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Performance of sewing timber joints applied to an origami timber pavilion: design and analysis.

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Abstract: During the last decades origami structures have presented great interest in the field of engineering and architecture because they can develop lightweight structures in an innovative way and with elegant shapes. Moreover, thanks to technological advances, fabrication and computational design have promoted new ways of building this type of structures. Thus, taking advantage of these, we present this research in which we make a timber pavilion that uses the Yoshimura pattern and we connect the panels with a thread of Kevlar of 3mm. The pattern is based on a mosaic composed of a simple polygon which is repeated indefinitely, creating triangles inside the pavilion. The goal of this research is to demonstrate the performance and structural analysis of the sewn joint system using Kevlar thread, which through different stress tests we conclude that the sewn joints present a great contribution to the development of this type of structures and present great structural performance and allow the development of complex shapes. Finally, a new connection system was developed through the geometry of the Yoshimura patterns and Kevlar sewn joints, we were able to create a structure that promotes sustainability, innovation, application of computational design and shows the potential when compared to conventional construction systems.

Keywords: Timber sewn joints, origami geometry, lightweight structure, parametric design, Kevlar thread, Yoshimura pattern

1. Introduction

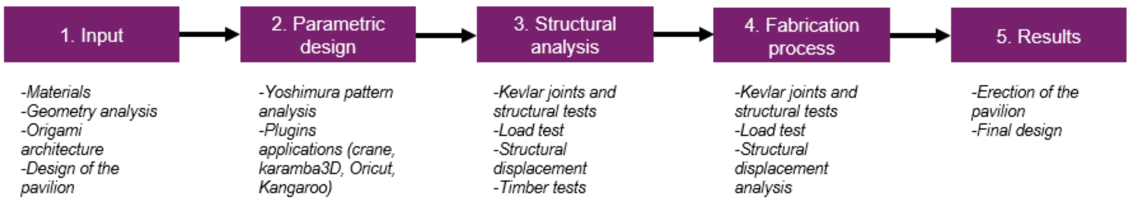
Origami is a very ancient art which can combine art, dynamism, statics, and technique through curved or straight lines represented by patterns to generate an object. The aesthetically pleasant patterns and shapes enabled by origami (from the Japanese words ‘ori’, meaning ‘to fold’, and ‘kami’, meaning ‘paper’) have long been admired, and origami inspired geometries have been used to obtain deployable structures for space missions, flexible medical stents and flexible electronic, devices [1]. Thanks to technological advances and computational design, that’s why they present many advantages compared to conventional construction. Origami architecture is based on developing folded shapes, greatly popularized in recent years, and was inspired by this art. The beauty of this type of design lies in creating elements and spaces using the least amount of material possible, preferably with flexible objects and materials, and with mobility. Thanks to the functional benefits, enormous possibilities, and innovative aesthetic aspects that origami architecture offers, many contemporary architects and engineers are beginning to apply it more frequently in their recent designs. In engineering and architecture, origami is implemented as a formal and spatial concept, projecting complex shapes created from acute angles that are pronounced on a single surface. Now, the visual patterns of origami can be combined with improvements and mechanical properties that would make buildings more functional, adaptable to the conditions of the environment and would considerably improve sustainability due to consuming less material.

Thus, this research begins with the purpose of taking advantage of origami structures and in this case, we use the Yoshimura pattern which is formed by isosceles triangles; Yoshimura origami is a sophisticated and artistic technique that allows to create complex and beautiful designs through the repetition and combination of folded paper units. In the case of the unions of each of the panels we use 3mm Kevlar thread to join each of the panels which culminates with the creation of an experimental pavilion made of 5 mm timber panels, showing positive results and generating new proposals to develop lightweight structures. Regarding the design part, we used parametric design to obtain a better result, designing in Grasshopper using different plug-ins taking advantage of computational design and, like the structural tests, different tests were carried out to measure the behavior under tension.

2. Aims and objectives.

The main objective of this research is to demonstrate the potential of sewn joints using Kevlar and how they can enhance the development of light structures. On the other hand, the geometry of the Yoshimura pattern will be studied, explaining it in detail. We present the structural, geometric analysis and design of origami structures, showing the potential they have and how they can be a great option for the development of highly sustainable, technological, and innovative light structures. For research, we carry out 3D modeling using different parametric tools to publicize the potential that technology currently has, just as the use of digital manufacturing can be catalysts for innovation in architecture.

