



Integrative Design and Engineering for Timber Folded Plate Structures of Free-Form Vaulted Systems

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Abstract

The present research describes the comprehensive development of a timber folded plate structure, and explores the potential of the folding principle for designing free-form vaulted shells. Corrugated structures are well-known for their efficiency with regard to material saving and structural reliability, by stiffening a thin surface with the introduction of a series of folds through and optimized geometric design. Their inherent composition of discrete planar elements allows a high degree of pre-fabrication, offering the possibility to benefit from one of the most advanced sectors in the industry, thereby attaining a responsible material consumption while minimizing the ecological footprint. This paper discusses the integrative design process and construction of the Pentaura pavilion, a timber folded shell locally joined with few stiff mechanical fasteners. The authors further investigate the influence of the creasing technique in relation to its amplitude of corrugation. By employing a blend of parametric graphical tools in conjunction with real-time simulations on a Finite Element Analysis Software, it becomes straightforward to assess the feasibility of the pleating configuration, establishing a comparison between the structure's bearing capacity, overall mass, material usage and a cross-section optimization. The interdisciplinary approach presented invigorates a close collaboration between architects and engineers throughout the design process, intertwining simultaneously the benefits of an excellent static system with a striking spatial experience.

Keywords: Timber folded plate structures, free-form vaulted shells, integrative design, form-finding, geometry optimization, modular system, structural engineering, computational fabrication.

1. Introduction

1.1. Folded plate structures

Timber folded structures, also referred to as “corrugated shells”, consist of a large number of discrete, thin planar elements, mutually connected to create an overarching folded surface, which harnesses the structural potential of the folding principle with regard to material saving and structural efficiency [1]. Based on a simple technique, complex geometries are generated, which respond both to engineering and architectural requirements. Folds not only introduce structural strength, but also contribute to the perceptual deepness, emphasizing the spatial flexibility through the dance of lights and shadows along the folded facets.

In nature, the concept of folding is extensively spread, with numerous plant leaves, shells and insect wings that employ folds to reinforce thin surfaces. Among humans, the origin of “origami” proceeds from the ancient China and was further developed in Japan, and it is a combination of the Japanese words “oru” (fold) and “kami” (paper). The art consists in transforming a flat sheet of paper into a

finished sculpture through creasing techniques, stiffening a thin layer with a specific target configuration. The ancient technique, interlacing materiality and geometry, emerged as a new research field with technological and structural applications, combining the mathematical and kinematic properties of folds.

1.2. Research statement

One of the considered limiting factors on shells axially compressed is the appearance of local buckling, which can lead to the loss of the structure's bearing capacity. The challenge of large scale shells is to minimize their dead weight, making them very thin, without compromising its stability. To avoid the buckling phenomenon, its inertia has to be augmented, either incrementing its section or gaining strength through an optimized geometric design. Following the folding principle, demonstrated on Pentaura's pavilion, a surface can be stiffened maintaining a thin cross-section by introducing a series of folds on its skin.

The authors aim to provide insights of the employed system and its interdisciplinary approach, as well as introduce the implemented structural modeling and optimization strategies for the shell. An extended research is developed with the aim to endorse the presented methodology's robustness in accommodating the changing topology of the original skeleton, and to showcase the optimal equilibrium between the folding pattern and its amplitude of corrugation, establishing a comparison between the structure's bearing capacity, overall mass, material usage and a cross-section optimization.

2. Pentaura pavilion

Inspired by origami, together with the aware observation of the pleated skin of seashells and leaves, the Pentaura pavilion is a shelter which utilizes form in order to save material. Installed on the playground of the primary school Escola Turó de Can Mates in Sant Cugat del Vallès, Spain, and built in an academic framework during the Master of Parametric Design in Architecture at the Polytechnic University of Catalunya (UPC), it covers a floor area of 85 m². The shell is designed as a large-span umbrella, with the main purpose of providing shadow and a space-enclosing envelope where to gather and develop the collective activities organized by the educational institution.



Figure 1: Pentaura pavilion at Escola Turó de Can Mates in Sant Cugat del Vallès, Spain. Photography by Andrés Flajszer.

2.1. Shell design

The structure followed an integrative strategy intertwining design, structural engineering and fabrication, to simultaneously evaluate and modify the complex geometry from an early design stage, employing visual representation and real-time computational feedback [2].

