**MPDA**
Master's degree
Parametric Design in Architecture

UNIVERSITAT POLITÈCNICA DE CATALUNYA
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# Amazon native bamboo for low-tech bending active structures

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## Abstract

This paper will study two different construction systems with Amazon native bamboo and introduce it as an alternative material for low-tech bending active structures. To accomplish this, bamboo splits and complete culms will be tested in flex traction and flection experiments, analyzing its fiber resistance, bending modulus of elasticity and yield strength according to different arrangements and knots proposed. Results will give different behaviors and properties for each of the different arrangements and knots, concluding on the best option for low-tech bending active structures. In this particular context its important to have in mind the details regarding a gridshell with this material in such a specific location, therefore, analyzing layers and element details, overlapping, erection process, assembling and transportation is decisive. For a fair comparison experiment, an analysis was made of a scaled Chebyshev gridshell that varies from a 5 meters span to a 40 meters span structure. Bamboo splits and complete culm systems were both studied at each scale and analyzed in terms of radius of curvature, bending stresses, maximum displacements, mass and amount of material needed. This analysis will determine which type of construction system is more appropriate at different scales.

**Keywords**: Amazon native bamboo, low-tech, bending active structures, bamboo splits, bamboo culms, flex traction, flection, gridshell, Chebyshev gridshell, radius of curvature, bending stresses, maximum displacements, mass.

## 1. Introduction

The Amazon rainforest is considered one of the capitals of biodiversity in the entire world, as it holds some of the most diverse and unique species of animals in the planet. Many National Parks are known for their virgin rainforest and rivers that are used as refuge for several endangered species. This region is also home to indigenous communities that promote ecotourism.

Unfortunately, in the last decades, illegal mining has become a big issue and very few has been done to reverse the situation. Deforestation is a serious problem that has taken away more than 90,000 hectares of rainforest in the last 15 years. There is also illegal logging in this area due to the huge demand of wood. People are cutting down Shihuahuaco trees that are approximately 1000 years old, without realizing these can absorb more CO2 than a whole hectare of rainforest, that they are not a renewable material and that they are indispensable habitats for some species of birds and mammals.

This is where native bamboo comes in as an alternative material to wood, not only for construction, but for many other uses and commercial possibilities. In this part of the Amazon there is a great amount of different kinds of native bamboo. Unfortunately, people look at this material as if it was a plague. Local people barely use it and are not aware of the possibilities it has. This quote from *Guadua Bamboo* explains in a very precise way the actual situation related to bamboo in these places: *"The incorrect use of bamboo in marginal construction has contributed to the misconception that bamboo is inferior to wood."*

Some of the advantages of bamboo is that it is a renewable material, it is easy to cut, handle and repair without any special set of tools, it has excellent properties for construction and it is a very lightweight material that can be used for temporary and permanent constructions.

## 2. State of the art

For the last several years many architects, engineers and constructors have found in bamboo unique characteristics and properties that have motivated them to research and build amazing structures all over the world. The examples we see below (Fig.1) explore different construction systems with complete culms of bamboo and with splits, achieving very lightweight structures, different span ranges, efficient assembling methods with remarkable results.

The variety of results, due to the different kinds of bamboo all over the world, and the infinite amount of construction possibilities that the material offers, took us to develop this research and determine which is the best way to take advantage of native bamboo in a specific context as the Amazon.

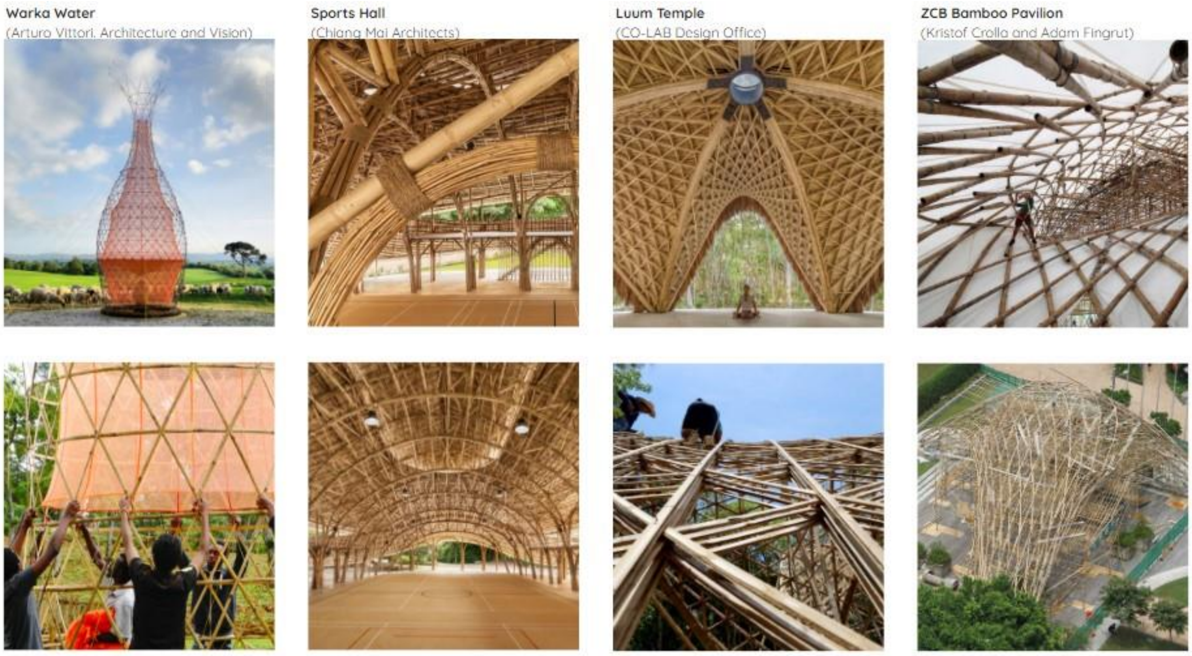


Figure 1: Reference projects. Warka Water (Arturo Vittori, Architecture and Vision), Sports Hall (Chiang Mai Architects, Luum temple (CO-LAB Design Office) and ZCB Bamboo Pavilion (Kristof Crolla and Adam Fingrut)

## 3. Research hypothesis

Our hypothesis indicates that after the flex traction and flection experiments, we will have a type of arrangement and knot that is more suitable for bending active structures with bamboo splits. Therefore, with these results we would be able to compare bamboo splits and complete culms, analyze in detail each of the construction methods and compare them in a scaled design of a Chebyshev gridshell.

We believe that for small and medium scale structures, bamboo splits will be more suitable, as they allow more curvature. For bigger spans, complete culms structures would be stiffer and easier to assemble. At some point in the experiment, as the scale of the design increases, bamboo splits structures will need too much layers and elements to stand up, increasing the amount of bamboo needed to build the structure and the mass, making the structure less efficient and expensive. At this scale, complete culms structures will be more appropriate.

## 4. Experiments

Two experiments are presented below for exploring and determining both mechanical and elastic capacities of bamboo splits, making the first filter to determine the construction system that we will develop later. For these experiments, bamboo splits of 3.5cms width and 0.5cms thickness were used.

### 4.1. Flex traction

For the first experiment, a 1.50 meter long structure with two fixed supports was built (Fig 2). We tested six kind of arrangement (Fig 3) for laminated bamboo (splits) with one simple outer brazing knot. Each arrangement was tested 3 times until the fibers collapsed and an average was taken. The experiment started by subjecting each sample to 1kg of weight and was increasing by 1kg until breaking the fibers, reaching maximums of 15kg.

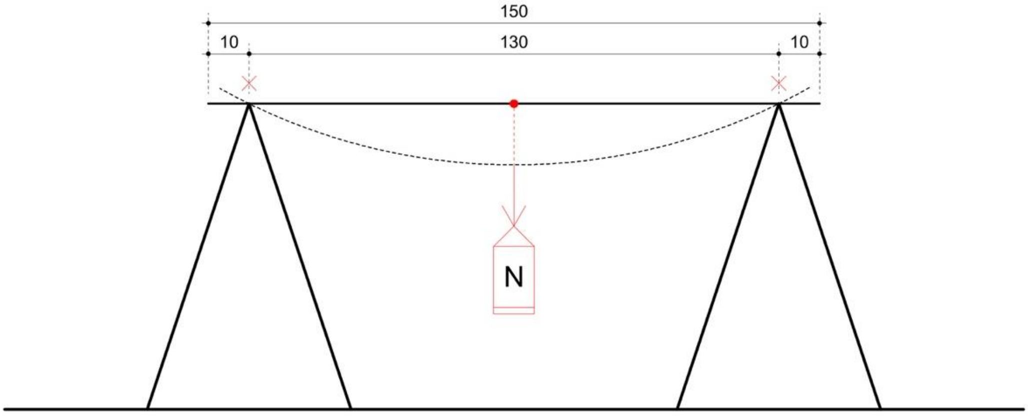


Figure 2: Explanatory diagram of the mechanism for the first experiment.

