JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES: **J. IASS**

DESIGN OF THREE HYPAR ROOFS MADE OF GUADUA BAMBOO

Tim MICHIELS[1], Lu LU[2], Russell ARCHER[3], Sigrid ADRIAENSSENS[4] and Greta TRESSERRA[5]

[1]Engineer, PhD candidate, Form Finding Lab, Princeton University, Dept. of Civil and Environmental Engineering, E-Quad, Princeton, NJ, 08544 – USA, michiels@princeton.edu
[2]Engineer, former undergraduate student Form Finding Lab Princeton University
[3]Engineer, former undergraduate student Form Finding Lab Princeton University
[4]Associate Professor, PhD, Form Finding Lab, Princeton University, sadriaen@princeton.edu
[5]Architect, Sustainable Architecture for Development, Santiago de Cali, Colombia, greta.tresserra@gmail.com

Editor's Note: Manuscript submitted 20 September 2016; revision received 28 February 2017; accepted 8 March. This paper is open for written discussion, which should be submitted to the IASS Secretariat no later than September 2017.

DOI: https://doi.org/10.20898/j.iass.2017.191.844

ABSTRACT

While seeking new ways to build inexpensive and attractive shells, designers have increasingly been exploring shells and space structures made of guadua bamboo. Guadua bamboo poles, with their relatively low mass, high strength, and great axial and bending stiffness are promising linear building components for curved grid systems. Guadua bamboo is also a sustainable building material that can be easily harvested and deployed to construct economically efficient and elegant yet durable large span roofs. However, rigorous numerical structural analyses of bamboo are not common practice. Therefore, we present the structural analysis of two roofs consisting of a set of hyperbolic paraboloid (hypars) (designer Greta Tresserra, Colombia, 2015) that are planned in Cali, a region where the giant bamboo species Guadua Angustifolia grows abundantly. Additionally, a prototype hypar built in Austria (designers Greta Tressera and Tim Michiels, Austria, 2016) is presented as well.

In this study we examine the relationship between the structural behavior of hypar grids and their most critical bamboo joint. A simplified analysis, as well as a finite element (FE) analysis is performed in order to determine how the overall hypar form influences the internal loads in the bamboo. Subsequently, the most critical joints that interconnect the bamboo poles are analyzed through laboratory testing. Particular attention is given to the "fish-mouth" connection with and without mortar inserts. A better understanding of the flow of forces in the hypar grid combined with a detailed quantification of the behavior of the "fish-mouth" joint, allows for a more informed and efficient use of the bamboo material used in Cali structures. More broadly, this study seeks to demonstrate how an eco-friendly, widespread and inexpensive material such as bamboo can be used at its full structural capacity for the design and construction of hypar roofs.

Keywords: *Grid shell, hypar, form finding, physical testing, bamboo, parametric design, spatial roofs*

1. INTRODUCTION

Hyperbolic paraboloids (hypars) made from guadua bamboo have been built sporadically over the last few years and show great promise as an ecological, low-cost, yet elegant way to employ bamboo poles into expressive shell structures [1]. The use of hypar surfaces in shell structures is of course not new, as during the fifties and sixties Felix Candela revolutionized the thin shell concrete hypars in and around Mexico City. As Candela himself put it: "*of all the shapes we can give to the shell, the easiest and most practical to build is the hyperbolic paraboloid*" ([2], p 226). The main advantage of these hypar surfaces is that their doubly curved anticlastic shape can be generated from a set of straight elements. Candela accomplished his concrete shells by building an elaborate formwork from standard straight wooden elements covered by planks just flexible enough to allow for double curvature. Candela's expressive concrete shells revolutionized the shell building world, but hypars did not become ubiquitous, as among other reasons, labor costs for concrete shells were prohibitive and expansion to other materials was only sporadically explored. Nowadays, designers of guadua bamboo structures, for example in Colombia and Bali, are picking up on the legacy of the hypar shape, not to build concrete shells though, but to design sustainable and low cost curved grids from guadua bamboo.

1.1. Guadua Bamboo

The giant American bamboo species *Guadua angustifolia Kunth* (further referred to as guadua) is exceptional compared to other bamboo species because of the guadua poles' length and axial and bending stiffness, making them particularly fit for the straight line elements needed for hypar grid construction. Guadua is prevalent in regions with altitude between 500 and 1500 m in Colombia, Ecuador, Brazil and Peru that have temperatures between 18 and 32 ºC and relative humidity higher than 80%. In Colombia this corresponds to the so called Eje Cafetero (Quindío, Risaralda and Caldas). A guadua culm can grow up to 25m tall and obtains its full height in a mere 6 months [3]. The guadua culms can be harvested and treated against rotting and insects with minimal efforts after 4 years of growth (for structural purposes) [4]. This speed of growth of the guadua and the ease of its harvesting is in stark contrast to the time and resources required to obtain other grid shell construction materials, for example wooden laths. The contrast between the 4 years of growth of a guadua column to the 20-30 years required before a tree can be converted into timber, makes guadua a potential alternative to mitigate deforestation. Additionally, at a cost of 1.60 USD per running meter, guadua poles are a very economical construction material in Colombia.

