BAMBOO GRIDSHELL: FROM THE MATERIAL TO THE STRUCTURE

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ABSTRACT: The majority of gridshell structures are built using timber lath and steel. only few are made from bamboo. Constructing a gridshell structure using bamboo is challenging because the anatomy, physical and mechanical properties affect the ability of bamboo culm to be bent. This paper aims to investigate the utilisation of bamboo for gridshell structures by examining bamboo as the material, the elements, and the whole gridshell structure. The experiments were conducted in three stages: testing material properties, examining bending capacity, and constructing a full-scale model of gridshell structure. The bamboo species used in the experiments was *Gigantochloa apus*, a species that is commonly found in Indonesia. The experiments showed that full-culm bamboo had a limitation on the depth of curvature, which then affected the height of gridshell, the form, and the structure.

KEYWORDS: bamboo, bamboo gridshell, material properties, bending capacity, form, structure.

1 INTRODUCTION

The construction sector has contributed significantly to global carbon dioxide (CO_2) emissions, and the use of environmentally friendly materials is highly promoted to maintain the sustainability of our planet [1]. Bamboo is one of the building materials widely known as a sustainable material. The sustainability aspect of bamboo has been researched, and findings have shown the capability of bamboo in sequestering carbon, reducing CO_2 emission, contributing to carbon storage, conserving water, controlling erosion and conserving energy, making a significant contribution to controlling climate change issues [2]–[4]. Moreover, bamboo is a fast-growing plant that can be harvested in 3 to 5 years, which makes bamboo an important replacement material for wood in terms of supply and demand [5]. Regarding workability, bamboo provides flexible and uncomplicated methods to work with, whether utilised as structures, such as portal frames, trusses and building envelopes, or as non-structural elements, such as walls and floors[6].

Gridshell structure is considered an efficient structure because it needs fewer materials than a solid surface shell structure, and is capable of enveloping a large span space [7]. Gridshell structure can be defined as a double-curvature shell built of grids instead of the usual solid surface [8]. In terms of construction methods, strained gridshell produce form by assembling the initial flat grid consisting of continuous members, which is lifted until the designated form is achieved. The curve is shaped by actively bending members; thus, the structural elements can be called active bending [9]. Gridshell built through this method also can be called 'elastic gridshell' which refers to the materiality and construction process [10].

Choosing a suitable material for elastic gridshell requires considering two important aspects. First, the material should have a sufficiently low modulus of elasticity (MOE) to minimise bending moments resulting during the shaping process. However, high MOE is needed to provide adequate global buckling stiffness. Second, materials with higher ultimate stresses can resist significant bending moments and adopt a lower radius of curvature; thus, they are suitable for achieving a strong curvature shape [11]. Bamboo has high flexibility and strength, making it capable of being employed as an active bending structure [12]–[14]. However, there is limited information about the degree to which the bamboo can be bent, especially for the utilisation in gridshell structures.

Literature on the construction and erection methods of bamboo gridshell is limited compared to timber gridshell. Rockwood's research [14] investigated the form finding and construction of bamboo gridshell. The form-finding process was through physical models, and the construction used very small-diameter bamboo. The experiments found that buckling and splitting were significant challenges in achieving desirable curvature, and some bamboo poles snap and break during the bending process. It also showed that despite bamboo being flexible, bending the material is challenging. Meanwhile, the ZBC pavilion designed by CUHK team showed the process of realising a bamboo gridshell designed through computational form-finding and modelling. During the construction, amendments were performed in response to the natural behaviour of bending bamboo which showed the discrepancy between the simulated model and the real material [15].

Therefore, some challenging questions need to be answered, such as the bending capacity of bamboo and

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bending methods that influence the depth of curvature and, hence, affect the maximum height of gridshell. Regarding the construction, there are some gridshell construction issues; whether the erection methods for timber gridshell are suitable for bamboo gridshell; whether gridshell as-design can be directly realised as-built.

This paper aims to investigate the utilisation of bamboo for gridshell structures from the material to the structure system. The paper discusses bamboo as the material by testing the material properties, as an element of the structure by investigating the bending capacity, and the whole structure system by erecting a full-scale model of bamboo gridshell.