Form-finding can be defined as the “forward process in which parameters are explicitly controlled to find an optimal geometry of a structure which is in static equilibrium with a designed loading” [3]. From an arbitrary starting two-dimensional network, with specific constraints to guide the architectural concept and limit design degrees of freedom, the geometry is found through a form-active system. The double-curved surface acquires its shape through the dynamic relaxation of the network, which is modelled from a topological skeleton. The medial axis of any form consist in a dimensional reduction of its surface into a collection of lines [4], which are equidistant to its boundary. Following these guides, a structured mesh is generated, with singularities arising from it. The pattern can be automatically densified by adding subdivisions on the strips for each side of the skeleton. The input mesh is then relaxed into a funicular shape, following Gaudí’s hanging chain models, by applying vertical loading (self-weight) in order to obtain a geometric representation of the shell axially compressed in equilibrium, with minimal bending forces. Edge arches are only supported at the corners, what in compression-only structures assume by definition a convex shape. Intertwined, searching for an efficient geometry with a high-quality structural performance, and discretized into a large number of lightweight elements, the overall shell is transformed following the ancient Japanese techniques of origami, employing the potential of the folding principle to strengthen its single-layer envelope.

The creasing process is carried out through the understanding of the folding as a dynamic procedure, which has the capacity to undergo transformations and adapt to the predetermined configurations. The technique is designed throughout a dynamic simulation that allows the pleating to find its most optimal shape, as well as the amplitude of corrugation which responds more efficiently to the established loading. As an initial approach, the model is introduced to the Finite Element Analysis Software as a continuous shell, to conceive the global stresses and displacement values, speeding up the process of form-finding, identifying and filtering out the indispensable parameters that primarily contribute to the folding principle. Subsequently, with the aim to obtain quantitative and qualitative conclusions, the pleated mesh is deconstructed into a set of triangular pieces. The initial monolithic geometry evolves in order to be analysed as a segmented timber shell, taking under consideration the weaknesses of employing a tessellated system.

The inherent composition of Pentaura’s pavilion offered the possibility to benefit from one of the most advanced sectors in the industry, pre-fabrication, integrating to the design sequence the optimization of material’s consumption, minimizing waste by maximizing the percentage of usage of timber boards arranged to send to laser-cut, what has allowed a reduction of the global ecological footprint.

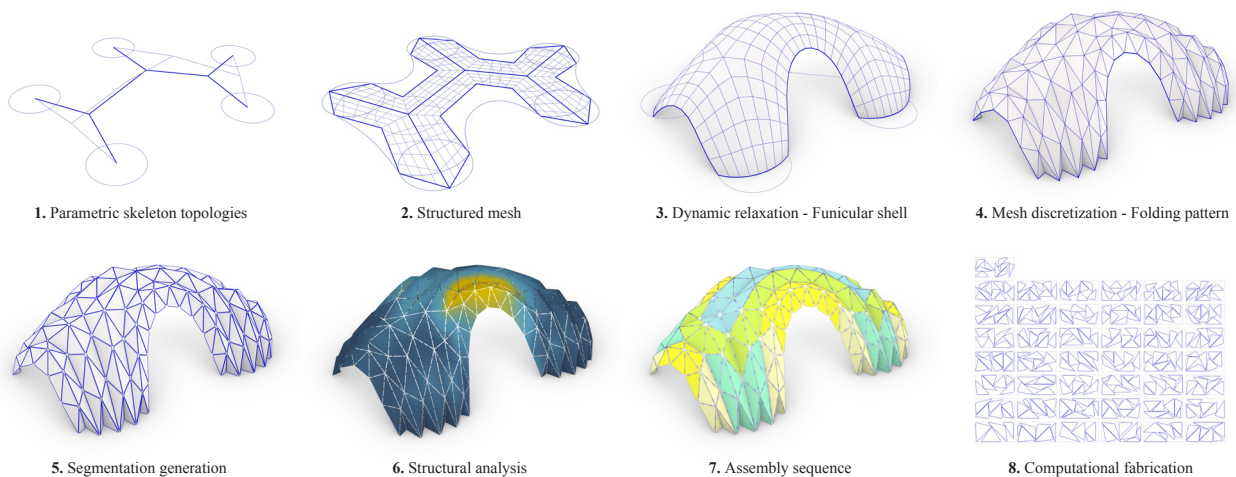


Figure 2: Parametric design process and optimization sequence for Pentaura’s pavilion construction.

2.2. Connection and foundation design

The intrinsic nature of segmented shells is their composition of multiple planar elements, which have to be tied along their longitudinal edges, potentially becoming one of the weakest points for the structure’s reliability. Such condition designates edge-to-edge connections a crucial design driver in the load-

bearing performance of the entire shell, as their properties particularly correlate with the global structural response.