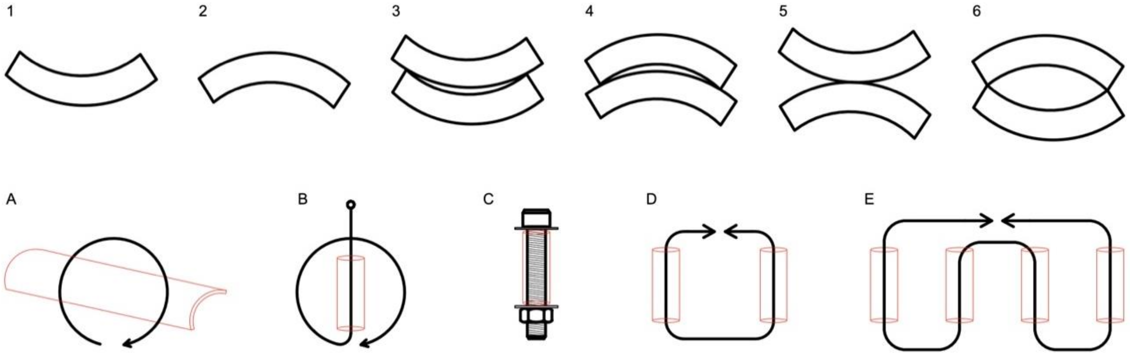


Figure 3: Six type of arrangements for the bamboo splits and the types of joints used for the first experiment. Knot A was used for the first part of the first experiment; nodes B, C, D and E were used in the following experiments.

As we can see in the graph (Fig 4) and as expected, results were favorable in the alternatives that combined 2 splits, where they held almost twice as single splits. Therefore, new samples were tested focusing only on double splits members. Each of the double split option were tested with 4 different types of unions (Fig 3): 1 bolt and 3 types of knots. They were tried to different loads until the point of collapse and the capacity of the fibers could be determined.

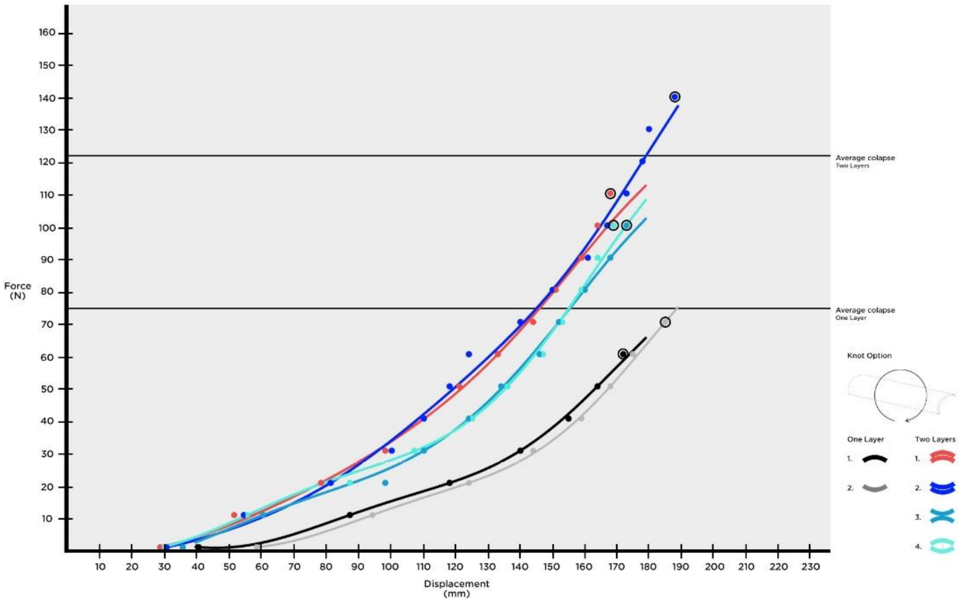


Figure 4: Graph that compares the behavior of the six arrangement with a simple knot while the loads are constantly increased until breaking the fiber.

Images below (Fig 5), shows some examples of what this experiment consisted of, in which 2 situations were found. The first and since supports were fixed, the breakage occurred at the anchor points between the split and the structure. Second, the breakage of the fibers was the resultant of the increasing loads.

Figure 5: Examples and situations founded during the experiment.

As it is shown in the new graph (Fig 6), the type of knot does not generate a great difference in results but the type of arrangement A2 and A3 held more weight until collapsing. Those who look up had a better behavior. This is due to the fact that the part of the bamboo with more fiber acted in tension and the part with less fiber in compression (Fig 7), which is favorable for this both type arrangement. We can determine that the type of arrangement does affect the behavior of the material but not the type of union. In any case, the behavior was better in the members that only one hole was made to make the joint, since the material was less affected (Bolt and Knot 1).

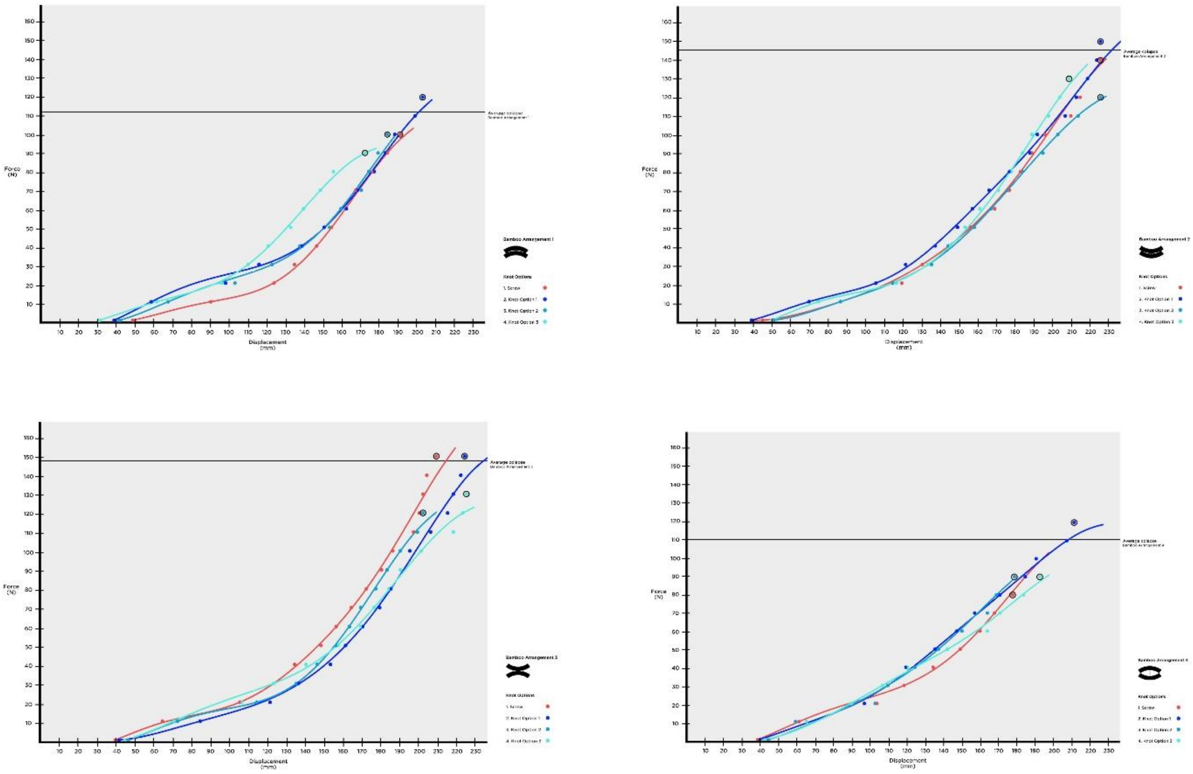


Figure 6: Results of the second test of the first experiment.

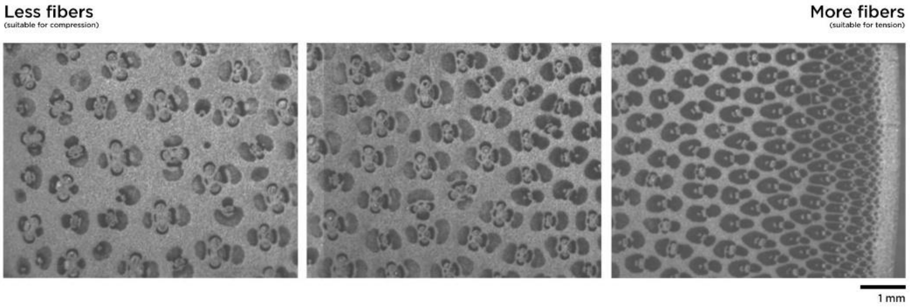


Figure 7: “The bamboo allows larger flexural deformation since its outer layer retains the tensile stress while the softer inner layer undergoes large compressive deformation” [1]

### 4.1. Flection

For finding the bending modulus of elasticity and the yield strength of the material, a flection experiment was carried out. For this case, the structure was modified to a shorter section (Fig 8) of 50cms long. One support was fixed and the other one was free to move in the horizontal way with restricted movement in the vertical axis. The four bamboo arrangements with four different joints alternatives were tried to increased loads until collapsing the fibers.