Figure 1. Workflow of the entire investigation



3. Novel characteristics of origami architecture

Origami architecture is made up of development surfaces which can be made completely flat or developed in three dimensions, this advantage has given it a lot of advantage over other types of structures. Furthermore, today technological advances and computational design have allowed us to design and manufacture like never before. Thanks to these advances, today technology and digital fabrication have a very important significance in architecture and engineering. In this order of ideas, it is important to highlight that one of the most compelling reasons for the application of origami in architecture is the numerous possibilities it offers in the choice of construction material. The use of origami as inspiration is being investigated to encourage the use and optimize the effectiveness of this and other sustainable materials in future constructions. In addition to its relevance and notable rise in the design of static buildings, the architecture of folded forms represents a significant advance for deployable and removable structures. Origami patterns offer a wide range of possibilities for creating foldable and kinematic structures, such as facades, tents and roofs. Three patterns are identified to be particularly interesting for architectural and structural applications: Yoshimura pattern, Miura Ori pattern and Diagonal pattern. The three of them are based on a combination of simple accordion folding and reverse fold: A series of straight valley and mountain folds are bent by the reverse folds to form simple curved surfaces [2].

For the experimental development of this pavilion, we used the Yoshimura pattern (Figure 1) which is also known as the diamond pattern, which is commonly used to generate folding cylinders. The valley folds in the Yoshimura pattern are completely perpendicular to the axis of the cylinder, this is where the radius of the curve will be in charge of defining the curvature. It is well known as rigid origami which can be folded even if the sheet material is rigid. Yoshimura pattern panel structure has two advantages; it can be folded compactly even if panels are not thin like a paper, and it behaves like a crossed-arch structure since it foams a barrel vault geometry [3].

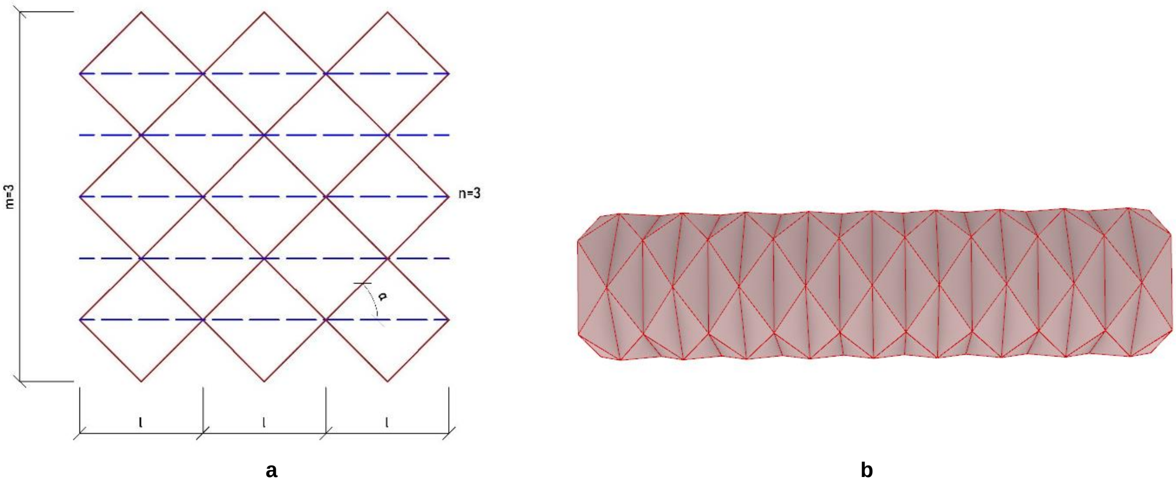


Figure 2. (a) Crease scheme of the Yoshimura pattern, mountain folds are represented by solid line and the valley folds by the dashed lines. l= length of the isosceles triangle, m= number of repetitions of the basic crease scheme, n= number of complete valley folds, α= angle between the valley and mountain folds. (b) Yoshimura inspired cylindrical structure