In timber construction, the attachment of thin planar elements with diversified connection angles can be challenging. Metallic fasteners such as steel plates offer beneficial properties due to their adjacent assembly and inherent stiffness, maximizing the in-plane loading capacity. For Pentaura pavilion, timber boards locally joined with steel plates of grade S255, with dimensions for the largest plate of 170x120x4mm, proved to be an appropriate universal connection strategy. The system's simplicity assumes the variety of angles, while at the same time guarantees the structural rigidity, high fixity, the use of only three-axis machining and further great constructability for a rapid and robust on-site assembly.

The design principle for Pentaura's foundations aims to avoid the use of unrequired material and follow the mechanical system proposed for the overall shell. This leads to five timber plate strips of 2750x700x40mm, placed in correspondence with each leg of the structure, which are connected to the building components through metallic fasteners. The platforms lie on top of two timber joists of 2400x100x100mm, which are fixed to the floor using spirafix mechanical connections, spiral ground screw anchors arranged vertically at a distance of approximately 600mm between them.

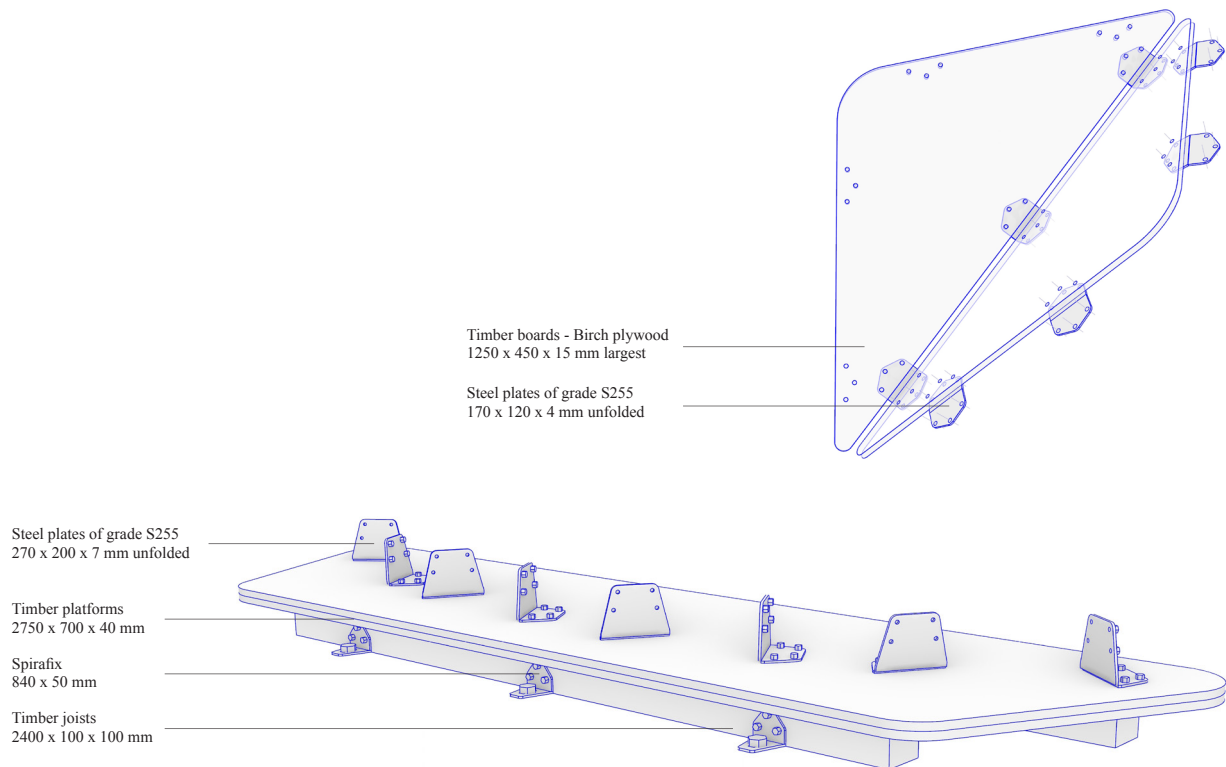


Figure 3: Connection and foundation detail.

2.3. Structural and loads design

Pentaura pavilion is planned as a permanent structure located on the playground of the school Escola Turó de Can Mates in Sant Cugat del Vallès, Spain. The shell is modelled in a Finite Element Analysis Software, under the load's configurations established below, with a utilization factor limited to 0,50 and maximum deflection admissible of 30mm.