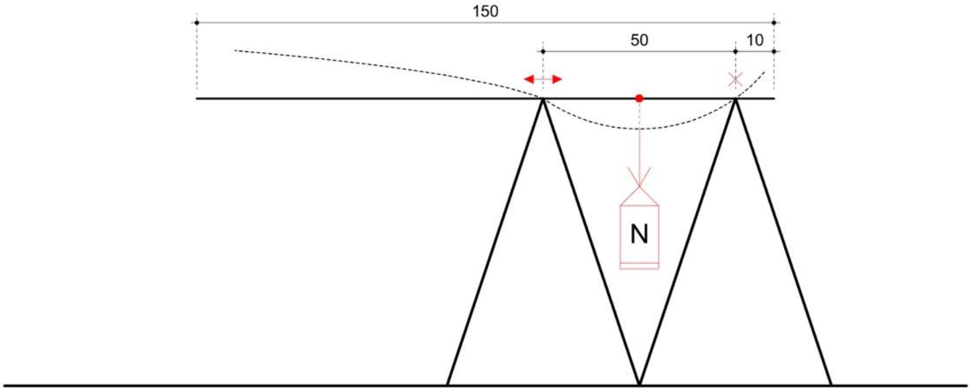


Figure 8: Explanatory diagram of the mechanism for the second experiment.

In the graphs (Fig 9), we can see the results for each of the samples with each type of joint. The curves show a constant stretch and an inflection point, revealing the bending modulus of elasticity and the yield strength for each member.

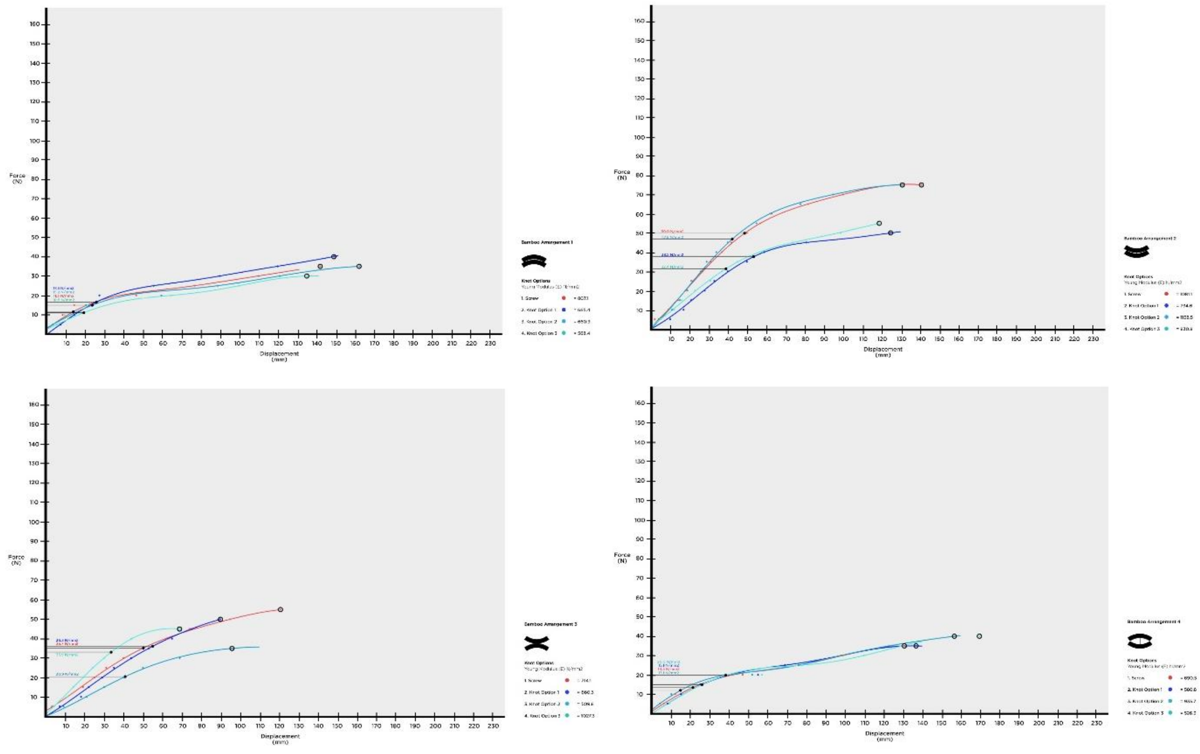


Figure 9: Results of each arrangement with each specific type of joint.

Final results of these experiments and as we can see in the final graph (Fig 10), determined that given the composition of the split and its geometry, the one that worked best in terms of fiber collapse, bending modulus of elasticity and yield strength was the arrangement 2. In parallel, and as was mentioned earlier, single-hole joints such as bolt and knot 1 responded better by weakening the material and reducing the risk ok splitting.

Considering both experiments and for practical reasons, it was decided work with the bolt joint, since it facilitates the construction system that will be presented later. At this stage, it was decided to test a complete bamboo culm to the same loads as the chosen split piece. The results obtained were compared with those found in the bibliography, obtaining values of 2,250N/mm$^2$ for the bending modulus of elasticity and 70N/mm$^2$ for the yield strength.

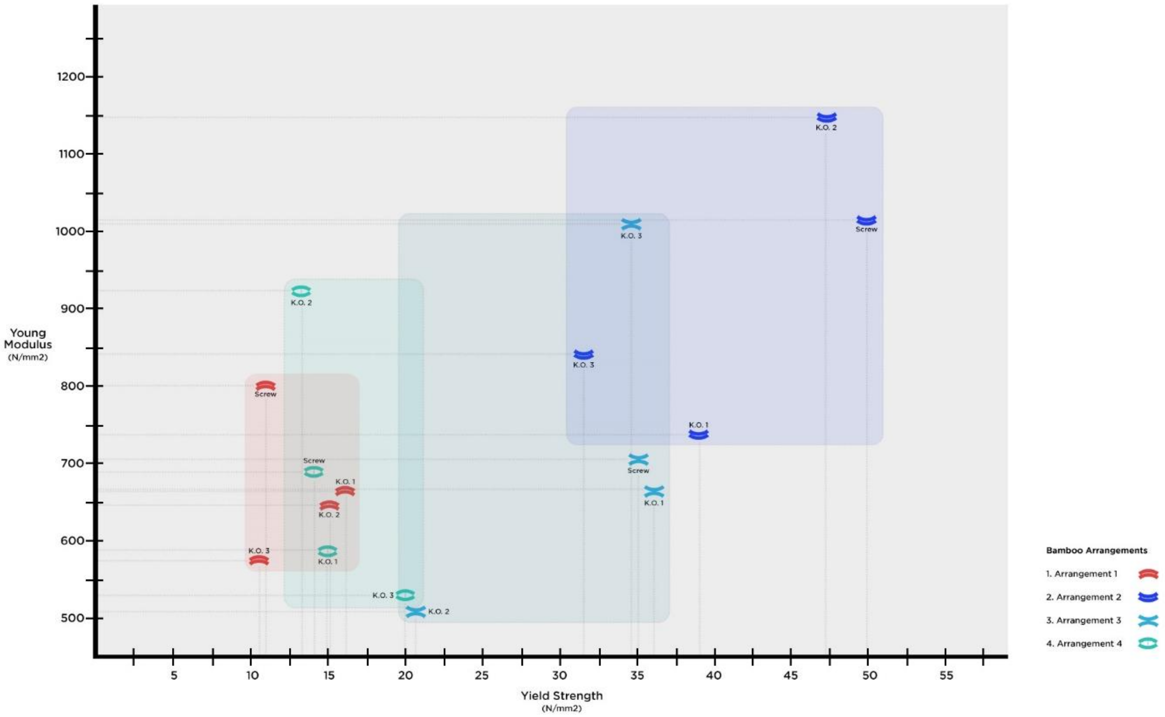


Figure 10: Final graph where it is shown that the geometrical composition of each arrangement does affect the behavior of each split.

## 5. Comparison analysis

### 5.1. Native Amazon bamboo (Bambusa Vulgaris)

Bambusa Vulgaris (Fig 11) it's a native and abundant bamboo of the Amazon. Its commonly cultivated because of its rapid growth rate; it takes between 3-4 years to mature. For the construction system that will be developed this choice is ideal, being able to provide at least 7 meter long culms, with knots every 30cms and a diameter that varies between 8 and 12cms.

This type of bamboo has different properties when it works as a full bamboo culm than as a split. For the comparison that will be presented, we will focus mainly on the results obtained in our experiments, which was contrasted with the bibliography, validating them as acceptable for comparison.

For the full bamboo culm, members of 10.0cm diameter and 1.0cm thickness will be considered. This kind of culms has a density of 543 kg/m$^3$, a bending modulus of elasticity of 24.000 N/mm$^2$ and a yield strength of 78 N/mm$^2$. For the case of bamboo splits, the full culm will be divided into 6, resulting on pieces of 5.0cms width and 1.0cm thickness. Density of 543 kg/m$^3$, bending modulus of elasticity of 10.400 N/mm$^2$ and a yield strength of 44N/mm$^2$ will be considered.