3.1 Structural and geometric analysis

Usually almost all origami structures are designed with the rigid folding system which gives it much greater resistance due to the angles that make it up. Geometry in origami is essential to understanding how precise folds can be made and how individual folds can be combined to create complex shapes. Origami designers often employ geometric and mathematical principles to create innovative and aesthetically appealing models. The opportunities provided by folded surfaces offer great opportunities for the development of lightweight structures, which are based on their geometric principles to generate effective structures. One of the principles on which structures designed according to origami are based is because they are flat surfaces but when folded they become three-dimensional surfaces. In the case of this structure, it was decided to integrate Yoshimura's pattern into a structure of 3 meters long and 2 meters high.

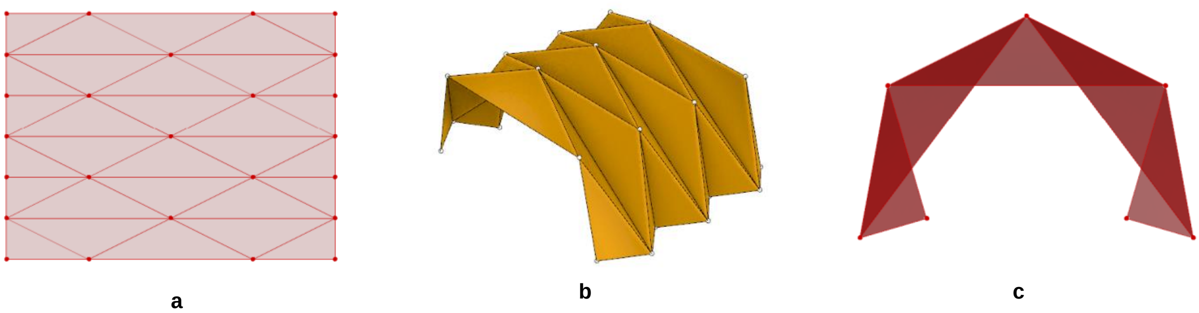


Figure 3. (a) In this pattern, the fold lines intersect, creating triangles with an apex angle β of 120°. While other apex angles are feasible, they must adhere to the condition of foldability, where $\pi/2 \leq \beta < \pi$. illustrates the wireframe model, featuring triangles with a 140° apex angle, across three successive deployment stages. (b) Parametric modeling of the pavilion and 3D perspective. (c) One of the advantages of origami structures is that they can be folded, this is how the structure would look.

The geometry of Yoshimura's pattern is based on a diamond-shaped fold, this is built by adding a diagonal line on the base of the pleat in this way it is possible to change the direction of the fold of the initial horizontal divisions, in such a way that the diagonal mesh becomes a valley and all horizontal traces become mountains. It is named after a Japanese scientist who observed that thin-walled cylinders show this kind of buckling pattern under axial compression [4]. The mechanical behavior of spatial structures is significantly improved by using folding techniques. A folding structure can cover a large span without bending of the individual plates, since they act primarily like membranes [5]. The Yoshimura pattern has the characteristic of generating surfaces that, when folded, "collect" into vaults until, once completely folded, they form regular polygons. The final figure will be marked by the folding angle of the initial diagonal mesh (figure3).