Guadua culms are straight hollow tubes with interspersing nodes positioned at about every 20 cm on average along their length. These nodes act as diaphragms. Typical lengths of the guadua poles used for construction in Colombia range from 6 to 12 m, with diameters of 9.5 - 13 cm and thicknesses of about 1.5-2.5 cm. These dimensions, in combination with the density of the fibers make the guadua poles much stiffer than most other bamboo, making them a perfect fit as straight element in hypar construction.

1.2. State of the art

While the structural analysis of bamboo structures has recently started to receive attention within the IASS research community, other work has mainly focused on the development of engineered (laminated) bamboo [5], or on synclastic doubly curved bamboo grid shells (for example the shell constructed at UNAM, Mexico which was presented at the 2015 IASS conference [6]). This shell was made from more flexible bamboo species and required bending of the bamboo elements using flames. Similarly, the design of a set of synclastic grid shells using flexible bamboo species was presented in the J. IASS [7] for a shell in Rio De Janeiro, while at the time of construction a book on similar bamboo grid shells in Hawaii and Vietnam was published [8]. These grid shells relied on the bending of bamboo cane to obtain doubly-curved structures. In contrast, we present the structural engineering of anticlastic grids, made of straight bamboo elements that need no manipulation. As it is opted not to rely on active bending for the shaping of the structure, the elements of the hypar grid will work in bending, and also be subjected to axial forces. The biggest challenge in the

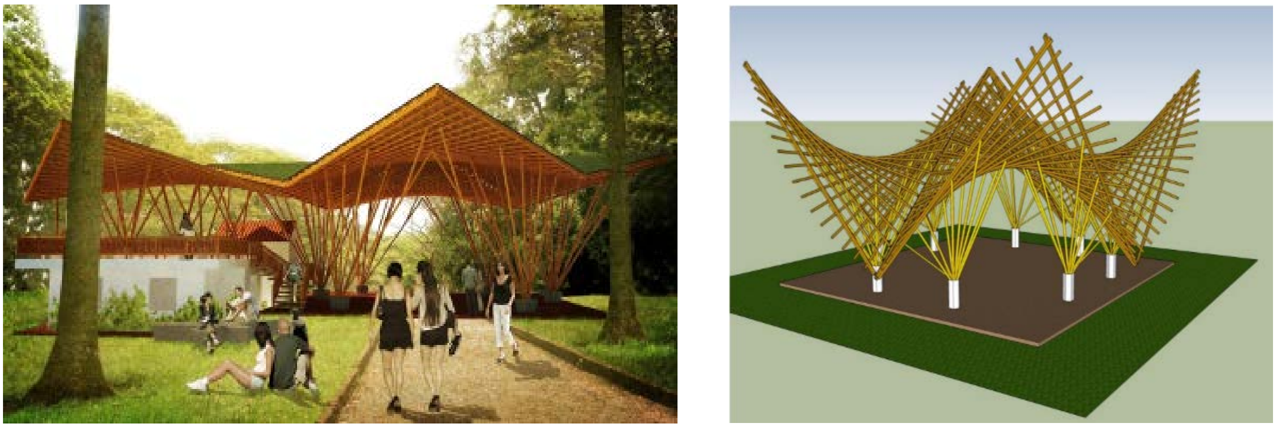

Figure 1 a and b: *Las Garzas roof (left) (courtesy of Karol Vega Tutasaura) and El Embudo roof (right) (courtesy of Ricardo Santacruz)* characterization of the behavior of these hypars relates to understanding the overall structural behavior of these curved grids, as well as to quantify and assess the behavior of the guadua joints. Test procedures for the assessment of the structural properties for these guadua culms have been presented before [9], but limited attention has been paid to the characterization of the joining techniques.

1.3. Case studies

In the presented research, we therefore first focus on two sets of hypar roofs that were designed by architect Greta Tresserra and her team in Cali, Colombia. The first structure, further referred to as Las Garzas, is a set of 4 connected shallow gabled hyperbolic paraboloids supported on guadua columns (see figure 1a). The second structure, further referred to as El Embudo (see figure 1b), is a more expressive gabled hypar, which is similarly supported on columns. Both structures are in the last planning stages at time of writing (August 2016), and construction is expected to start shortly.

The objectives of the presented research are 1) to increase the understanding of the behavior of the joints that interconnect the guadua poles in the hypar grid, and 2) to analyze and improve the overall structural behavior of the 2 roofs. Additionally, the understandings from studying these case studies were applied in the parametric design of a 5.10 m by 5.10 m prototype hypar which was constructed at the 2016 BaseHabitat International Summer School in Altmünster, Austria, a 2-weeks workshop organized by the Kuntsuniversität Linz. (see figure 2).

2. METHODOLOGY

In a first stage, the different types of connecting joints in the hypar grid system were identified. Subsequently, the most crucial of these joint, the so called “fish-mouth” (see figure 4) connection was analyzed in detail. This study was done through analytical hand calculations, which were complemented and validated by physical testing. These laboratory tests sought to determine the material properties of *Guadua angustifolia*, as well as the maximum load capacities of T-shaped “fish-mouth” joints. The compressive strengths parallel and perpendicular to the grain of guadua were evaluated, as well as the ability of the “fish-mouth” to resist tensile loads. A mortar filled “fish-mouth” connection was also tested to evaluate the effect of mortar insertion on the global connection’s strength. The results of these individual tests were then combined to make an overall evaluation of the effectiveness of the “fish-mouth” connection. All testing was executed on an INSTRON testing frame in the materials lab at Princeton University.