These properties will be used for compare and analyze, where we will determine in which cases it is convenient to build with splits and / or full bamboo culms and conclude what advantages and disadvantages they have.

Figure 11: Native amazon bamboo. Bambusa Vulgaris specie.

## 5.2. Form finding

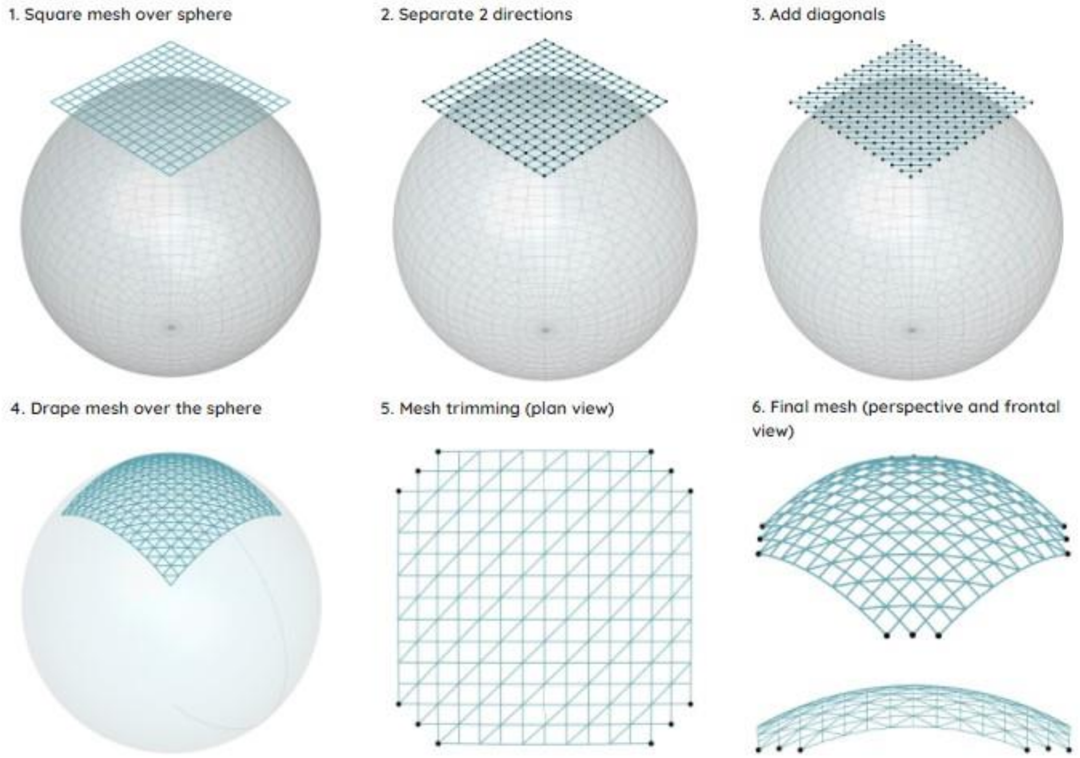


Figure 12: Form finding steps for a Chebyshev gridshell.

A Chebyshev net is conformed by a three-dimensional structure that resist applied loads through its inherent shape. It has segments of equal length and their intersections allow rotation when it is relaxed into a determined surface.

In this specific case, for fair comparison purposes, we wanted a gridshell that would not have too much curvature but at the same time not be too flat so we could analyze both construction systems, bamboo splits and complete culms, with the same structure. This is because systems have big differences on minimum radius of curvature allowed, as bamboo properties and characteristics vary considerably when the complete culm is chopped down into splits.

To achieve this, a square mesh was created over a sphere (Fig.12), separating both directions and adding diagonals (bracing) to the mesh. After this, using an implementation of the dynamic relaxation method with Kangaroo2, drape the mesh onto the sphere, taking in consideration the length of the segments. Finally, trim the corners of the relaxed mesh to locate the supports. This is the gridshell that further on in the investigation will be analyzed and evaluated with bamboo splits and complete culms at different scales.

The decision to make a Chebyshev gridshell over a geodesic gridshell, for example, has to do with the possible low-tech applications that one system has over the other one. Further on the research, topics like the erection process or the transportation will be mentioned and explained, giving support and showing the benefits of a Chebyshev net for such a specific context as the Amazon.

### 5.3. Layer details

Before a general comparison between both construction systems, we focused on the layers detail that would come up when we face this situation. For both, bamboo splits and complete culms, we analyzed the problem, evaluate their advantages and disadvantages and finally proposed a solution, always having in mind low-tech strategies.

#### *5.3.1. Complete culms structures*

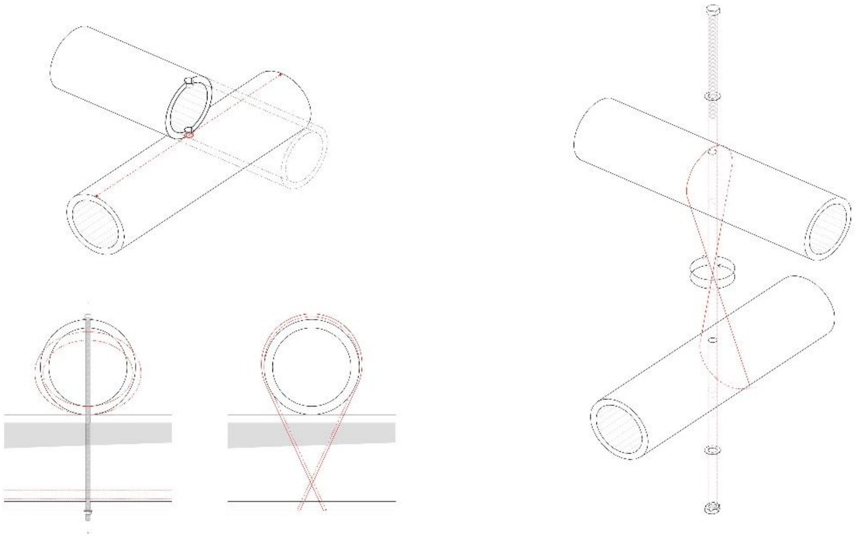


Figure 13: Details of layers intersections for complete culm structures.

For the majority of complete culm structures that have been built, a bolt is used for the intersection of two layers. In this specific case, depending on the type of bamboo, its thickness and the pressure applied, the bolt could damage the material, deforming the bamboo from its original shape and causing possible cracks.(Fig.13) For Chebyshev gridshells, rotation movement on the intersections is key, so developing a knot that could allow this movement could be an option, as it does not damage the material and permits tightening the structure after it is in final position.

#### *5.3.2. Bamboo splits structures*

For bamboo splits structures the problem is different. By having only two points of contact in the intersection of layers, (Fig. 14) the force applied with the bolt will also affect the material, deforming it and possibly breaking it.

The solution proposed consists on a piece of the same bamboo that is being used for the structure that can be applied just on the intersections to have a bigger surface of contact between the two layers. This piece varies on shape if it goes on the layer that is on top or at the bottom and can be easily achieved by cutting little pieces of bamboo and giving the special shape with a machete or similar tool. These added pieces will also allow the rotation that Chebyshev gridshells need to get into final shape.

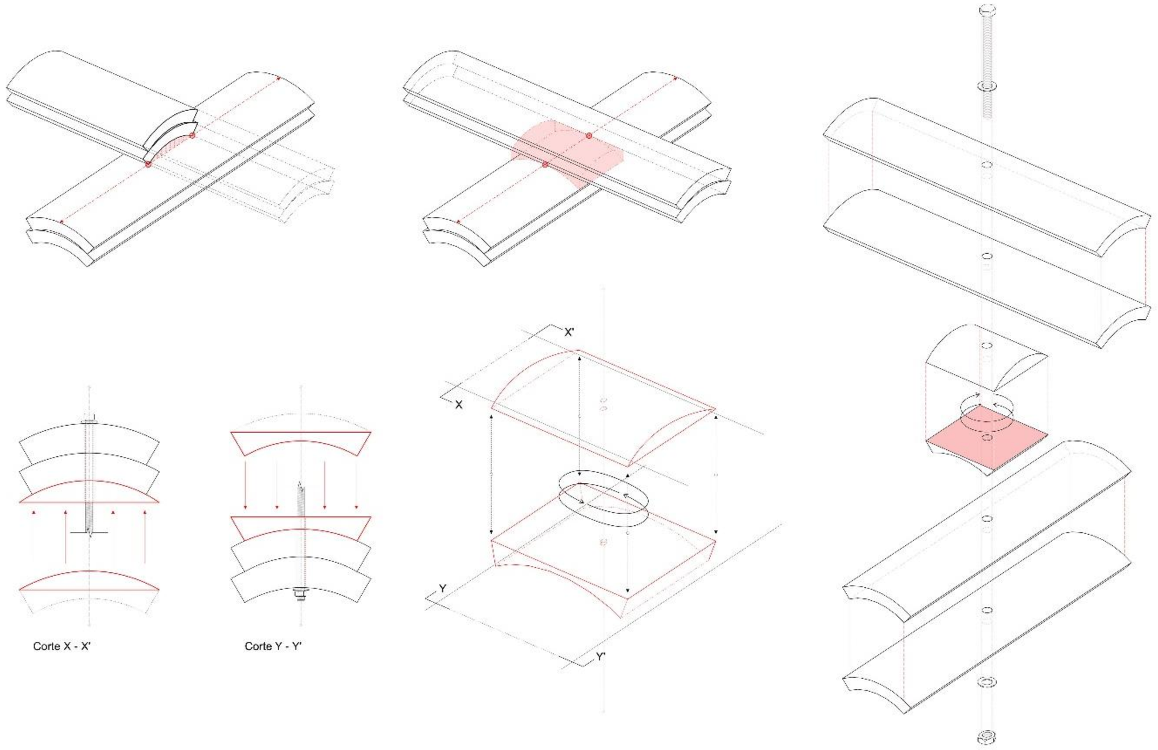


Figure 14: Details of layers intersections for bamboo splits structures.