2.3.1. Load cases

The subsequent values are obtained following the CTE DB SE (*Código Técnico de la Edificación, Documento Básico - Seguridad Estructural*).

2.3.1.1 Dead loads (DL)

The structure consists of 306 timber boards made out of birch plywood with a thickness of 15mm, connected with 846 steel plates of 4mm. Dead loads correspond to the weight of all pavilion's structural elements, and is calculated by assessing the density of the specified materials and their volume.

2.3.1.2 Wind loads (WL)

The distribution and values of the pressure exerted by the wind on a structure and the resulting forces depend on the shape and dimensions of the construction, the characteristics and permeability of its surface, as well as the direction, the intensity and gusting of the wind. According to its location, the static pressure, q_e , a perpendicular force to the surface of each exposed point, is calculated as follows,

$$q_e = q_b \cdot c_e \cdot c_p$$

q_b , dynamic pressure of 0,52 KN/m², determined by the structure's geographical situation, which corresponds to zone C

c_e , exposure coefficient of 2,10

c_p , wind or pressure coefficient, equals to 0,40 for pressure and -0,50 for suction

2.3.1.3 Snow loads (SL)

Situated at an altitude of +124m above sea level, the shell is considered to be in snow load zone 2, which determines a load value of 0,50 KN/m².

2.3.1.4 Live loads (LL)

Taking into consideration that Pentaura pavilion is installed on a playground of a kindergarten, further imposed loads, such as live loads, are considered in a gravitational direction due to the presence of children on top of the shell. Such forces are defined and applied as punctual loads of 0,20 KN/m² on different points of the surface. These actions are not considered to act in conjunction with other dynamic load combinations.

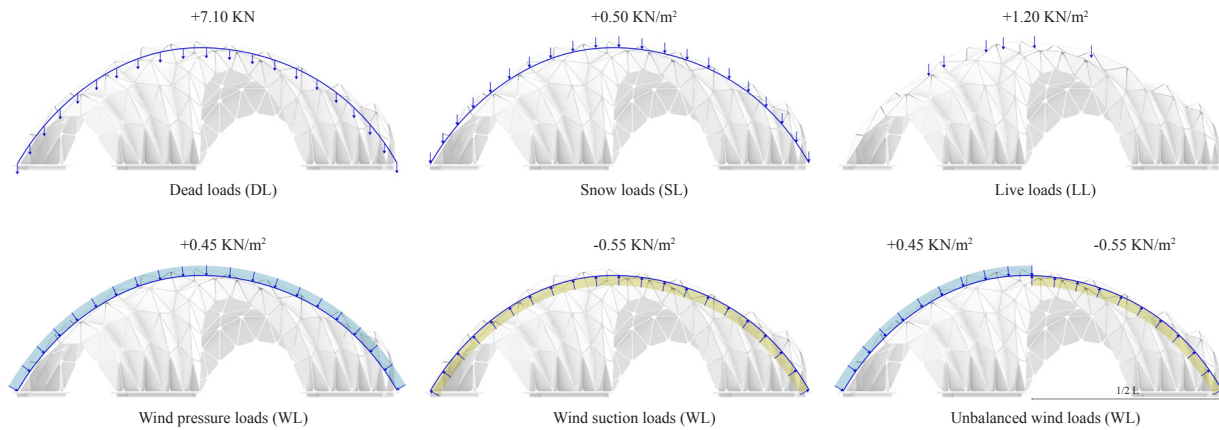


Figure 4: Schematic design of the predominant load cases for Pentaura pavilion.

2.3.2. Load combinations

Ultimate limit state (ULS), load groups that occur persistently and transiently have been combined using the partial safety factors of the ultimate limit state. Serviceability limit state (SLS), load groups that occur quasi-permanently have been combined using the partial safety factors of the serviceability limit state. Load combinations are written below:

$$ULS1 = 1,35 \cdot DL$$

$$ULS2 = 1,35 \cdot DL + 1,50 \cdot SL \cdot 0,50$$

$$ULS3x = 1,35 \cdot DL + 1,50 \cdot W_x \cdot 0,60$$

$$SLS1 = DL$$

$$SLS2 = DL + SL \cdot 0,50$$

$$SLS3x = DL + 1,50 \cdot W_x \cdot 0,60$$

$$ULS3y = 1,35*DL + 1,50*Wy*0,60$$

$$SLS3y = DL + 1,50*Wy*0,60$$

$$ULS4x = 1,35*DL + 1,50*SL*0,50 + 1,50*Wx*0,60$$

$$SLS4x = DL + SL*0,50 + Wx*0,60$$

$$ULS4y = 1,35*DL + 1,50*SL*0,50 + 1,50*Wy*0,60$$

$$SLS4y = DL + SL*0,50 + Wy*0,60$$

2.4. Pre-fabrication and on-site assembly

In contrast with conventional concrete shells, segmented timber structures are much easier to build, thanks to timber's low weight, dry nature, the absence of casting-curing requirements and the use of simple scaffolding [5]. The overall shell is conceived as a three-dimensional puzzle, pre-fabricated with millimetric precision, which allows to set up the numbered pieces in a rapid and efficient way. Furthermore, the building system's simplicity guarantees a successful construction without the requirement of specialized professionals, facilitating the access and implementation of folded plate structures to all audiences, and carries the potential for disassembly and re-erection of the structure within the ever-changing confines of urban architecture.

All building components for Pentaura's pavilion are grouped in five clusters according to the assembly sequence. The modular character speeds up the erection of the structure, enabling the pre-assembly of the grouped components, packed strategically depending on their size, volume and weight, as well as their position, reducing the high-bending stresses when they are attached to the main shell.

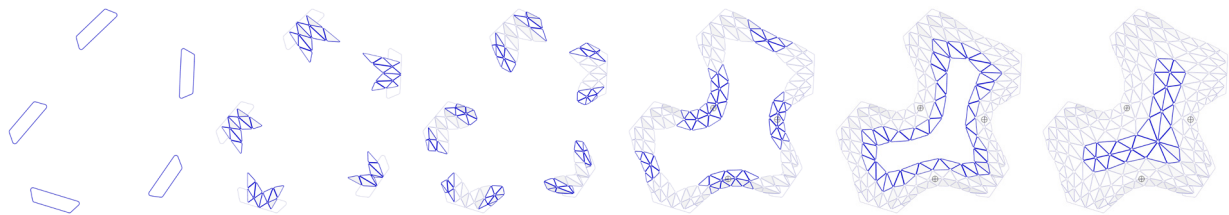


Figure 5: Assembly sequence of Pentaura pavilion with indication of the scaffolding props.

3. Folding patterns exploration and structural reliability

When designing foldable shells, it is required to understand and take under consideration the relationship between the amplitude of corrugation and its structural performance in order to acquire an optimal result. Although origami techniques have a wide range of target patterns, not all configurations are feasible when translated and used with technological and structural applications. Likewise, not necessarily the higher the percentage of creasing a structure has, the better it will perform. An extended exploration is presented below addressing the raised questions.

- a) For a free-form vaulted system, which folding pattern offers the greatest surface stiffness against global deflection?
- b) Chosen the most efficient pattern, which amplitude of corrugation provides the optimal equilibrium between the structure's reliability while maintaining shell's weight at a minimum?
- c) How does the introduction of additional conditions influence and enhance the structural performance through a post-optimization algorithm?

The subsequent parameter investigations were embedded within the structural analysis processes and optimization sequences of Pentaura pavilion, sharing the same customized interfaces for obtaining comparable results. In addition, required constraints were introduced in each one of the following sections, unifying the framework and homogenizing the general conditions for the case studies.

3.1. Folding patterns

From the fundamental collection of guidelines or topological skeleton, several double-curved shapes are generated. For each case study, the density and pattern of the structured quad mesh are preserved, and modifications are introduced by varying the number of supports, what in correspondence increments the amount of singularities or nexus connecting the network.

The double-curved surfaces obtained are discretized into two typologies of patterns, the longitudinal folded strips and Yoshimura.

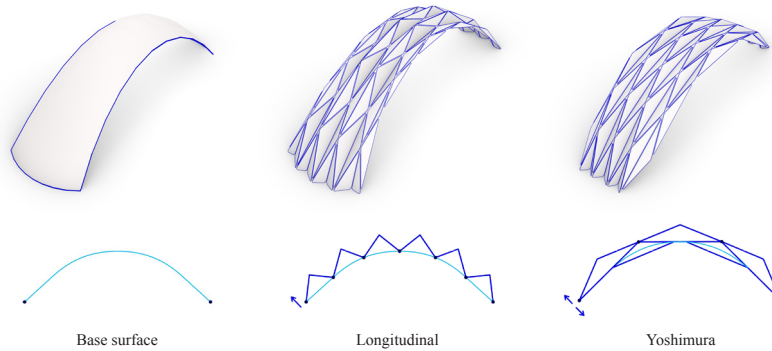


Figure 6: Folding patterns applied for the discretization of the double-curved surfaces, exemplified on the shell with two supports.