Figure 2: *Prototype hypar constructed at the 2016 Base Habitat Summer School, Altmünster (Austria)*

In order to link the test data to the real structures, the results of the testing were combined with the results of an extensive structural analysis. Three different approaches were taken to improve the structural understanding of the hypar roofs. To analyze Las Garzas structure, analytical hand calculations were combined with a simple SAP2000 FEM model of one hyperstatic beam [10]. The El Embudo roof, as well as the design for the BaseHabitat hypar were characterized through an in-depth FEM analysis using the finite element analysis plugin Karamba3D for Grasshopper in the 3D drawing environment Rhinoceros [11, 12]. After initial structural analysis, the most important design parameters such as reinforcement of edge and ridge beams, curvature, height of overhang, grid density, and support configuration were altered to see the effect of the structural behavior and improve the design. The detailed discussion of this structural

Table 1: *Material properties used for the structural analysis*

Property		**Unit**	**Source**
Young's modulus	9.5	GPa	NSR 10
Shear Modulus	3.52	GPa	NSR 10
Specific Weight	7.74	kN/m3	NSR 10
Yield Stress	18	MPa	NSR 10
Diameter	0.12	m	Design team
Thickness	0.02	m	Design team

analysis falls outside of the scope of this paper. The materials properties used for the analyses are displayed in table 1.

3. CONNECTIONS

3.1. Physical joint testing

A critical aspect of guadua construction is the effective transfer of the forces from one pole to another. A wide array of connection techniques, ranging from wires or ropes, to wooden dowels, metal fasteners using bolts and specially shaped metal connectors are available. The price of these prefabricated metal connectors makes their use in rural areas undesirable, especially as the joint-crafting techniques can be easily taught to local construction workers.

Three main connection details are found in both Las Garzas and El Embudo structures. The first connection detail is the one from the concrete foundation to the bamboo columns. Steel rebar is placed inside of the bamboo culms, which are subsequently filled with mortar up to the first 2-3 nodes (see figure 3 a). This connection is not further analyzed, and is –conservatively- assumed to a pinned in the structural analysis model. The second set of connections of importance in the structures, is the connection of the guadua poles onto the ridge and edge beams, and of the columns onto the grid shell. These connections are realized using (slanted) fish mouth joints. The behavior of these joints is poorly documented, but the Colombian structural code NSR 10 prescribes to model them as pinned [13]. The third and final connections within the structures are the joints within the roof grid. While the guadua poles are mainly fixed at the edge and ridge beams, perpendicular poles are also fixed to one another when they cross within the grid. This connection is realized with a steel bolt, pinning the crossing elements together (see figure 3 b). Additional in-plane stiffness for the grid is provided by the split guadua that is nailed on top, and is further facilitated by the rigid frame of edge and ridge beams.

The joint that thus connects the most crucial construction elements is the “fish-mouth” joint (see figure 4). “Fish-mouth” cuts are made either with a hole-saw, or using a hand or hack-saw to make two diagonal cuts at the desired edge. The surface then needs to be smoothened to ensure a good fit, eliminating stress concentrations around the edge. Two perpendicular interconnecting bolts are inserted as well. Normally, the lower bolt in figure 4 b is placed right under a node to make use of the extra strength of the diaphragm. The space between the two nodes where the bolts attach to the bamboo is sometimes filled with a cement mortar. This is done when the bolts cannot be attached right next to a node, or when the joint is expected to transfer an exceptionally large amount of internal loading.

Figure 3 a and b: *connection of guadua poles to foundation (left) and interconnection of guadua poles (right)*

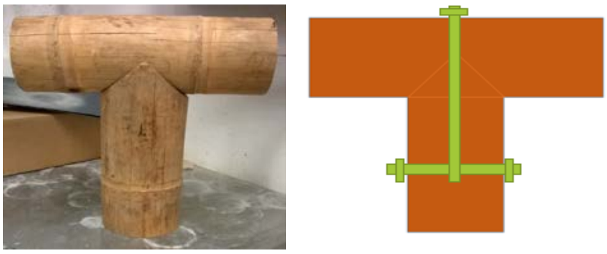

Figure 4 a and b: *“fish-mouth” T-connection without bolts (left) and schematic view including bolts (right)*

In order to assess the capacity of the joint, following mechanical properties were characterized in the lab: (1) compressive strength parallel to the grain (with and without mortar); (2) edge bearing test (with and without mortar) [14]; (3) compressive strength of T-section; (4) pull-out testing of the cross-bolt.

3.1.1. Testing the “fish-mouth” connection in compression

3.1.1.a Compressive strength parallel to the grain

Compressive strength parallel to the grain was executed at a loading rate of 10 mm/min until failure. Compressive strengths of guadua culms ranged from 57 to 80 MPa corresponding to strains around 0.02. Sample heights ranged from 9.8 to

10.4 cm, other dimensions are provided in figure 5. Failure mechanism was splitting and crushing throughout the culm. Based on the Colombian code NSR-10, the average allowable stress taking into account the imposed safety factors can be determined as 39.1 MPa, which is significantly larger than the prescribed absolute minimum value of 14 MPa for *Guadua angustifolia* [13]. Additionally, the tests were executed on samples without nodes, which is again conservative as the nodes act as rigidizing diaphragms that contribute significantly to the compressive strength parallel to the grain. Therefore, employing the prescribed minimum value for the compressive stress in the Colombian code could possibly lead to over dimensioning.