### 5.4. Overlapping

The overlapping of the gridshell, either it is with bamboo splits or complete culms, will be set according to the 7 meters from the Bambusa Vulgaris. The overlap itself will be between 0.50m and 1.0m depending on the scale of the structure wanted to be built.

For bamboo splits structures, the overlap must be vertically and using bolts, to make it as stiff and tighter as possible. For complete culms structure the overlap must be horizontally for it not to interfere with the other layers of bamboo. This joint could be done with bolts or different knot options, making sure the structure remains as firm as possible. For both cases, its ideal that the overlap does not match the layers intersection. (Fig. 15)

The foundation details of the bamboo splits structure work with a steel frame. The same bolt which connects the layers and elements of the structure will pass through the steel frame, which will be attached to the concrete foundation. It is important that bamboo structures are well protected from the humidity of the soil, specially in the Amazon area, so foundations must have at least 60 cm from the ground. For complete culm structures the foundation detail is a bit different. The iron bar that comes out of the foundation can be deformed and adapt to the inclination in which the structure is arriving at this point. This iron bar will be introduced in the bamboo, and then, using the same bamboo as formwork, fill up the air space inside the material with more concrete. This type of foundation will ensure that the structure will remain firm. For both type of constructions, 3 supports per corner will be needed, this means that each structure will have 12 support points. The dimensions of these will vary according to the size, the weight and the type of roof the structure will have.

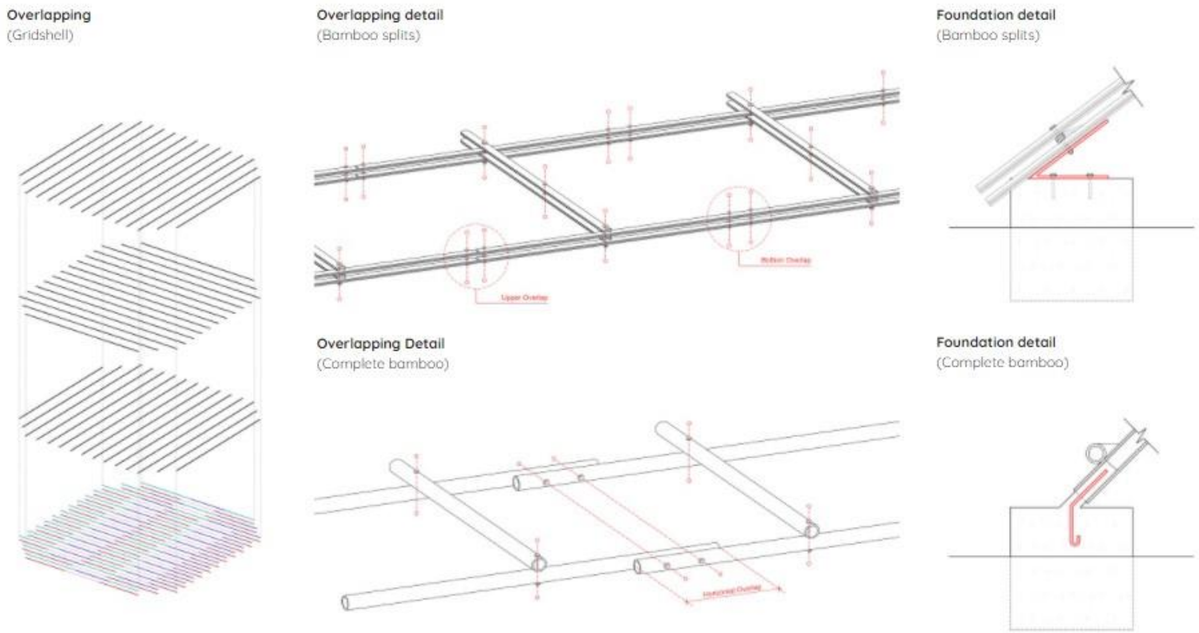


Figure 15: Details of foundations and overlapping for bamboo splits and complete culms structures according to the properties of the Bambusa Vulgaris.

## 5.5. Erection process

One of the main reasons why the Chebyshev gridshell was the type of structure chosen, in this specific context, was because of the assembling and erection process. This kind of gridshells allow the first two directions to be built in a flat surface. After assembling the grid with the amounts of layers and elements required to cover a specific span, the supports can be moved into final position (Fig. 16), allowing rotation in the intersections and eventually adapting to the final form. Depending on the scale of the structure, a bamboo scaffolding might be needed to place the grid in position. Once the supports are fixed in final position and the intersections are tightened for stiffness, the bracing can be implemented by putting them one by one. Bracing elements can be fixed with screws or bolts.

This kind of system is efficient and practical as you can have the grid already assembled on the ground and just lift it up. Bracing implementation is also fast and straight forward. In the other hand, for geodesic gridshells, bamboo splits or complete culms structures need to be assembled on site one by one. This system, clearly, will take more time and will need a more elaborated scaffolding structure to work on it.

After evaluating the advantages that the Chebyshev gridshell over a geodesic gridshell (in these specific circumstances) we need to understand that these structures can adapt to simple and not that corrugated forms, which is why many other structures with bamboo have been constructed with other systems. Said that, we can still conclude that for practical, efficiency and low-tech motives, Chebyshev gridshells are a more suitable construction system for the Amazon context.

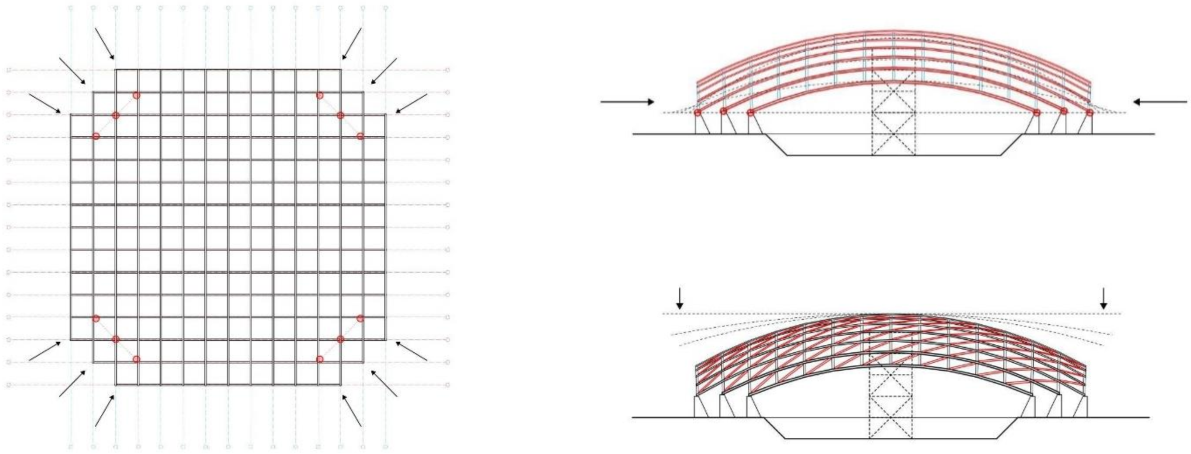


Figure 16: Erection process. Plan view and sections of supports translation, bamboo scaffolding and bracing application.

### 5.6. Transportation

In terms of transportation, Chebyshev gridshells have a huge advantage. The two-direction grid, as it has intersections that allow rotation, can fold. This converts the regular grid into a rhombus shaped one, allowing to enter on a simple truck. For small scale structures, the single principal grid can be folded and tucked in the truck. For medium and large-scale structures, the grid can be subdivided and then folded to enter the truck. (Fig. 17)

This means that a great amount of the assembling work does not necessarily needs to be done in the same place where the structure will be built. Grids of different scales can even be already built and ready to transport to any location near. Bracing pieces will have no problem for transportation as they are single pieces that will attach afterwards.