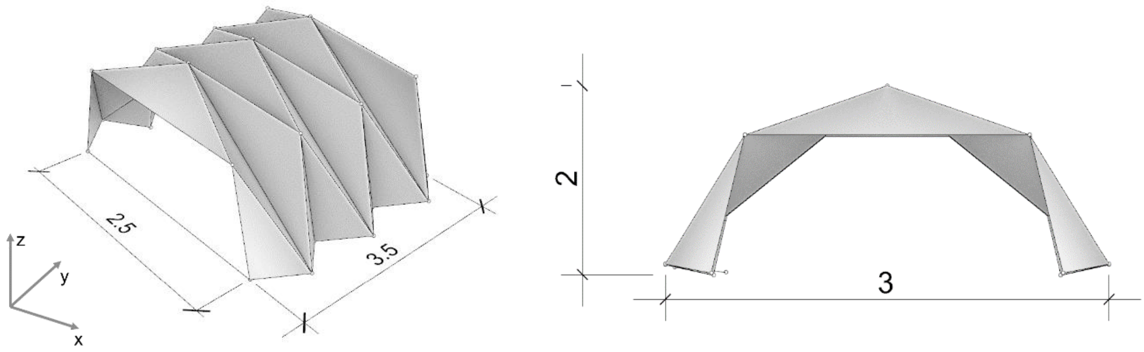


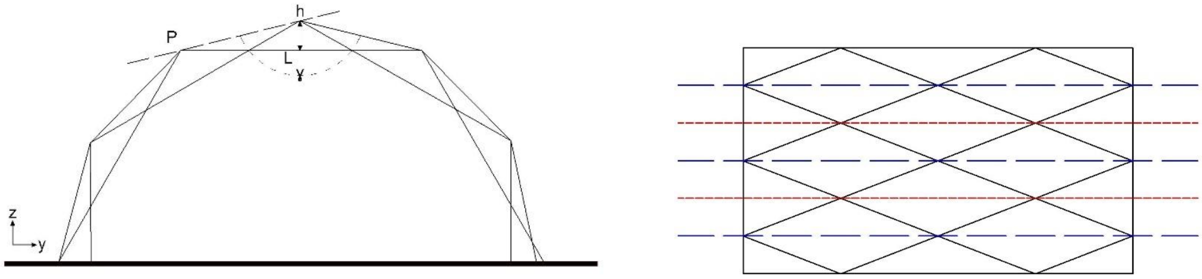
Figure 4. General measurements of the structure which consists of 22 5mm wooden panels that are joined together by Kevlar thread.

One of the first stages to develop the pavilion is to seek to integrate a geometry that adapts to the needs; That's how we identified the Yoshimura pattern and that's how we developed an algorithm in Grasshopper applying the geometry of this pattern. One of the most important aspects of this pattern is based on the development angle which is responsible for developing the development of the system (this parameter is very important to consider in any origami structure). Thus, after the geometric analysis of the parameters and angles, we concluded that the best option for the structure was to apply the 140° angle since this provided better design options and structural efficiency (table1).

Parameters	Dihedral angle	Height (meters)	Length (meters)
α= 45° n= 2	130.2	2	2.75
α= 30° n= 2	89.3	2	2.2
α= 25° n= 2	56.5	2	1.98
α= 45° n= 3	142.9	3	3.1
α= 30° n= 3	128.6	3	2.72
α= 25° n= 3	95.2	3	2.62

Table 1. Through the analysis and study of the angles, the dimensions of the pavilion were found. It was thanks to the results that we came to the conclusion that the angle of 140° presents the best option and gives the best height of the pavilion.

After identifying the parameter that best describes the geometry, we proceeded to establish the measurements of the pavilion as well as the measurements of each of the panels that make up the structure. So, we carried out different tests regarding the direction of rotation as well as the adjacent faces (figure 4). Parametric methodology seems to be the ideal instrument, in which both geometric and technological features are integrated. The design of foldable structures requires understanding the structural behavior of the model in terms of the geometric parameters to find the best configuration of deployment. Computational methods can strongly contribute to this aim, allowing drawing and modifying complex models and simultaneous carrying out the structural analysis [6].

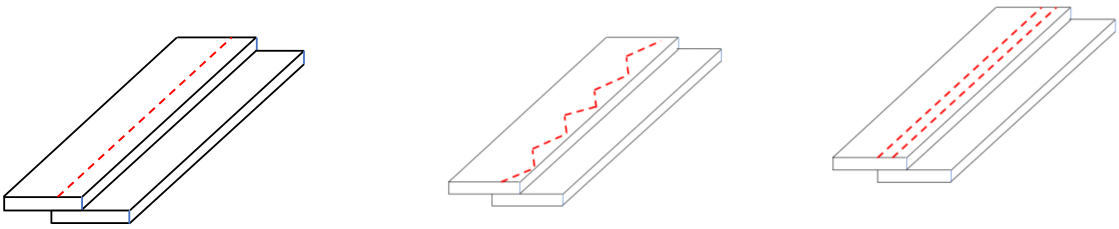


a b

Figure 5. (a) After the geometric analysis we found the final measurements of the pavilion, it was thus that through the angles and the established measurements they gave the best option, the image shows the mountains and the folds of the structure. (b) Lines, measurements and vertices that make up the pavilion and the integration of the Yoshimura pattern