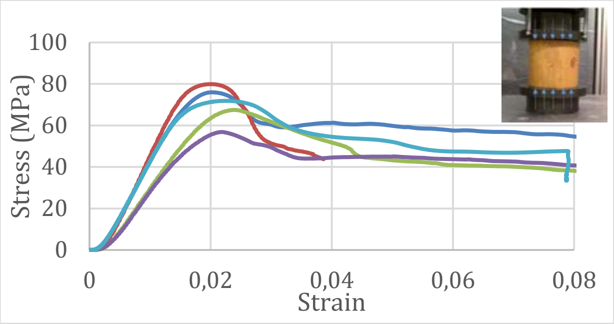

Figure 5: *Stress – Strain curves and test setup for five compressive strength tests parallel to the grain. Thickness and diameter of the samples range respectively from 12 to 16 mm and 113 to 119 mm*

3.1.1.b Compressive strength of T-configuration

The compressive strength of the T-configuration as a unit was analyzed in a compressive test as well. The sample, shown in figure 4 a, did not include steel bolts or mortar. The joint's only resistance to compressive forces thus arises from the compression resistance of the guadua parallel and perpendicular to the grain. A test was conducted with a horizontal sample with nodes (as shown in figure 4 a) and one without nodes. For the sample with nodes, the "fish-mouth" was placed in the middle between the 2 nodes to simulate a worst case scenario test. In construction, the fish mouth is placed on top of a node or as close as possible to make use of the diaphragm provided by the node (see figure 6). The sample with nodes failed under a compressive load of 17.7 kN, while the sample without nodes failed at 3.46 kN. An important difference in failure mechanism was exhibited between both samples. The sample without nodes failed as in the edge bearing test (see next paragraph) by splitting of the top horizontal member due to the tensile forces as a result of the compression forces. The sample with nodes, a more realistic scenario, experienced splitting in the vertical member instead, and thus exhibited failure similar to the one observed during the compression tests parallel to the grain.

3.1.2. Testing the "fish-mouth" connection in tension

To test the capacity of the "fish-mouth" when subjected to tension, the pulling out of the cross-bolt was analyzed. The cross-bolt in the T configuration is loaded when uplift forces cause the eye bolt to move upwards, inducing a point load at midspan of the cross bolt (see figure 7). To ensure proper behavior in tension of the "fish-mouth" joint, it is again important to locate the "fish-mouth" on top or close to a node (typically 2-3 cm) to utilize the node's load resisting capacity (see figure 6).

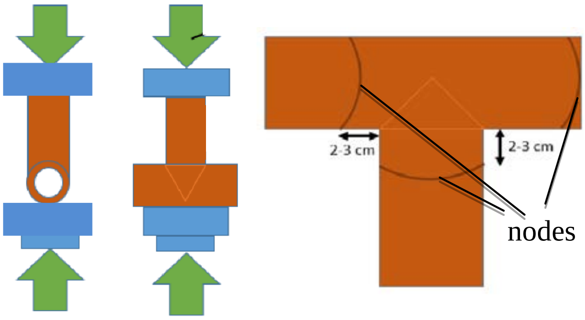

Figure 6: *Test setup for compression of entire T and dimensional arrangement of "fish-mouth" joint. The connection is placed ideally on top of a node or otherwise in close proximity to the nodes taking advantage of the additional strength and stiffness provided*

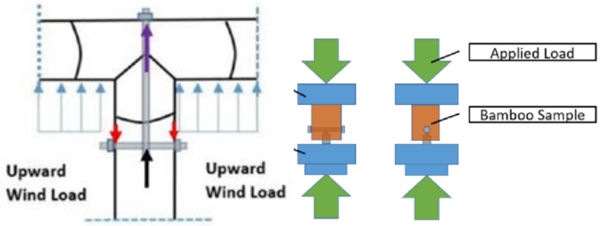

Figure 7: *Effect of upward wind load exerted on the fish mouth and associated reactions (left). Test to simulate the effect on the cross bolt and the guadua – front and side view (right)*

The load displacement curve of the test in which it is attempted to make the guadua split due to a force perpendicular to the cross bolt is presented in figure 8. This load displacement curve shows that in both samples the cross-bolt started yielding before the guadua culm failed. The yield range of the 12.7 mm diameter grade 8 bolt could be predicted based on the assumption of its support condition as simply supported or as a fully fixed beam. This yield range was a very accurate prediction in both test cases as can be seen in figure 8. Even after yielding of the bolt (around 15 kN), it took another 2 kN (for wall thickness of 12 mm) and 10 kN (for wall thickness of 23 mm) to make the guadua culm effectively split and fail. The failing of the guadua can be explained as a “mode I” crack propagation. This type of crack propagation involves tensile forces pulling apart the crack, allowing it to further develop it trajectory [15].

The test shows that tensile capacity will depend on the capacity of the bolt rather than on the capacity of the guadua culm. NSR-10 specifies that the bolt should be made of structural steel with minimum yield strength of 240 MPa [13]. In comparison, the grade 8 bolts used in the tests had a yield strength of 893 MPa. Therefore, it can be expected that the yield strength and section of the bolt will govern the failure mechanism of the “fish-mouth” in tension, rather than failure of the guadua.