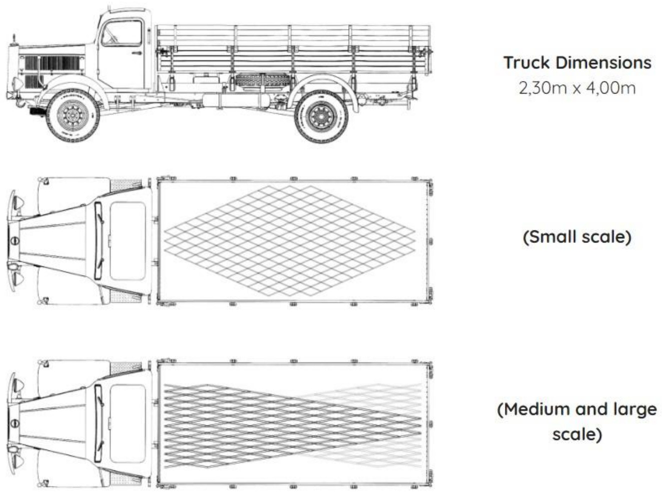


Figure 17: Folding method of Chebyshev gridshell for transportation of small, medium and large span structures.

### 5.7. Radius of curvature

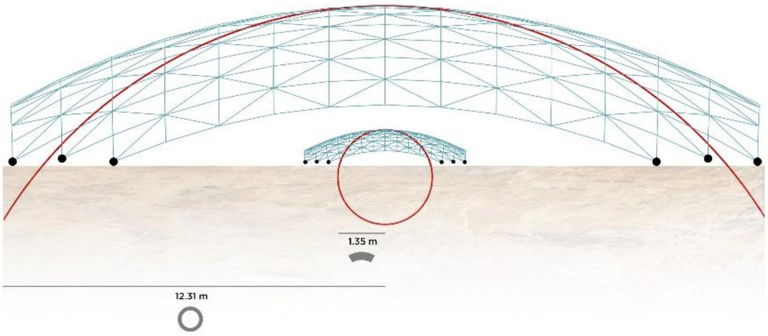


Figure 18: Different minimum radius of curvature for bamboo splits and complete culm structures.

Considering the properties and characteristics of the Bambusa Vulgaris, we calculated the minimum radius of curvature for bamboo splits and complete bamboo. Where:

E = Bending modulus of Elasticity

Sigma = Yield strength

t = Thickness

(E*t/(2*sigma))/1000

The minimum radius of curvature for bamboo splits was 1.35 meters while for complete culms was 12.31 meters. In Fig. 9 we can clearly see the difference between the possibilities of construction between both.

### 5.8. Scaled design

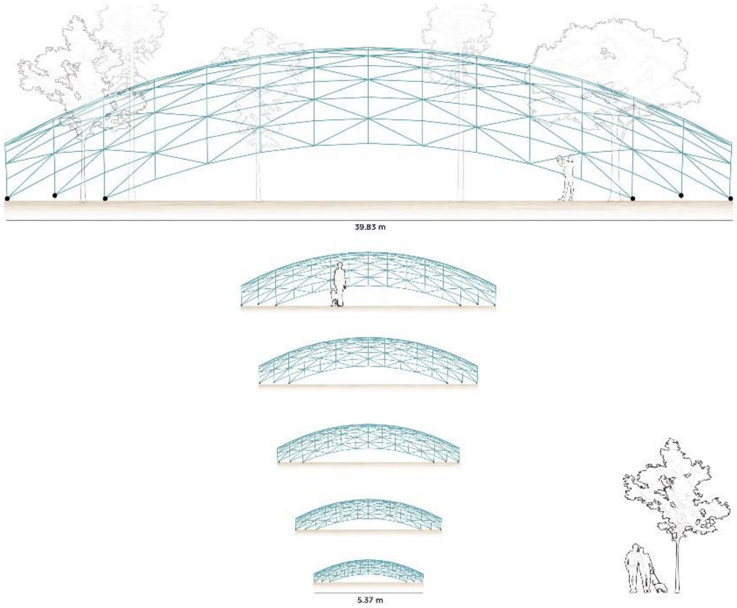


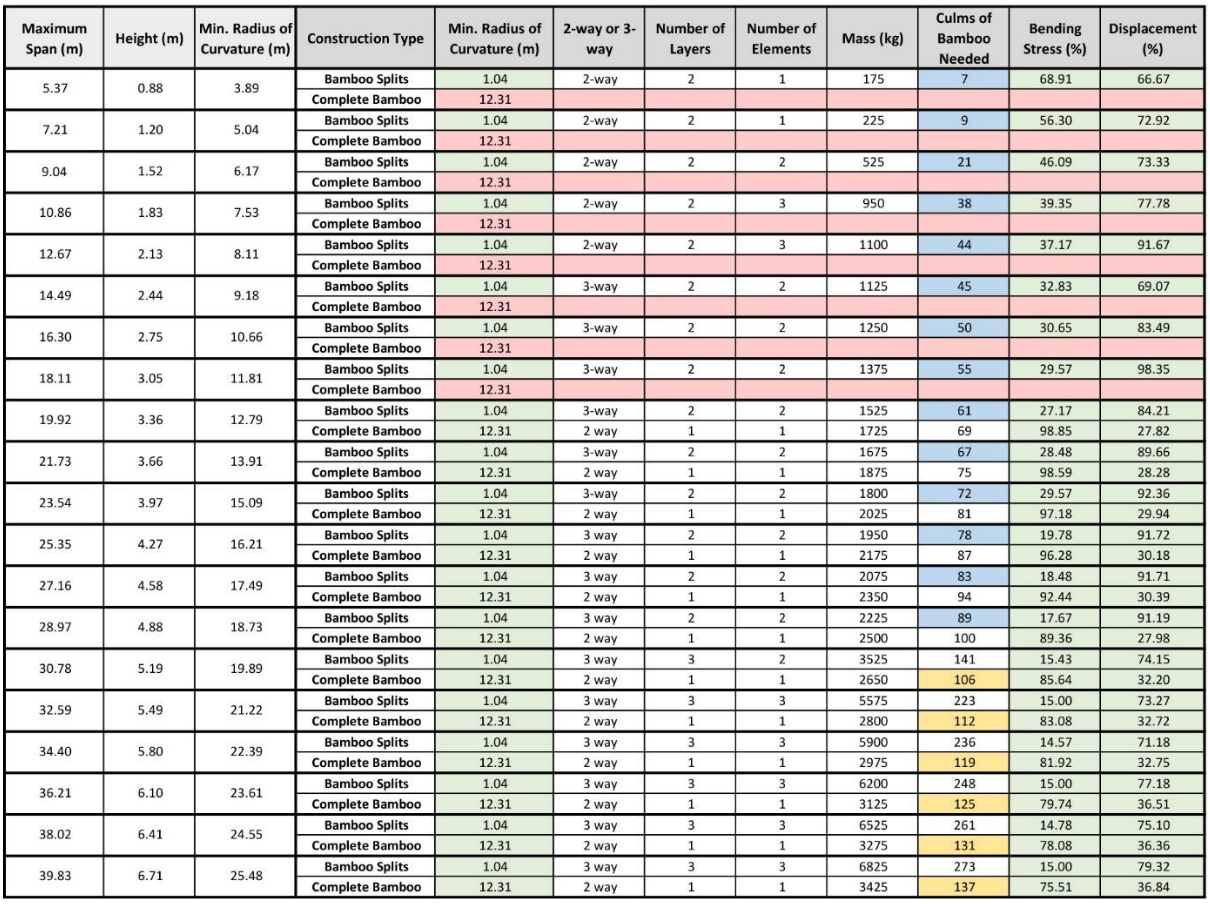
Figure 19: Scaled design of gridshell from 5 meters to 40 meters span.

To evaluate both construction types that differ as much in minimum radius of curvature, a final experiment was designed to explore a fair comparison. A scaled design that varies in span from 5 meters to 40 meters (Fig. 19) was tested in 20 different steps, increasing the span proportionally at each scale.

By analyzing one equal gridshell at different scales we would be able to compare both construction types (complete bamboo and splits) and see at which point it is more convenient to use one or the other in terms of bending stresses, maximum displacements allowed, mass and amount of material used.