2 MATERIAL AND METHODS

2.1 MATERIAL SELECTION

The experiment used the bamboo species *Gigantochloa apus* from Indonesia, known by the local name *bambu tali*. *Bambu tali* is readily available in most areas and cultivated in lowlands and highlands. It is known by local people for its flexibility and has been used for building construction. The features have a relatively small diameter with medium wall thickness (Figure 1). Thinner wall bamboo with a larger diameter would break easily during the bending process, while big diameter and thick wall bamboo would be hard to bend. Meanwhile, a very small-diameter bamboo was not selected because this research aimed to utilise bamboo for large-span gridshell. Bamboo with a very small diameter certainly has more flexibility, but its strength is questionable. Thus, *G. apus* was selected in consideration of its dimensions and wall thickness, and when the structure would need more than one layer, multiple layers of *G. apus* might not create a thick surface for the gridshell.

The experiment used full-culm bamboo aged 3-4 years and 5-7 cm in diameter. The age was considered the optimum age for bamboo for construction purposes. The bamboo was brought from a supplier in Magelang, Central Java province in Indonesia.

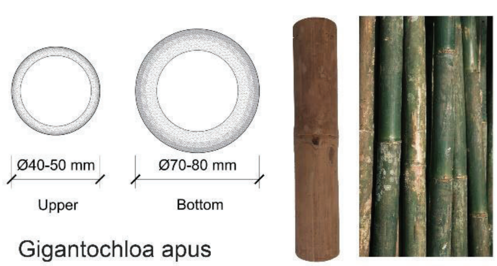

Figure 1: *Bamboo species Gigantochloa apus for the experiments.*

2.2 MATERIAL TEST

The material tests were carried out in accordance with BS ISO 22157:2019 tensile parallel to the fibres [16]. The specimens were taken from 20 bamboo culms with a length of six meters and extracted from three parts within the culm: upper, middle, and bottom. In total, 60 specimens were tested. For the tensile test, the bamboo had been treated by soaking in the boric borax solution for two weeks, then aired-dried and stored for at least six months before the testing.

The mechanical tests were carried out using JTM Universal Testing Machine with a maximum capacity of 30 Ton. The ultimate load at failure (F_{ult}) and displacement (Δ) were recorded, and the cross-section of the specimens (A) was measured from the specimen width (b) and wall thickness (δ) to calculate the strength. The formula used to determine the tensile strength was as follows:

$$\sigma_t = \frac{F_{ult}}{A} \quad (1)$$

2.3 TEST ON THE DEPTH OF CURVATURE

To design a bamboo gridshell, it is crucial to identify the maximum depth of curvature that can be reached by a bamboo culm. Whilst bamboo can be bent, due to its anatomy, there was a limitation in actively bending the bamboo. The bending capability and capacity of bamboo would determine the final geometry, apex height, and could be a consideration in determining the suitable erection method. To determine the depth of curvature, the tests were carried out in the laboratory through a bending test, and at the construction site by bending the bamboo on-site.

The first test on bending parallel to the fibres was conducted in accordance with BS ISO 22157:2019 [16]. The load was given continuously using Enerpac hydraulic jack, and a load cell was installed to record the load (F) and ultimate load (F_{ult}). To measure the displacement (Δ), three laser meters were positioned at the centre, left and right sides (Figure 2). The measurement taken for calculation were clear span (L), shear span (a), outside diameter of bamboo (D), and wall thickness (δ). Seven bamboo poles with a clear span of 3.60 meters were tested.

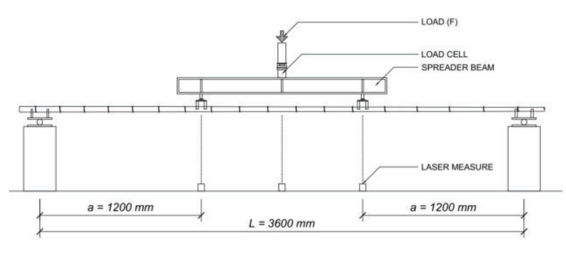

Figure 2: *Bending test set-up*

The formula used to calculate the bending moment (M_{ult}), bending strength parallel to the fibres (f_m) and tangent bending stiffness ($E_m.I_B$) were as follows:

$$M_{ult} = \frac{F_{ult} \times a}{2} \quad (2)$$

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$$f_{m,0} = \frac{M_{ult} \times D}{2 \times I_B} \quad (3)$$

$$E_m \cdot I_B = \frac{(F_{60} - F_{20})a(3L^2 - 4a^2)}{48(\Delta_{60} - \Delta_{20})} \quad (4)$$