3.2. Discussion of fish-mouth

The behavior of the “fish-mouth” connection is further considered based on two scenarios, one scenario under compressive loading, and the other under tensile loading. In compression, the joint can fail due to two mechanism depending on whichever mechanisms’ ultimate capacity is lower. The first failure mechanism, which was experienced in a test when no nodes were present, is the splitting of the horizontal member of the T. Filling the horizontal section between nodes with mortar was shown to be an effective technique to increase the capacity of the horizontal member to values well over 12 kN. While the maximum capacity of the joint in the presence of nodes has not been characterized yet, the compression of the full T-section with nodes did not exhibit the splitting failure mechanism in the horizontal member. The second failure mechanism in compression is the breaking of the vertical supporting member. This failure was observed when the T-section with nodes was compressed until its ultimate capacity. The tested joint, which was aligned unfavorably in the middle between two nodes, resisted 17.4 kN. While more tests need to be conducted to confirm the obtained compression resistance of the joint, and especially to determine the capacity of guadua perpendicular to the grain in the presence of nodes, the presented test results indicate/hint at a very high resistance of the joint in compression.

It was further shown in the tests that under tensile loading, the component that defines failure of the joint might not be guadua poles, but the steel bolt connecting the guadua poles. Excessive tensile loading will lead to either yielding of the bolt, or splitting of the guadua culm. In our tests conducted with a 12.7 mm diameter bolt with yield strength of 893 MPa (a realistic value for the steel typically used for bolts), the steel bolt yielded before the guadua failed. Taking into consideration the prescribed minimum strength of 240 MPa for steel bolts in NSR-10, it is evident that when employing such steel of lower strength, the capacity of the governing failure mechanism will a fortiori be determined by the bolt. Thus, depending on bolt diameters and steel yield strengths, it is possible to determine the upper boundary limits for the tensile forces which are allowable in the joints. NSR-10 similarly provides the maximum tensile force that guadua joints can be subjected too. The calculated values based on the lab tests are in correspondence with this data found in NSR-10 [13].

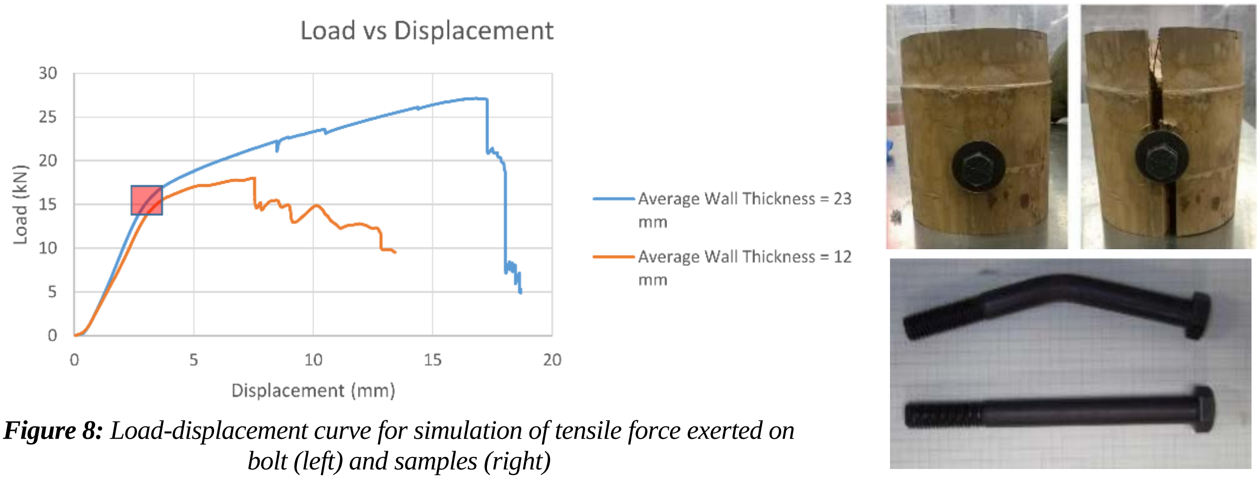

Figure 8: *Load-displacement curve for simulation of tensile force exerted on bolt (left) and samples (right)*

4. CASE STUDIES

4.1. Las Garzas

In order to check the adequacy of the joints for the Las Garzas roof, a simplified analysis was made for the ridge beam carrying the heaviest loading based on a tributary area of 2.5 by 18 m (see figure 9). The guadua frame is covered by split guadua roofing (commonly referred to as esterilla in Colombia) which allows for covering the doubly curved surface and provides further in-plane rigidity to the grid. The extra loading (20 kg/m^2) from this split guadua roofing and asphalt shingles was taken into account, as well as wind load. The maximum windward load for the beam corresponding to a pressure of 0.66 kN/m^2 was 2.64 kN/m, while the maximum suction was -0.96 kN/m. The largest compressive force experienced in the joints was 15.32 kN, corresponding to a stress of 5.77 MPa. The largest tensile force exerted on the joints was 1.55 kN.