## 6. Results

### 6.1. Table



| Maximum Span (m) | Height (m) | Min. Radius of Curvature (m) | Construction Type | Min. Radius of Curvature (m) | 2-way or 3-way | Number of Layers | Number of Elements | Mass (kg) | Culms of Bamboo Needed | Bending Stress (%) | Displacement (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.37 | 0.88 | 3.89 | **Bamboo Splits** | 1.04 | 2-way | 2 | 1 | 175 | 7 | 68.91 | 66.67 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 7.21 | 1.20 | 5.04 | **Bamboo Splits** | 1.04 | 2-way | 2 | 1 | 225 | 9 | 56.30 | 72.92 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 9.04 | 1.52 | 6.17 | **Bamboo Splits** | 1.04 | 2-way | 2 | 2 | 525 | 21 | 46.09 | 73.33 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 10.86 | 1.83 | 7.53 | **Bamboo Splits** | 1.04 | 2-way | 2 | 3 | 950 | 38 | 39.35 | 77.78 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 12.67 | 2.13 | 8.11 | **Bamboo Splits** | 1.04 | 2-way | 2 | 3 | 1100 | 44 | 37.17 | 91.67 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 14.49 | 2.44 | 9.18 | **Bamboo Splits** | 1.04 | 3-way | 2 | 2 | 1125 | 45 | 32.83 | 69.07 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 16.30 | 2.75 | 10.66 | **Bamboo Splits** | 1.04 | 3-way | 2 | 2 | 1250 | 50 | 30.65 | 83.49 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 18.11 | 3.05 | 11.81 | **Bamboo Splits** | 1.04 | 3-way | 2 | 2 | 1375 | 55 | 29.57 | 98.35 |
| | | | **Complete Bamboo** | 12.31 | | | | | | | |
| 19.92 | 3.36 | 12.79 | **Bamboo Splits** | 1.04 | 3-way | 2 | 2 | 1525 | 61 | 27.17 | 84.21 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 1725 | 69 | 98.85 | 27.82 |
| 21.73 | 3.66 | 13.91 | **Bamboo Splits** | 1.04 | 3-way | 2 | 2 | 1675 | 67 | 28.48 | 89.66 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 1875 | 75 | 98.59 | 28.28 |
| 23.54 | 3.97 | 15.09 | **Bamboo Splits** | 1.04 | 3-way | 2 | 2 | 1800 | 72 | 29.57 | 92.36 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 2025 | 81 | 97.18 | 29.94 |
| 25.35 | 4.27 | 16.21 | **Bamboo Splits** | 1.04 | 3 way | 2 | 2 | 1950 | 78 | 19.78 | 91.72 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 2175 | 87 | 96.28 | 30.18 |
| 27.16 | 4.58 | 17.49 | **Bamboo Splits** | 1.04 | 3 way | 2 | 2 | 2075 | 83 | 18.48 | 91.71 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 2350 | 94 | 92.44 | 30.39 |
| 28.97 | 4.88 | 18.73 | **Bamboo Splits** | 1.04 | 3 way | 2 | 2 | 2225 | 89 | 17.67 | 91.19 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 2500 | 100 | 89.36 | 27.98 |
| 30.78 | 5.19 | 19.89 | **Bamboo Splits** | 1.04 | 3 way | 3 | 2 | 3525 | 141 | 15.43 | 74.15 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 2650 | 106 | 85.64 | 32.20 |
| 32.59 | 5.49 | 21.22 | **Bamboo Splits** | 1.04 | 3 way | 3 | 3 | 5575 | 223 | 15.00 | 73.27 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 2800 | 112 | 83.08 | 32.72 |
| 34.40 | 5.80 | 22.39 | **Bamboo Splits** | 1.04 | 3 way | 3 | 3 | 5900 | 236 | 14.57 | 71.18 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 2975 | 119 | 81.92 | 32.75 |
| 36.21 | 6.10 | 23.61 | **Bamboo Splits** | 1.04 | 3 way | 3 | 3 | 6200 | 248 | 15.00 | 77.18 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 3125 | 125 | 79.74 | 36.51 |
| 38.02 | 6.41 | 24.55 | **Bamboo Splits** | 1.04 | 3 way | 3 | 3 | 6525 | 261 | 14.78 | 75.10 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 3275 | 131 | 78.08 | 36.36 |
| 39.83 | 6.71 | 25.48 | **Bamboo Splits** | 1.04 | 3 way | 3 | 3 | 6825 | 273 | 15.00 | 79.32 |
| | | | **Complete Bamboo** | 12.31 | 2 way | 1 | 1 | 3425 | 137 | 75.51 | 36.84 |

Table 1: Results for all scales tested.

The table (Table. 1) basically, shows for each row a different scale that was tested. In the first three columns, the characteristics of the gridshell, and further on the differences between constructions with bamboo splits and complete culms for each scale. Gridshells can’t be compared until the maximum span reaches 20 m because of the radius of curvature allowed for the complete culm bamboo design. Blue represents that structures with bamboo splits at this scale, require less culms of bamboo. Yellow represents that structures with complete bamboo at this scale, require less culms of bamboo.

To make this comparison possible some parameters were fixed, giving maximum number of elements and layers to each of the construction types.

Bamboo Split maximum:

3-way/3 layers/3 elements

Complete bamboo maximum:

2-way/1 layer/1 element

### 6.2. Mass vs. span

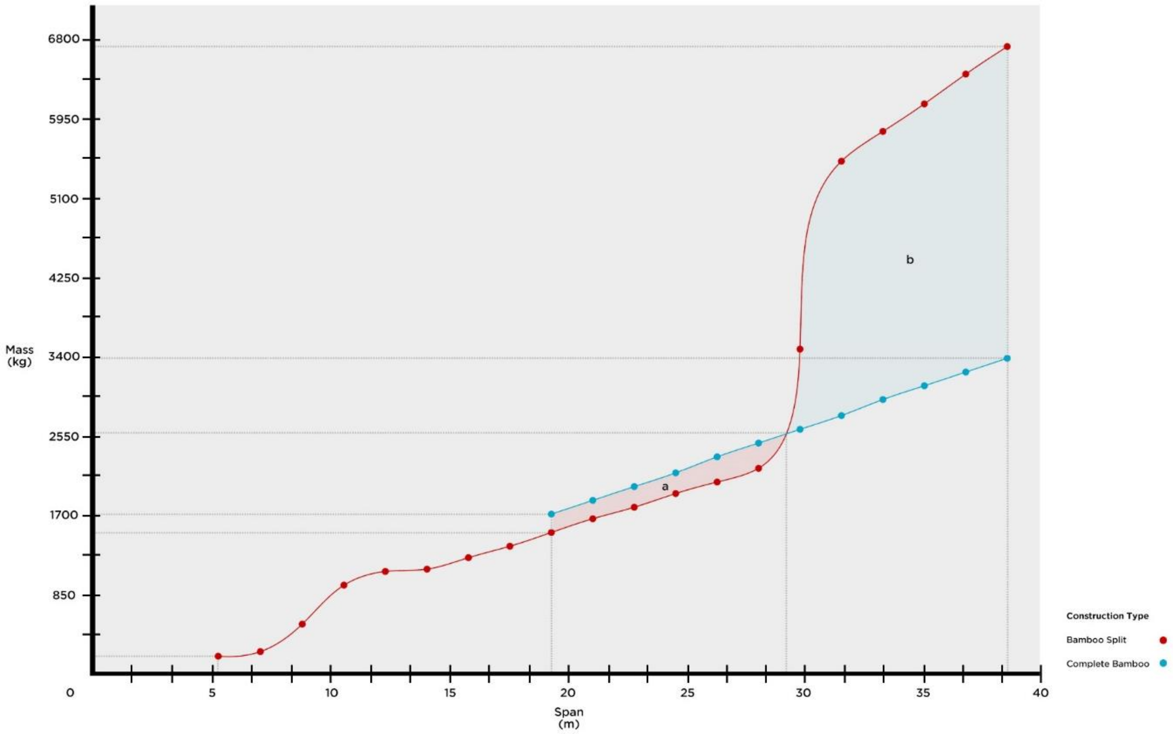


Figure 20: Mass vs. span results.

This graph (Fig. 20) shows the relation between span and mass of each of the structures at each scale. We can clearly see that the first scales are only possible to achieve with bamboo splits due to the minimum radius of curvature allowed by the complete culm. Once it reaches almost 20 meters of span, both construction types can be compared.

The red zone represents when bamboo splits structures require less mass to cover the same span as complete bamboo structures. In the other hand, the blue zone represents when span continues to increase, more layers and elements are needed in the bamboo splits structures. This increases the mass and therefore the amount of bamboo that is needed for construction.

This graph represents that for some determined spans, building with bamboo splits will require less amount of bamboo than complete culms. Nevertheless, we will see how structures behave in terms of stresses and displacements in the next analysis.