The apparent modulus of elasticity (E_m) was determined by dividing the tangent bending stiffnees (E_m I_B) by the second moment of area (I_B)

$$E_m = \frac{4(F_{60} - F_{20}) \cdot a(3L^2 - 4a^2)}{3\pi(\Delta_{60} - \Delta_{20}) \cdot [D^4 - (D - 2\delta)^4]} \quad (5)$$

The second test on the depth of curvature was done on the construction site by setting up bamboo poles with scaffolding and bending the bamboo manually. A set of bamboo poles was laid on two sets of scaffolding, a rope was tied at the middle of the poles, and two ropes were tied at the left and side parts. The ropes were knotted in a certain way that made them capable of being shortened by twisting a short blade installed in the middle. Alternatively, ratchet straps can also be used as a replacement for the ropes (Figure 3). The heat from a gas torch was applied to soften the bamboo's fibres in attempt to make the bamboo culm more flexible and add depth of curvature. Water was continuously applied to prevent the culm from overheating and getting burnt.

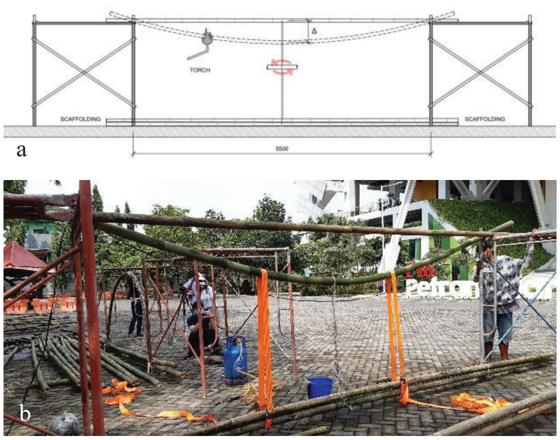

Figure 3: *Setting up of bending test on the construction site*

2.4 CONSTRUCTION METHOD

The full-scale model was built inside the campus area of Petra Christian University in Surabaya, Indonesia. Construction was carried out by building a full-scale model made from bamboo culms with a span dimension 10.80 m x 10.80 m. The entire process needed six days to complete a full-scale bamboo gridshell. The construction was done by hiring five construction workers with experience constructing bamboo buildings. However, even though they had long experience with bamboo, it was their first time constructing a bamboo gridshell.

Adjustments were made to the gridshell design and the erection method following the findings from the tests on the depth of curvature. The initial plan was to move the anchor inward and pull up the lattice. However, during several pre-construction testing events, it was hard to bend the whole culm of *bambu tali* by pushing the two tips inward. The bamboo tended to swing and return to its original shape, which would be dangerous for the workers; they could get hurt and thrown if the bamboo swung back to its original shape. Therefore, it was decided to lay the members one by one using scaffolding, then slowly pull down the members and tie them to the other members and boundary (Figure 4).

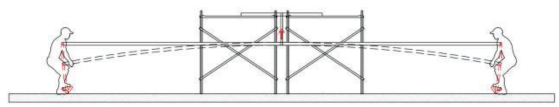

Figure 4: *Illustration of bending method to erect the bamboo gridshell*

The gridshell structure was erected by bending each member and utilising scaffolding. The two main arches at the centre were assembled and erected first, followed by other members. The connections were tied using ropes to allow rotation during the erection process. Later, the connections to the boundary were fixed using nuts and bolts.

3 DISCUSSION

3.1 TENSILE STRENGTH OF BAMBOO

A summary of the tensile test results can be seen in Table 1. The tensile strength of bamboo was particularly high but not evenly distributed within the culm, and the variation within the upper, middle, and bottom was quite significant. From the test, the highest strength was found in the upper section, with an average of 301.67 N/mm^2. Meanwhile, the middle section had an average of 289.61 N/mm^2, and the bottom section was 255.69N/mm^2.