3.2 Sewing joints and timber connections

The performance of any structure depends greatly on the type of connections since this help to correctly transmit the loads that a structure has. In recent years, almost all timber structures use a combination of nuts, screws and glues to join the panels of the structure. Today, thanks to rapid advances in technology and materials, there is a range of possibilities to use new materials in construction, materials that have great potential and can be used currently. In the case of the design of this pavilion, we chose to use sewn joints to connect each of the triangular panels of the pavilion (figure 5). The material was 3mm Kevlar thread, which is a material that has shown great interest in recent decades due to its advantages that shows, through different types of sewn joints we found that a double sewn joint was the best option (table 2).



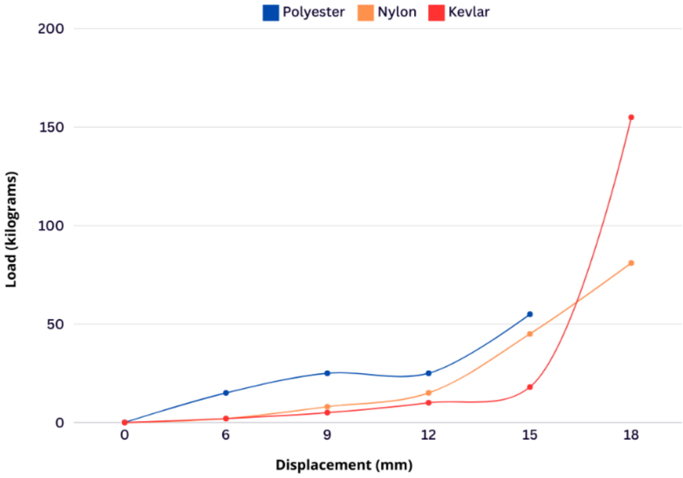
a b c

Figure 6. (a) straight line seam. (b) zig-zag seam. (c) double line seam

Seam type	*Displacement, (mm)*	*Breaking point (kilograms)*
Line	22	102
Double line	10	183
Zig-zag	15	125

Table 2. Through a break point analysis, we found that the joint sewn with two threads was the best option due to its mechanical properties.

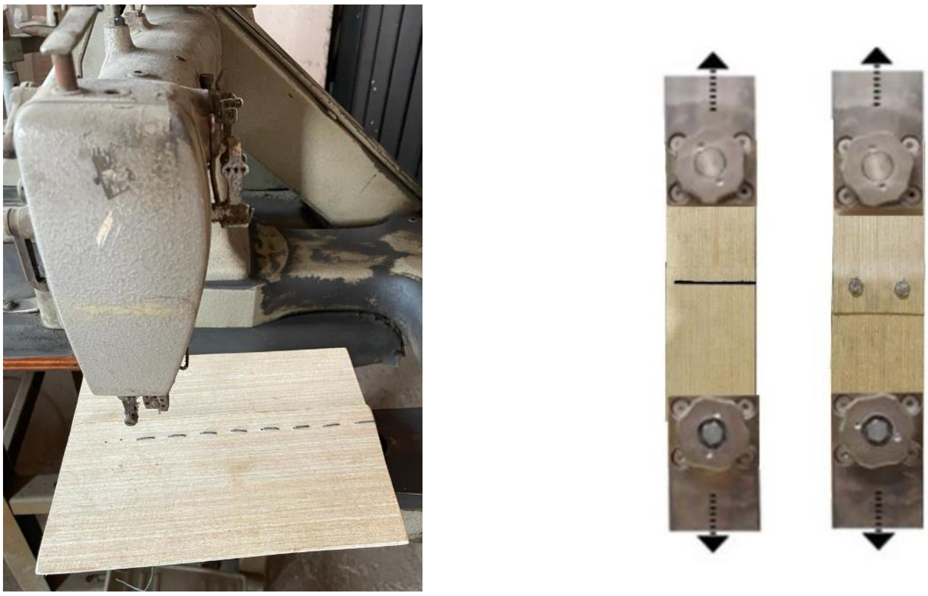
Kevlar is an organic fiber that belongs to the family of aromatic polyamides. Kevlar has exceptional tensile strength, around 3.5 GPa, steel has a strength of 1.5 GPa. There are two types of Kevlar, Kevlar 29 and Kevlar 49. The first is the fiber directly obtained from its manufacture and is generally used as reinforcement. Kevlar 49 has a surface treatment of its fibers to promote their union with the resin. After the design of the pavilion by the pattern Yoshimura, we looked for how to join each of the panels that make up the pavilion, we tried with screws, nuts and glues but we sought to integrate a new material that was innovative and presented great mechanical advantages, it was so later When reviewing different materials, we found Kevlar, which caught our attention due to all the properties it offers, which made it the ideal material to make the sewn joints of the pavilion. To know the mechanical resistance of Kevlar (Graph 1), we carried out different tests in which we compared it with similar materials (nylon and polyester) to demonstrate which one was suitable to be able to integrate it into the sewn joints.