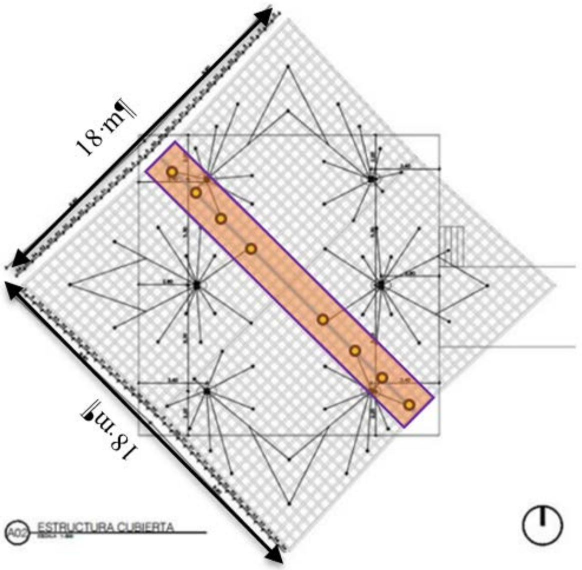

Figure 9: *Plan view of Las Garzas roof with tributary area highlighted*

4.2. El Embudo

To find the reactions in the bamboo columns supporting the roof of El Embudo, a complete 3D finite element model developed in Karamba3D was used. The loading combinations were based on combinations of dead load and super dead load (roofing), as well as four wind loading scenarios. Additionally, seismic action was analyzed using an equivalent horizontal acceleration of 0.41g in one direction, with an acceleration of 0.12 g (30%) in the perpendicular horizontal direction. All 88 columns present in the initial design are attached to the roof using "fish-mouth" connections. All "fish-mouth" connections and connections to the foundations were conservatively modeled as pins. The connections within the grid were modeled as fixed as the extra roofing material will prevent rotations between beams. Safety factors were applied based on the ISO 2004 standard [Iso [16]]. The locations of the "fish-mouth" joints are indicated in figure 10. The maximum compressive force transmitted through the "fish-mouth" joints was 12.48 kN, which occurred due to a combination of dead and super dead loading and wind (1.2 dead load + 1.6 wind). The maximum tensile force expected in the joints was 6.57 kN, experienced due to 0.9 dead + 1.6 wind loading.

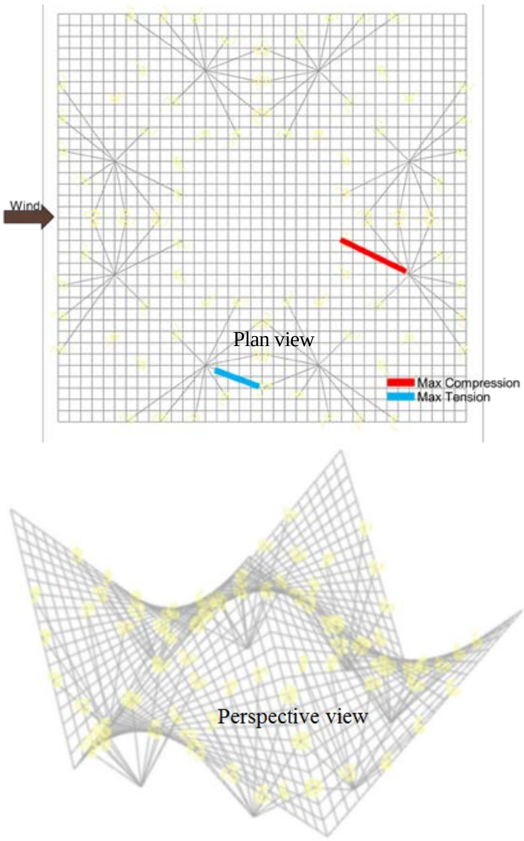

Figure 10: *Locations of "fish-mouth" connections in El Embudo. The maximum compressive force (12.48 kN) is exerted on the joint occurs at the connection of the post marked in red. The maximum tensile force (6.57 kN) exerted on a joint occurs at the connection of the blue member to the roof grid*

4.3. Discussion El Embudo and Las Garzas

The overall largest compression force in the joints is 15.32 kN, while the compressive force in the majority of the other joints is well below 50% of this value. Given the maximum compressive load capacity of the tested T-section of 17.4 kN – tested in the unfavorable case where the “fish-mouth” is positioned between two nodes – it is unlikely that the “fish-mouth” joint will fail in compression. The maximum allowable compressive stresses in the vertical member (14 MPa according to NSR10, 39 MPa according to our tests) is not exceeded. In order to ensure the safety of the horizontal member, the “fish-mouth” should attach to a node (the capacity of which needs to be further determined in future testing). Additionally, although not necessary in the vast majority of connections, it is recommended to fill the space between the nodes of the heaviest loaded joints with mortar to guarantee resistance to crushing in the upper member.

The largest tensile force experienced in the joints of Las Garzas is 1.55 kN. According to NSR-10 the smallest bolt diameter (9.5 mm) provides a tensile capacity of 2 kN, which would be sufficient for Las Garzas. Based on our calculations (assuming the minimum yield stress of 240 MPa as prescribed in NSR-10) a thicker bolt, with diameter of 12.7 mm would be advised for guadua poles with 120 mm outer diameter (under the conservative assumption that the bolt will behave as a simply supported beam).

The largest expected tensile force in the joints of El Embudo is 6.57 kN. This exceeds the maximum tensile force of 3 kN prescribed by the Colombian code [13]. Our calculations, however, show that a bolt – considered as a fixed beam – of 15.9 mm diameter would have an ample capacity of 8.4 kN. Using the bolt as a simply supported beam with steel with yield stress of 240 MPa would only allow for a capacity of 4.7 kN though. Thus, support condition of the bolt should be changed, or the bolt’s steel quality should be improved (a grade 8.8 bolt would yield at 600 MPa). The former, change the support condition, can be accomplished by inserting mortar between the nodes near the connection, which will ensure the beam behaves as fixed and thus provide the necessary resistance of the joint in tension.