## 6.3. Bending stress vs. span

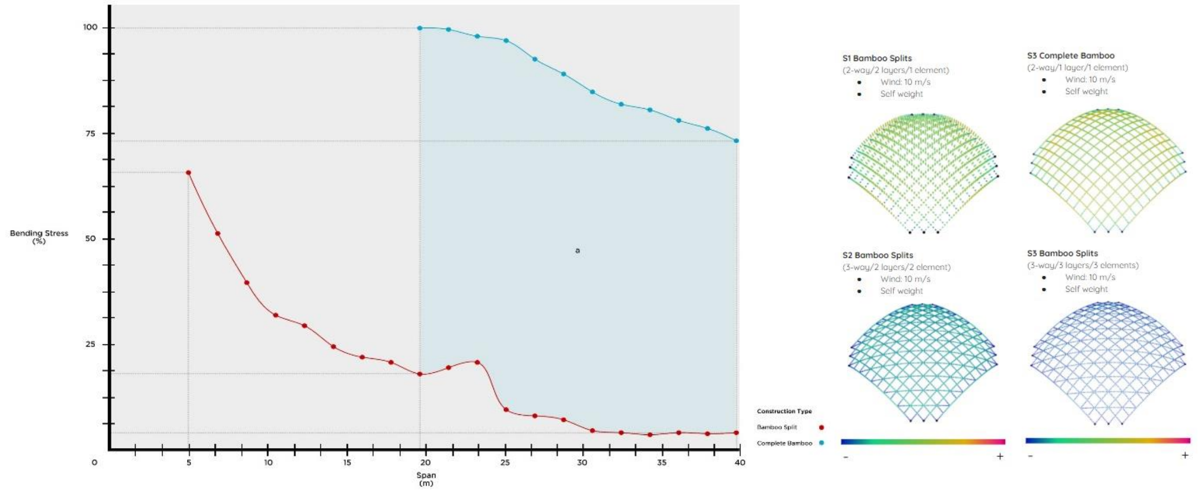


Figure 21: Bending stress vs. span graph and structure behavior in three different scales.

This graph shows the relation between the maximum bending stress (according to the corresponding yield strength of each type of material) and the span of each of the structures evaluated. As the span increases, the bending stresses of both, bamboo splits and complete culms structures decreases as well. (Fig. 21) However, the bending stresses of bamboo splits, further on 25 meters span start to decrease too much, showing that the structure is not working properly. In the other hand, complete culm structures have higher bending stresses as the complete bamboo is harder to bend, and therefore, performs better.

## 6.4. Displacements vs. span

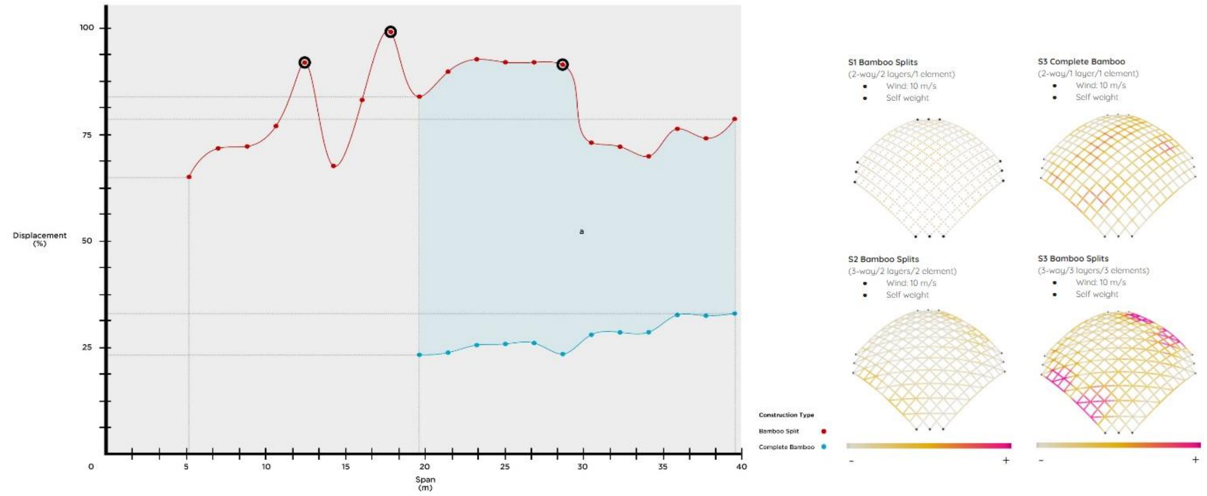


Figure 22: Displacement vs. span graph and structure behavior in three different scales.

This graph (Fig. 22) shows the relation between the maximum displacements and the span of the structures. The surrounded black points show the peaks of displacements of the bamboo splits structures.

These peaks are caused when the same structure can’t hold the increasing span, so therefore, more layers and elements are added, causing a decrease on the displacements of the next scale. The graph also clearly shows that from the displacements allowed at each scale, complete culms structures are stiffer than bamboo splits structures.

If we focus on the complete culm structures, as the span increases almost the double (from 20 meters to 40 meters) the displacement percentage remains very similar. In the other hand, bamboo splits, as span increases need more mass and have higher displacements.

### 6.5. Model

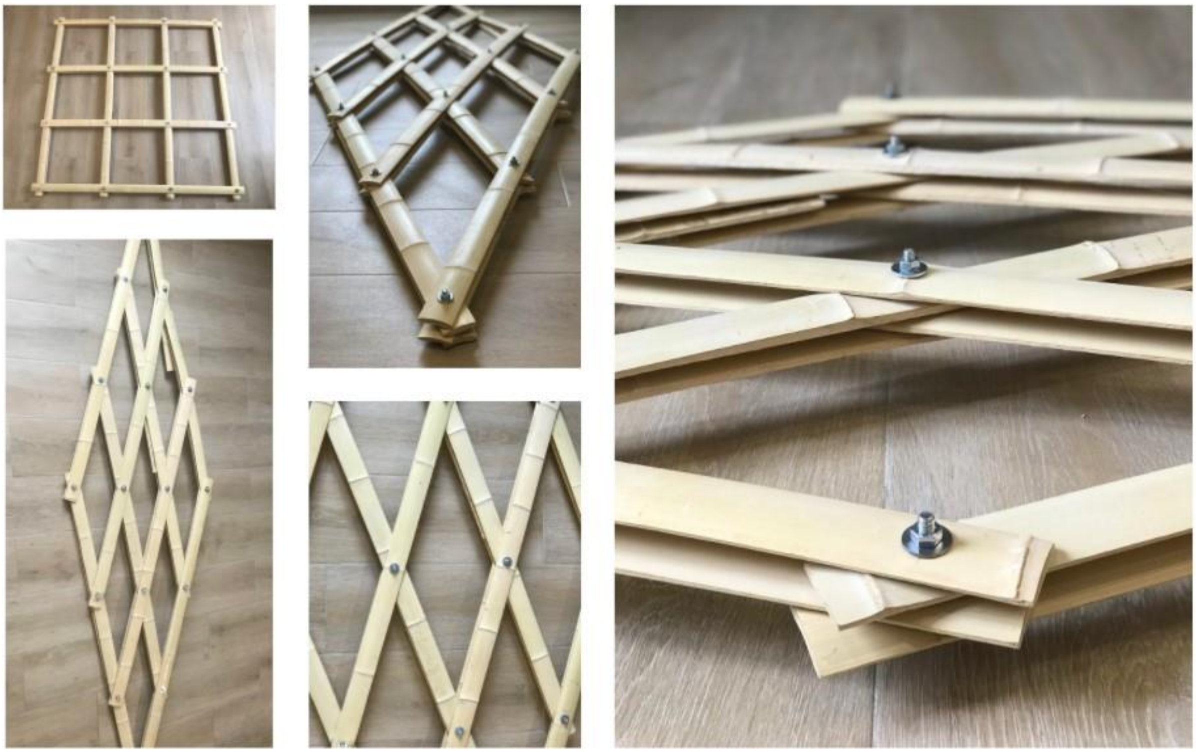


Figure 23: Physical model of Chebyshev gridshell and folding method.

## 7. Conclusions

Experiment 1: Bamboo splits can handle more weight before collapsing when fibers work properly in terms of tension and compression.

Experiment 2: Besides being the most resistant in experiment 1, arrangement 2 also had the best results for Yield Strength and Bending Modulus of Elasticity.

Different knot options do not make a big difference in terms of fiber resistance and flection results. In practical terms, making as few holes in the material reduces the risk of cracking it.

Chebyshev gridshells are more suitable for this context in terms of time and efficiency over geodesic gridshells.

Bamboo splits are suitable for small and medium scale structures that have more curvature and allow more corrugated designs.

Despite that at some scales bamboo splits structures require less material to build, they often need more work and time invested.

For bigger spans, using complete bamboo is more convenient as they work more properly in terms of bending stresses, displacements and are faster to assemble.

Figure 24: Bamboo splits structure render.

Figure 25: Bamboo splits structure render.

## 8. Further research

A first investigation and comparison on the possibilities of the split vs the full bamboo culm has ben developed, demonstrating that there exist some cases in which building with split could be an option for reducing the amount of material or achieving more complex geometries. As a future research, we believe it is important to explore the possibilities of other types of native bamboo that can help to regulate and prevent the massive deforestation that occurs in different countries of the world. Investigate the capacities of bamboos with similar characteristics; abundant, fast growing and with physical properties suitable for medium or large span constructions. On the other hand, we find it interesting to be able to develop a table in which these types of bamboo can be easily recognized, showing the building possibilities of each one and under what context, what advantages and disadvantages they have and when it would be convenient to work with splits or full bamboo culm according to each specie.

Finally, it seems important also to explore other types of geometries, where the level of corrugation of each one will directly influence on the results.

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