Graph 1. Load-displacement curve of the shell prototype. A longitudinal line load was introduced along the top of the shell. Vertical displacement was measured at the center point

4. Construction, design and fabrication of the pavilion

For the construction of the pavilion, we chose to build it using timber since this material has great advantages when compared to other materials since it can be adapted to any shape, it is economical but mainly one of its great advantages is that it can protect a large amount of CO_2 gases, which is why many projects are currently being built with this material. Architectural and structural cooperation usually takes place at the stage of form conceptualization [7].



a

b

Figure 7. (a) Joints sewn by means of a pneumatic sewing machine which has the possibility of passing a thread on wood up to 12 mm thick. (b) Different analyzes that were carried out to compare the mechanical efficiency of sewn joints

To fabricate the panels, it was decided to use 5mm timber since is more prone to bending under applied loads. As the thickness of wood decreases, its ability to resist bending forces also decreases, so it still has reasonable compressive and tensile strength in the direction of the grain. 5mm timber may be suitable for applications where lightness and flexibility are required, but it is important to consider its structural limitations when designing and building with this material. In order to develop this type of structures and integrate Yoshimura's pattern, the parameterization of the entire structure must be carried out in a simple module including the panels; In order to integrate each of the pieces and develop the pavilion we use the angle of the apex (β), the length of the bar (L), the height (H) and the width (W) as well as the number of bars (n). which is taken from the extension area. The primary determinant is the deployment angle, denoted as θ, which is the angle between a triangular face and the vertical axis. As θ dictates the extent to which an individual module is opened or closed, and given the uniformity of modules within the structure, θ exclusively governs the deployment of the entire structure (figure 7). Its values span from π/2 (representing a folded flat configuration) to 0 (indicating a fully compacted configuration. The specific θ of interest corresponds to the fully erected position, which for a regular structure manifest as a semicircular shape. In the case of a right-angled structure, our focus is on achieving a configuration where the side walls stand perfectly vertical.