Longitudinal folds is a simply-corrugated surface consisting of an accordion-shaped folding of a series of parallel strips. Creases increment their section following the perpendicular vector to the funicular shell, whose direction points outwards. On the other hand, Yoshimura pattern is a geometric folding technique which involves a repetition of triangular or diamond-shaped facets that are creased along one of its diagonals. It is obtained by pleating a series of parallel lines, constituting diamond's diagonals, gaining section through inwards and acquiring the shape of valleys. The edges or side folds are transformed into mountain creases, which increment their depth through outwards. The understanding of the folding process as a dynamic procedure, within the frame of this section, the amplitude of the corrugation is fixed at 250mm, in order to adjust the simulation specifically to the shell's pattern comparison and to homogenize general conditions.

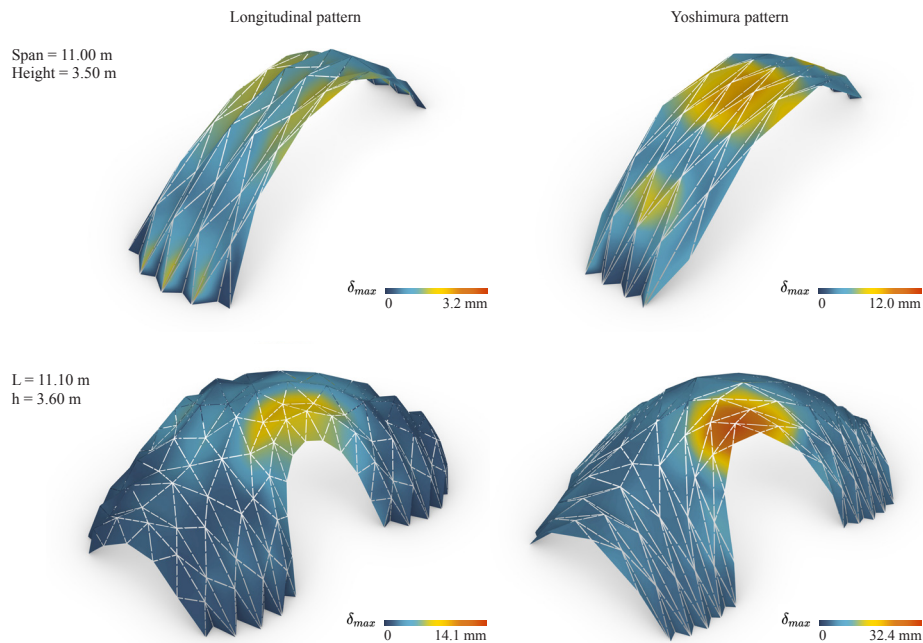


Figure 7: Comparison of two topological skeleton-based shapes, analysed in both folding pattern configurations, with regard to the structure's global deflection.

The comparison between both typologies of patterns denotes that for a greater overall depth, the structure responds more favorable in terms of global deflection. The creasing of the accordion-shaped folding achieves a wider amplitude in section, due to the uniformity of vector's direction during the growth of the corrugated skin. Therefore, based on the findings acquired, the subsequent section delves into

examining the influence of the amplitude of corrugation to the applied loading conditions, and is developed employing the pattern whose results proved to be the most beneficial.

3.2. Amplitude of corrugation, A_{max}

Amplitude is an essential variable which directly influences the stiffness of folded plate structures, since creases introduce an analogous moment of inertia greater than the one of the single components, and provide structural depth to hold out against bending. By employing a blend of parametric graphical tools, it becomes straightforward to assess the feasibility of the pleating configuration, allowing to establish a comparison between the structure's reliability in terms of global deflection, overall mass, efficiency on material usage and a cross-section optimization. The goal is to reduce excessive stresses resulting from bending in the ultimate segmented geometry, striving to maintain the shell's weight at a minimum, while achieving the most suitable configuration for the manufacturing boards. In the graphs, the amplitude of corrugation is represented by a percentage, which covers a range from 0 to 500mm.