Table 1. Summary of tensile test result

Specimens		δ (mm)	A (mm^2)	F_{ult} (kN)	σ_t (N/mm^2)
Bottom	Max	11.90	40.10	9.89	327.40
	Min	6.30	15.75	3.77	176.38
	Ave	8.42	26.23	6.52	255.69
	Stdev	1.50	7.23	1.45	40.95
Middle	Max	9.14	23.31	6.18	367.44
	Min	5.40	14.50	3.51	205.14
	Ave	6.66	17.26	4.96	289.61
	Stdev	0.85	2.20	0.78	48.24
Upper	Max	6.07	16.39	5.54	345.34
	Min	4.70	12.69	3.10	215.13
	Ave	5.30	14.05	4.32	307.67
	Stdev	0.36	0.94	0.56	31.87

The results showed good performance of bamboo in tensile, especially at the upper part. The difference between the upper and bottom sections was significantly high at 51.98 N/mm^2. The tensile test results showed that an increase in wall thickness resulted in a decrease in

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tensile strength, which caused by the composition of fibres and lignin within the culm wall.

3.2 BENDING TEST OF BAMBOO

Results from the bending test are summarised in Table 2. The average bending strength parallels to the fibre (f_m) was 71.02 N/mm2, with the minimum being 41.04 N/mm2 and the maximum reaching 100.80 N/mm^2. The results were not significantly different from the previous research for *G. apus* [17], which found the modulus of rupture (MOR) of *G. apus* ranged between 376.5 kg/cm^2 (36.92 N/mm^2) and 965.6 kg/cm^2 (94.69 N/mm^2) with an average of 686.7 kg/cm^2 (67.34 N/mm^2). While the modulus of elasticity (E_m) from the experiment was found as 22,277 N/mm^2 on average. The specimens with an average culm diameter between 68.21 mm to 83.38 mm had variation in flexural rigidity with an average of 2.56E+10 Nmm^2.

Table 2. Summary of bending test result

Speci-mens	D (mm)	Δ_{max} (mm)	f_m (N/mm^2)	E_m (N/mm^2)	$E_m.I_B$ (Nmm^2)
AP 1	81.44	119.00	69.25	21,832.31	3.23E+10
AP 2	78.70	138.00	61.11	21,981.45	2.55E+10
AP 3	76.38	134.00	86.85	29,194.56	3.08E+10
AP 4	81.53	125.00	68.18	20,511.05	2.60E+10
AP 5	83.38	151.00	63.92	16,275.87	2.68E+10
AP 6	78.00	77.00	47.04	17,519.89	1.98E+10
AP 7	68.21	161.00	100.80	28,623.84	1.82E+10
Ave	78.23	129.29	71.02	22,277.00	2.56E+10
Min	68.21	77.00	47.04	16,275.87	1.82E+10
Max	83.38	161.00	100.80	29,194.56	3.23E+10
STdev	5.03	27.18	17.67	5,003.04	5.21E+9

The characteristics of failure observed during the bending test were due to compression and buckling (Figure 5), which can be seen from the crushing and splitting in the compression area. While from all specimens, no damage was found in the tension area. Previous research [17] on the flexural properties of *G. apus* showed the failure were shear and compression, and similarly, no failure in tension area and mode were found. Hence, the result presented the compression strength of the bamboo, which was significantly smaller than the tensile strength shown in Tabel 1. The failure characteristics also showed buckling in the compression area, in which the fibres were wrinkling at the top. The failure also happened due to load concentration at the saddle. The stress concentrated at one point, which caused the breaking located at the saddle.

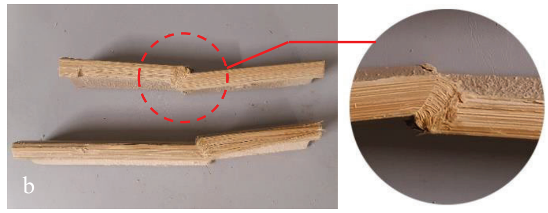

Figure 5: *Failures due to bending*

Similar failure characteristics were obtained through the bending test on the construction site using bamboo six metres in length. Failure modes recorded during the experiments were identified as splitting and fibres crushing within the uppermost area of the culm, which was the compression area. Buckling also occurred and caused sudden collapse during the bending process (Figure 6. a).