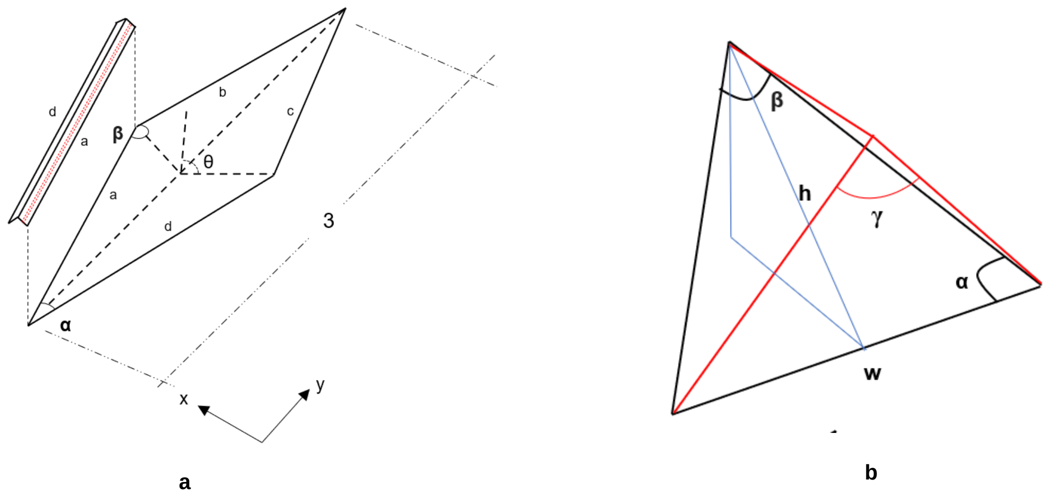


Figure 8. (a) Each of the panels consists of 4 sides (a,b,c,d) which are connected to each other, the sewn joints were made by a 5 mm wood which has an angle of 140° and adapts to the triangles, this piece is the one that is responsible for joining all the loaves. (b) Through the geometric analysis of Yoshimura's pattern, it was possible to find the result of each of the panels. This pattern is integrated through two isosceles triangles and thanks to its angle the interior curve of the pavilion can be generated.

If we examine a single isosceles triangle element, we can determine its properties based on two interior angles, α and β. The apex angle, β, is limited by the assembly of connection details, necessitating it to be greater than 140° for simultaneous assembly along multiple edges. To prevent extremely acute angles for α, a minimum value for β is selected. Additionally, from the vertical projection of the inclined element, we derive the transversal folding angle, γ, and the dihedral angle, ϕ. The dihedral angle, ϕ, is constrained by fabrication possibilities for connection details, thus falling within the range of 50° to 140°.

The formulas for calculating the deployment angle θ, applicable for $n \geq 4$; $0 \leq \alpha \leq \pi/4$; and $0 \leq \theta \leq \pi/2$, can be expressed as follows to calculate the folded pattern we use the following formula:

$$n \, \text{ArcTan} \, [\text{Tan}(\alpha) \, \text{Cos}(\theta)] = \pi/2$$

Yoshimura's pattern was applied to a vault which has a width of 3 meters and a height of 2 meters.

Each of the wooden panels were connected to each other through joints sewn with Kevlar thread, thus avoiding the use of screws and glues. Due to the fold that was made for each of the panels, it gives greater resistance to the wood if compared to a completely flat structure, this fold also has an interior angle of 140 which helps it give much greater rigidity and allows the perfect coupling of each of the panels.

5. Furter work

This research has the goal of being able to integrate new ways of building with wood and take advantage of the use of digital manufacturing and build light structures. Thanks to the construction of the pavilion, we were able to obtain as a result that the sewn joints present a great mechanical and structural advantage throughout. which helps us understand how we can take advantage of this construction system in the future. Which motivates us to continue exploring different complex geometric shapes since the material allows it to be used for different structures. In the future we seek to demonstrate how this construction system can be applied to different projects which respond to mechanical, sustainable, and innovative needs. When compared to other conventional construction systems, sewn joints can be a great option for optimally building lightweight structures. Future work will be concentrated on taking advantage of parametric tools in different types of surfaces that can be used for facades, roofs using intelligent materials and taking advantage of computational design.

6. Conclusions

We live in a world in which urbanization, construction and engineering contribute to approximately 40% of CO2 emissions. This has motivated engineers and architects to take new considerations when designing, thus the actions that architects and engineers develop in the coming decades will modify the existence of the inhabitants in the coming decades. One of the best strategies to mitigate these effects is the way construction materials are chosen; Regarding the above, timber in recent decades has gained a very important role in construction due to its mechanical, economic and environmental possibilities. Thus, this research investigated the geometry, mechanics and structural performance of an origami structure; Thanks to the help of computational design, we managed to obtain a good result due to the use of different Grasshopper plug-ins. Regarding the geometric analysis, an investigation was carried out regarding the performance of the Yoshimura pattern, which supported better structural performance.

It should be noted that this pavilion could be achieved thanks to the advantages that the Yoshimura pattern presents by generating the wrinkles, despite everything the Yoshimura pattern has multiple benefits due to the freedom it has to attach its pieces to different degrees which can be exploited. in different ways. The manufacture of the experimental pavilion expands the use of Yoshimura's pattern which can be adapted to different surfaces and structures.

7. References

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