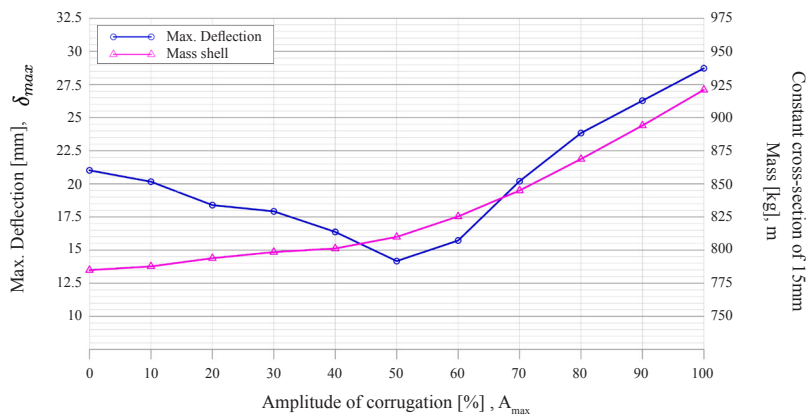


Figure 8: Influence of the creasing amplitude for longitudinal strips, A_{max} , on the structure's mass and bearing capacity against axial loading, for a constant cross-section of 15mm for the building components.

It should be noticed that, in terms of maximum deflection, the curve acquires a convex trace, with the lowest index located around the 50% of corrugation. The shell's inertia increments in correspondence with the amplitude of corrugation, gaining strength against buckling phenomenon through the folding principle, however, the graph illustrates how the structural performance decreases after arriving at the half of the pleating applied, at around 250mm.

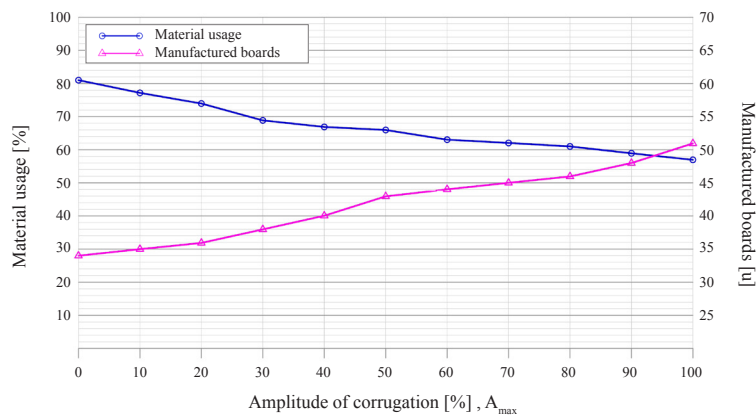


Figure 9: Feasibility of the creasing configuration, A_{max} , in relation to the percentage of material usage on a computational fabrication framework. Manufactured timber boards have dimensions of 2500x1250x15mm.

On a computational framework, the distribution of the building components on the manufacturing boards is automatically generated during the design optimization sequence. Given the timber sheets dimensions,

the percentage is obtained by dividing the area occupied by the elements between the total surface. The graph illustrates how a segmentation with smaller plates adopts a more favorable configuration when compared to shells with a greater degree of corrugation. As a result of the surface expansion, the wooden elements acquire larger areas, making it more challenging to accommodate them efficiently on the manufacturing boards.

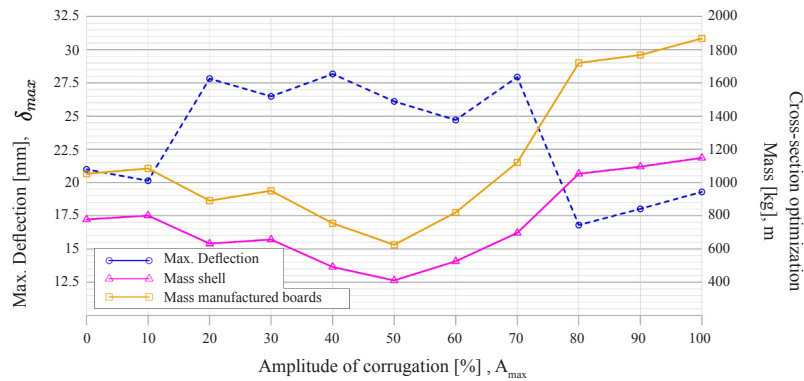


Figure 10: Effect of the cross-section optimization in relation with the creasing amplitude for longitudinal strips, A_{max} , on the structure's mass and bearing capacity against axial loading, with utilization factor limited to 0,50 and maximum deflection admissible of 30mm.