The application of heat by torching the bamboo added flexibility to the fibres and allowed the culm to reach deeper curvature. However, the heating process did not eliminate the limitation, and there was a maximum depth of curvature that the culms could reach. In the experiments, the bamboo culms were able to reach deeper curvature compared to the culms without heating; but when the culms were cooled down, they suddenly broke without any loads applied (Figure 6. c). It showed that the fibres returned to the original length and stiffness after removing the heat and showed buckling characteristics. Thus, applying heat to add the depth of curvature did not significantly help in reaching deeper curvature. Actively bending bamboo culms can only produce narrow curvature.

Figure 6: *Failures due to bending test on the construction site*

The tests on the depth of curvature resulted in a major revision to the initial design of the full-scale model. The initial design of gridshell form was based on the basic form of a simple gridshell structure (Figure 7). The form had been used by Labonnote [18] and Dyvik [19] and was based on form-finding from Pone [20]. The form finding

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was done in Rhinoceros using plug-ins Grasshopper and Kangaroo. The initial construction plan was to build gridshell form by constructing a flat lattice and moving the anchor inward to create maximum curvature and form the gridshell surface.

Based on the experiments, the initial plan could not be realised. It was not possible to bend a whole culm bamboo into the expected depth of curvature based on the initial design. As can be seen in Figure 7, middle members had narrow curvature, but members near the boundary had deeper curvature. The depth cannot be formed and certainly would result in buckling and breaking. Therefore, the initial design was revised, and several adjustments were added concerning the bending capacity of bamboo.

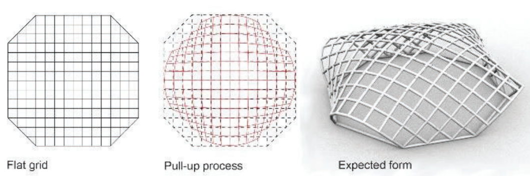

Figure 7: *Initial design of bamboo gridshell*

The adjustments involved lowering the apex height and increasing the span from 8.40 m x 8.40 m to 10.80 m x 10.80 m (Figure 8) to gain higher curvature. Following the result of bending tests, the maximum curvature a bamboo culm or pole could achieve was limited. Thus, by increasing the span, it was expected that the depth of curvature would also be increased, and the maximum apex height could be determined.

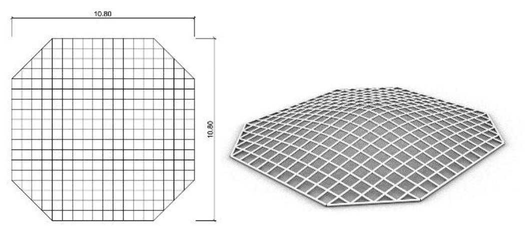

Figure 8: *Final design of bamboo gridshell for the experiment.*

3.3 CONSTRUCTION PROCESS OF BAMBOO GRIDSHELL

Methods of bending the bamboo to reach the maximum possible curvature and form a lattice structure became a crucial part of this construction stage. Based on their experience and craftsmanship, the workers preferred to employ slicing methods to create bamboo arches. Slicing methods provided a quick and easy technique; however, only small strips of the culm were left to bear the loads. The strength would be greatly reduced, and the deeper the curvature, the more slicing would be needed. Therefore, in this research, it was decided to actively bend the bamboo culm and use the heating method to help raise the curvature's depth

The span dimension of the full-scale model was 10.80 m x 10.80 m, and the mesh grids were 0.60 m x 0.60 m. Eight bamboo poles were assembled to form the boundary structure, which had an octagon shape. Around 120 bamboo culms, including those used for the depth of curvature test, were prepared for the construction. The model consisted of 34 long members to construct the surface. As the shortest members for the surface was 7.2 meters, two bamboo culms were joined into one long pole and cut according to the length. No joinery to lengthen the poles were needed for the boundary since the members' length did not exceed 6 meters.

The construction process began with the erecting of the first arch as the centre arch, which played a significant role in defining the maximum height of curvature or the apex of gridshell. Two sets of scaffolding were assembled, and a bamboo pole was strung across the centre to form the first arch (Figure 4 and Figure 9). Two workers held the tips of the bamboo pole and carefully pulled down the tips until they reached the ground. The bamboo was raised to its greatest possible height without snapping. After six poles were tested, it was determined to lift the arch to a height of 1.20 m, which could potentially break the bamboo poles. The height was considered narrow compared to the potential reach of timber gridshells. Afterwards, the arch was tied to a horisontal beam to hold the curvature (Figure 9).