It should further be noted that the presented research is done under the assumption that the horizontal and vertical members of the “fish-mouth” T connection attach in an angle of 90 degrees. In reality, these connections will be executed at different angles depending on the location of the joint in the structure. The effect of this inclination, and particularly the shear capacity of the connection in such case, could be the subject of further research.

4.4. Parametric design of BaseHabitat hypar

The in-depth structural analysis of the parametrically defined El Embudo roof shell showed that the elements that required most attention in the structural design were the “fish-mouth” joints, and the supporting columns, which could be prone to buckling. The maximum spacing between the guadua roof beams was constrained to around 60 cm due to the limited distance the split guadua can span without excessive deformation. Because of this spacing, which is smaller than the structurally optimal one, stresses in the 5.10 by 5.10 m hypar are guaranteed to be well below the allowable stresses in the guadua beams. Thus, more important in the design of the BaseHabitat hypar was its rise (the height difference between the highest and lowest point of the grid), as well as the location of the support columns. A parametric study was performed to analyze the effect of the rise on the maximum displacement under the same live loads used for the El Embudo roofs (see section 3.3). Figure 11 shows different shapes for the hypar with changing rise and indicates the maximum displacement associated with each shape under a combination of wind and dead load. The results show that when rise, and thus curvature, increased the maximum displacement dropped. The rise of the hypar needed to be determined while also keeping into account the overall appearance of the structure, as well as constructability (the grid was constructed on the ground and then lifted, making a lower rise more convenient to avoid scaffolding – see figure 12 a). A rise of 2 m was chosen as a good tradeoff, providing an expressive shape (see figure 12 b) and limiting the maximum displacement over rise ratio to 1/100. Supports were placed on the two lower outer ends of the hypar. The resulting stresses in the ridge beams were mostly due to axial compression (74% of the total stress due to axial force) under gravity loading, while the elements in the center of the beam were subject to more bending (66% to 79% of the total stress due to bending). As the stresses in the roof are mostly due to bending in a some of culms, but due to axial forces in others, the structure behaves as a curved grid of beams rather than as a gridshell (where axial forces tend to dominate over bending action). The maximum

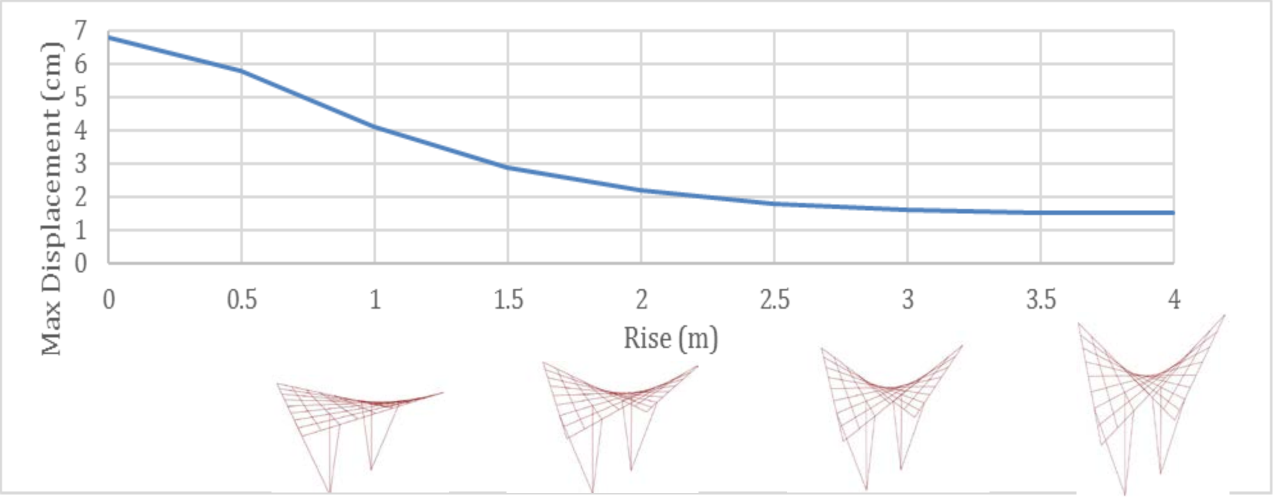

Figure 11: *Plot of the maximum displacement versus the rise of the hypar under the combination of dead loads and wind load. An increase in rise increases the stiffness of the grid*

reactions in the joints due to this configuration were 9.48 kN in compression, and 4.05 kN in tension. This last value exceeded again the maximum tensile value (3 kN) prescribed by the Colombian code. Nevertheless, our lab tests showed that the connection will perform satisfactory if a bolt of 15.9 mm diameter (f_y = 240 MPa) is used, or when a similar 12.7 mm diameter bolt is used and the space between the nodes is filled with cement mortar.