Using standardized plywood sheets ranging from 6 to 28mm in thickness, and maintaining the steel plates at a constant thickness of 4mm, a structural optimization is conducted to observe how the structure's behavior is affected by the variations in cross-section and amplitude of creasing. It should be emphasized how the curve corresponding to the shell's optimized mass acquires a convex trace, similar to the one representing deflection in Fig. 8. The significant decrease in thickness suggested by the software aligns with the efficiency of the folding pattern, reaching its lowest index at approximately 50% of corrugation. The numerical results for the total mass of the shell are represented in pink, with a cross-section of 15mm at the starting position, and a thickness of 7,1mm at a 50% of pleating. The origami technique leads to a reduction of the 52% of mass between the initial geometry and its most efficient shape, moving from the 405kg for the lowest index up to 784kg. On the other hand, the analysis of the total weight consumed with the fabrication boards suggests a reduction of the 59% between both extremes. Accordingly, the curves associated with mass exhibit an exponential growth upon reaching the lowest index, due to a decrease in the folding efficiency, an expansion of the surface area, and the loss of a favorable configuration of the building components on the manufacturing boards.

3.3. Additional conditions

Simple pleated surfaces, composed of parallel folds, present a uniform corrugation profile that remains consistent across the entire shape. However, where higher deformations appear in branched vaulted shells suggest that the optimal design criteria to enhance the structural resistance should be through the reinforcement of the supports and areas close to the openings, either by incrementing the cross-section of the building components or gaining strength through geometry. In this context, following the principle used throughout the design process, it is proposed to adjust the functions of the corrugated profile, by incrementing the amplitude around the weakest areas.

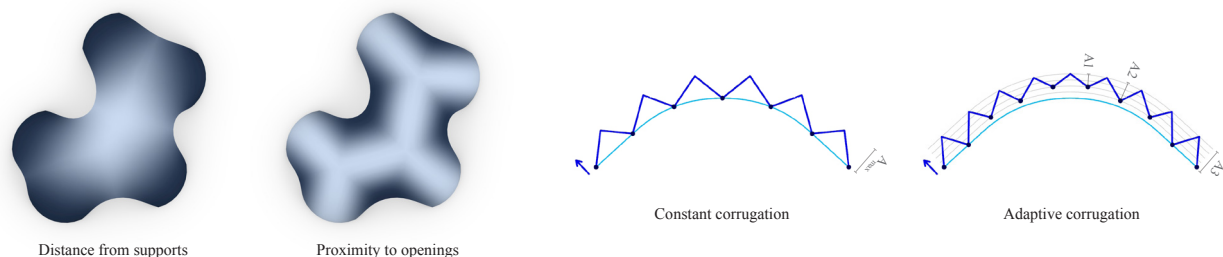


Figure 11: Representation of the additional conditions introduced. The colour intensity visually highlights the regions that require more reinforcement. Figure 12: Longitudinal pattern with constant and adaptive corrugation.

Maintaining a constant cross-section of 15mm for timber boards and 4mm for steel plates, and with a creasing amplitude of 250mm, the profile is modified by relaxing the shape, to undergo the adjustment and transformation of the constant corrugated profile into an adaptive one, as shown in Fig. 11 and 12. Both conditions are implemented through the analysis of vertices position concerning their proximity to supports and arched openings. A shorter distance to the assessed areas leads to an increased displacement of the strips, while for a larger distance, the sectional depth decreases. The results denote that the condition related to proximity to openings exerts a more significant influence, as it directly addresses the regions with the highest deflection. However, mirroring the conclusions from the evaluation of creasing amplitude's impact, excessive intensity levels lead to a decline in structural performance.

4. Conclusion

Folded plate structures offer promising possibilities due to their inherent nature involving the folding principle and their composition of discrete thin planar elements, what intertwines the benefits of strengthening a shell through an optimized geometric design while at the same time allows a high degree of pre-fabrication.

The research presented in this paper introduces Pentaura's pavilion, a successful corrugated shell of a free-form vaulted system, locally fastened with stiff universal connections. Through computer-aided design tools, an integrative design methodology has allowed a cross-cultural approach involving architecture, engineering and fabrication throughout the continuous planning process, embedding from an early design stage spatial, structural and manufacturing requirements. The proposed framework discusses the influence of the folding pattern in relation to its amplitude of corrugation, and demonstrates through an optimization algorithm the optimal equilibrium between structure's bearing capacity, overall mass and material's consumption. The results exhibit that the performance of a pleated shell does not necessarily improve with a higher percentage of creasing, nor does it reduce the amount of waste generated during the fabrication process. Therefore, the ultimate geometry of Pentaura's pavilion reflects the highest possible agreement between architectural purpose, structural reliability and its ecological impact.

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