Figure 9: *Erection process of the centre arch*

The second arch was erected perpendicular to the first arch by constructing another two sets of scaffolding, tying the centre of the second pole to the first arch, then carefully lowering the tips to the ground and tying the arch to straight poles, following a similar procedure as the previous arch (Figure 10). After constructing two major arches, the boundary was created. Then, other members were set one by one on top of the major arches and then carefully lowered and tied to the boundary. Throughout the assembly process, short poles were installed under the connectors as supports to maintain the curvature. To ensure that the connection could rotate during assembly, each connection was secured using ropes that permit rotation (Figure 11).

Figure 10: *Assembly process*

Figure 11: *The connections and the temporary supports*

After the members had assembled, the bamboo was heated by torching the culms. Water was regularly applied during heating to prevent the bamboo culms from overheating and cracking (Figure 12.b). The structure was then raised using a chain block. However, the outcome of attempts to increase the height of the apex was insignificant. The apex only raised around 3-5 cm during the process. In the last stage, nuts and bolts were used to secure the connection between the lattice and the boundary. Then, all supports were removed, resulting in the lattice independently forming the whole curvature of the gridshell.

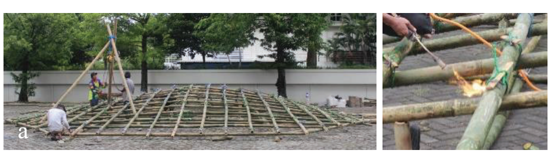

Figure 12: *Heating and pulling the gridshell using chain block to add height*

Once all supports were removed, the gridshell structure quickly lost a certain height, and the final apex height only reached 1.12 m. It was recorded that when the supports were removed, the lattice members pressed against the boundary beams. The bamboo culm showed a tendency to swing back to its original shape, and the boundaries were crucial in holding the form.

During the construction, many bamboo culms failed and broke. Several causes of the failures were buckling and splitting, and some failures occurred at the connections. Buckling happened during the bending process, which has been discussed in section 3.2. However, when the curvatures were getting narrow near the boundary, the occurrence of buckling was not found. The critical failure resulting from bending was at the highest curvature area. Splitting was recorded to occur mainly at the boundary. The pressure from lattice members to the boundary increased the stress, and the beams started to split (Figure 13.a). The pressure also affected the connections between lattice members and boundary. One connection was heavily damaged and broke (Figure 13.b). The connection had been fixed using nuts and bolts, and thus, it no longer could move. On the other hand, fixing the connections was necessary to hold the curvature when the supports were removed. Otherwise, the gridshell would lose its height, and the bamboo would swing back to its original shape.

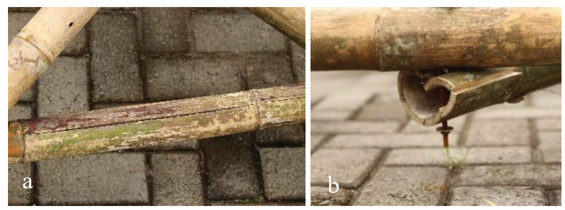

Figure 13: *Failures in the construction: a. due to splitting; b. due to breaking*

4 CONCLUSION

The experiments showed that the choice of bamboo as material influenced the final gridshell design and the construction method. As a material, bamboo has high tensile strength. However, limitation in bending significantly impacted its flexibility. Majority of failures in bending, both during the depth of curvature test and construction, was caused by fibres wrinkling in compression area, splitting, and buckling.

The bending limitation affected the depth of curvature of bamboo arches and the apex height of bamboo gridshell. The apex height produced by the full-culm bamboo was narrow, especially compared to the apex height that a timber gridshell can reach. The maximum depth of curvature or apex height in this study was compared to the span at a ratio of 1:9.64. Hence, designing a bamboo gridshell should take into account the maximum depth of curvature, and the curvature would have to be narrow if the gridshell were entirely made of full-culm bamboo.

The boundaries structure was crucial in keeping the curvature shape, particularly in holding the bamboo culm from returning to its original shape. Therefore, the connection between the lattice members and the boundaries should be considered to prevent breaking, in which, can cause the collapse to the whole structure system. Further analysis of stress distribution in boundaries and alternatives of suitable connections will surely be necessary for future research.

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