Figure 12 a and b: *a: Guadua hypar grid ready to be lifted, note that the limited rise allows to work on the joints without scaffolding. b: finished hypar at the Base Habitat workshop*

5. CONCLUSION

In this paper we discussed the behavior of the “fish-mouth” joint in hyperbolic paraboloid guadua bamboo grid roofs. It laid forth the different connection types in these hypar roofs and identified the “fish-mouth” connection as the most crucial one to be investigated in detail. The results of laboratory tests on this “fish-mouth” connection were presented and the first steps to determining the ultimate loading capacity of these joints were made. It was shown that the compressive capacity of the joints depends on the ultimate compressive stress of the bamboo in the vertical member, as well as on the capacity of the nodes in the horizontal member. The effect of these nodes needs to be further characterized, but tests indicated that the primary mode of failure will be splitting of the vertical culm.

Tests show that the ultimate tensile capacity of the “fish-mouth” joint is determined by the steel bolts’ strength and diameter, rather than by the properties of the guadua. These findings are in correspondence with the ultimate joint load values prescribed in NSR-10. Based on a bending stress calculation of the steel bolt, the ultimate tensile load capacity of the joint can be determined and the need for inserting mortar between the nodes can be assessed.

It was established that the reactions in the joints expected in the “fish-mouth” joints in Las Garzas or El Embudo roof do not exceed the joints’ ultimate load capacity in compression or tension. Additionally, the outcomes of this study were applied in the design and construction of a prototype hypar at the Base Habitat workshop in Austria, while awaiting the start of the construction of the larger roof shells in Cali, Colombia.

ACKNOWLEDGMENTS

The authors would like to thank the design team in Colombia for sharing their design and practical knowledge on guadua construction. The bulk of the data for this paper was collected through two senior theses [17, 18]. This work was generously supported by Princeton's School of Engineering and Applied Sciences Dean's Office through the SEAS McIntosh fund, as well as by the Community Based Learning Initiative (CBLI) Office. Furthermore, the authors would like to thank BaseHabitat from the Kunstuniversität Linz and particularly Prof. Roland Gnaiger for facilitating and encouraging the dissemination of bamboo construction on an international level.

REFERENCES

[1] ***Stamm, J.*** La evolución de los métodos constructivos en bambú. in *Documento presentado en el Segundo Congreso Mexicano del Bambú, Puebla, México*. 2008.

[2] ***Faber, C.***, Candela, the shell builder. 1963: Reinhold Pub. Corp.

[3] ***Parsons, J.J.***, Giant American bamboo in the vernacular architecture of Colombia and Ecuador. *Geographical Review*, 1991: pp. 131-152.

[4] ***Lopez, O.H.***, Bamboo: The gift of the gods. 2003: O. Hidalgo-Lopez.

[5] ***Sharma, B., et al.*** Engineered bamboo for shell structures. in *Proceedings of the International Association for Shell and Spatial Structures (IASS)*. 2015. Amsterdam. [DOI: 10.17863/CAM.7308].

[6] ***García, B., et al.***, Parametric design and structural analysis of sustainable bamboo grid shells in Mexico, in *International Association for Shell and Spatial Structures (IASS) Symposium 2015, Future Visions*. 2015: Amsterdam. p. 17-20 August 2015.

[7] ***Seixas, M.A., J.L.M. Ripper, and K. Ghavami***, Prefabricated Bamboo Structure and Textile Canvas Pavilions. *Journal of the International Association for Shell and Spatial Structures (J. IASS)*, 2016. 57,No. 3: pp. 179-188.
[DOI: 10.20898/j.iass.2016.189.782]

[8] ***Rockwood, D.***, Bamboo Gridshells. 2015: Routledge.

[9] ***Harries, K.A., B. Sharma, and M. Richard***, Structural use of full culm bamboo: the path to standardization. *International Journal of Architecture, Engineering and Construction*, 2012. 1,2: pp. 66-75.
[DOI: 10.7492/IJAEC.2012.008]

[10] ***SAP2000***, 15.0.0 Integrated Finite Element Analysis and Design of Structures-Basic Analysis Reference Manual. *Computers and Structures Inc, Berkeley*, 2011.

[11] ***McNeel, R.***, Grasshopper-Generative Modeling with Rhino, McNeel North America, Seattle, USA. 2010.

[12] ***Preisinger, C.***, Karamba 3D, Parametric Structural Modeling. User Manual for Version 1.1.0. 2015.

[13] ***NSR-10, C.A.P.P.e.R.D.C.S.R.***, NSR-10. Reglamento Colombiano de Construcción Sismo Resistente. Título G - Estructuras De Madera Y Estructuras De Guadua. 2010: Colombia.

[14] ***Richard, M.J.***, Assessing the performance of bamboo structural components. 2013, University of Pittsburgh.

[15] ***Shao, Z.-P., C.-H. Fang, and G.-L. Tian***, Mode I interlaminar fracture property of moso bamboo (Phyllostachys pubescens). *Wood science and technology*, 2009. 43,5-6: pp. 527-536.
[DOI: 10.1007/s00226-009-0265-2]

[16] ***ISO***, ISO 22156:2004 (E): Bamboo - Structural Design. 2014, ISO: Geneva, Switzerland.

[17] ***Archer, R.***, An investigation of the effectiveness of the "fish-mouth" joint in bamboo structures, in *Department of Civil and Environmental Engineering*. 2016, Princeton University: Princeton.

[18] ***Lu, L.***, Parametric structural analysis of a hyperbolic paraboloid bamboo grid shell roof, in *Department of Civil and Environmental Engineering*. 2016, Princeton University: Princeton.