be exploited, namely: membrane, organic form, its plasticity in design and the ability to create unique spaces and efficient structures, capable of revolutionizing the design and form of contemporary timber structures design.

It is expected that the developed work has resulted on a useful tool, to know better these structures, and as a methodology for the development of new architectural solutions, new technical details, and resolution of any problems related with timber gridshells solutions.

6.2 Future work developments

Despite the success in the construction of the prototype and the results obtained in the development of this dissertation, there are still many developments and improvements to be made in the design, analysis and construction of timber gridshells. This type of structure has a great potential still to be explored, in modular construction and pre-fabrication. The partitioning of modules, partial or total, can bring a new market for gridshells. Its sinuous forms bring great challenges for prefabrication industries and bring great spatial and formal changes to the traditional prefabricated constructions.

In addition, it is still necessary to reflect on the ability of architects and engineers to control the process, instead of leaving the digital tools control the project. It seems that, in many situations, designers get carried away by the easy use of software forgetting the reality and the context of the place. It has transformed their buildings into craft works. Perhaps the future of these solutions may be through the creation of standardized models to be used in social events, as well as, emergency architecture (Hurol, 2016).

It is important to refer that research with bamboo could be an advantageous step in the future, because it is a popular material in the Pacific region, and it can been used in some large-scale buildings, working in a very similar mechanical manner (Panasonic, 2015). Another point to be taken into consideration would be the study of composite materials, which are being used in a vast number of applications in the construction industry over the last few years (Liuti, 2016).

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