BAMBOO CANOPY: TOWARDS A LIGHT CONSTRUCTION OF BAMBOO

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ABSTRACT

Despite the abundance of highly sustainable bamboo, people tend to overlook its structural performance for construction purposes. This paper therefore explores the potential of bamboo architecture to develop light-weight building systems and also to create an effect of lightness. Developed by a team at the School of Architecture of Southeast University, Bamboo Canopy is an outdoor stage canopy in Anji, China, that pushes the boundaries of bamboo as a material for building woven gridshell structure. The work is designed as a long-lifespan bamboo structure, with the design team and locals participating in its construction. Positioned on a public stage, Bamboo Canopy experiments with the combination of sustainable construction and local craftsmanship to produce a highly engaging architectural intervention that activates the existing place. With its wing-like form, it invites visitors to join the performance scene—as they approach the shell, the structure reveals itself—with a 12.4-metre span and 6-metre roof overhang, the canopy covers more than 150 square metres with only 1.2 square metres touching the ground. Through analysing the form, structure and details of this experimental project, this paper clarifies not only the potentiality but also the feasibilities in using bamboo for light construction.

KEYWORDS

modern bamboo structure, light construction, woven gridshell structure, structural performance of bamboo

'Lightness [. . .] goes with precision and determination, not with vagueness and the haphazard.'

Calvino, 1988

BACKGROUND

Although bamboo is rapid generative and abundant across China, contemporary architecture generally overlooks it entirely as a construction material with reliability in engineering performance. In the southern region of China, the attempt to spread the usage of bamboo as construction material is quite demanded. At least half of the concentrated clusters of rural settlements are to be found within the natural bamboo forests of southern China. The provinces with the highest density of rural settlements and also the largest presence of bamboo in China are Hunan,

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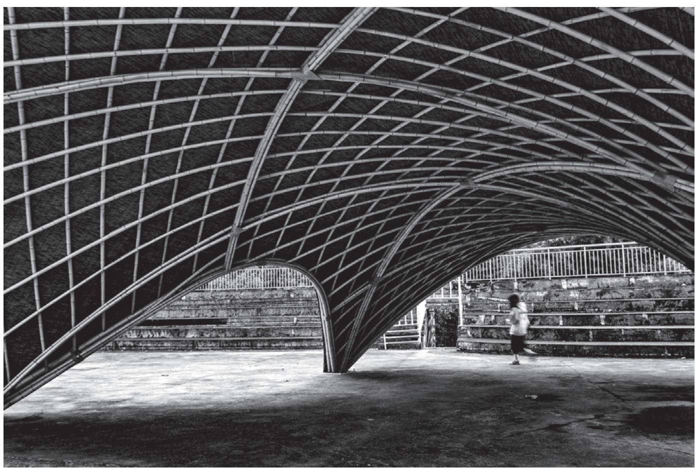
Hubei, Jiangxi, Anhui and Zhejiang—with the Anji county located in a mountainous area of Zhejiang being the location for the Bamboo Canopy project to be discussed later in this essay.

Anji County is near the prefecture-level city of Huzhou in northwest Zhejiang province, a developed area in the Yangtze River Delta in Southern China. The county had a population of 470,700 in 2018. It is particularly known for its bamboo, containing as it does 60,000 hectares of bamboo groves, with over 40 different species of bamboo of which the most common is Moso bamboo (*Phyllostachys edulis*). Anji is indeed considered to be China's 'bamboo town'—winning multiple awards including the China National Habitat Environment Award, UN-Habitat Scroll of Honour, and National Ecological County Award, due to its leading position in the bamboo industry.

As a renewable and ancient symbol in Asian societies like China, the constructional use of bamboo however still lags far behind its potential. Therefore, the Anji County Government and the International Bamboo and Rattan Organization (INBAR) has launched the National College Bamboo Design and Construction Competition in China since 2017. The competition sites are located in Anji, most of which are abandoned or in disuse. The contestant teams, representing architecture schools nationwide, are invited to propose innovative design for bamboo structures that are required to meet local needs and to be long-lifespan. In order to get the works built to budget and schedule, the design teams also conduct building site work through a communicative process involving local communities. The highly engaging architectural inventions bring design talent of bamboo to the countryside, laying a foundation for local tourism and rural revitalization, while promoting the development of the bamboo industry in Anji.

Developed by a team at the school of architecture of Southeast University, the Bamboo Canopy project is part of the Second Bamboo Design and Construction Competition (Figure 1). It is situated in Anji Bamboo Expo Park. A concrete outdoor stage in the park had been abandoned for several years, thus a timely redesigning was needed for holding future events while promoting tourism. Meanwhile, the design team saw it as an opportunity to explore the boundaries of bamboo as a material with eminent mechanical performance. With this premise in mind, the team started the project by investigating modern bamboo structures, especially into the various structural forms and their many applications.

FIGURE 1. View of Bamboo Canopy.



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BAMBOO-DRIVEN ARCHITECTURAL DESIGN

Bamboo as a material for light construction

Bamboo is a renewable material which grows extremely fast, and is obviously abundant in many regions widely distributed around the world (Birkeland 2012). Traditionally, bamboo has been common in building houses and shelters across East and Southeast Asia, Africa, and South America. Although modern technology and materials, such as concrete and steel, have largely replaced bamboo construction, the bamboo scaffolding system is still widely used in contemporary constructions because of its structural properties and low cost (Laleicke et al. 2015).

It is nature that 'engineers' bamboo. When growing in nature, bamboo's efficacy in lateral resistance has few peers in the plant kingdom. Varied in diameter, length and colour as it is, the key unifying physical characteristics of bamboo result in many innate structural properties, optimizing its strength, elasticity and weight (Correal 2016). Its longitudinally extending fibers effectively improve the tensile and compressive capabilities. Taking the most commonly used Moso bamboo as an example, its tensile and compressive strength is about 2 times that of cedar (Rittironk and Elnieiri 2008). While providing an equal tensile strength, bamboo has a much higher strength to weight ratio compared to that of steel, thanks to its hollow profile and nodes (Janssen 2000). Bamboo has no cross-fibers, which allows easy bending and keeps resilient to adapt organic form (Nurdiah 2016).

On the other hand, proper treatment is needed to enable bamboo structures to last for long. That is to say, one has to overcome some disadvantages of the material. The shrinkage ratio of bamboo is much larger than that of wood. It has a high water content and is susceptible to corrode (Stamatis and Tan 2019). There are now certain techniques that are able to increase significantly the durability of bamboo construction: protection by design, preservation treatment, suitable joinery systems, and maintenance over the lifespan (Yuan et al. 2018; Li et al. 2015; Trujillo and Malkowska 2018; Disén and Clouston, 2013).

Modern bamboo structure design and innovation

Bamboo has been considered as a reliable material that can be used to build long-span structures due to its flexibility, durability, reduced dead weights, as well as its availability in most tropical regions. Regarding the potential of bamboo in lightweight structures, Frei Otto writes 'bamboo is one of the oldest construction materials: the history of building with bamboo probably begins with the history of Man's development, and it is most likely that it has not yet come to an end' (Otto 1985, p.10). He turned to bamboo as a primary building material for the 21st century, not only for its creative potential and material efficiency, but also for its qualities as a natural, renewable material which has the capacity to sequester carbon and help heal the planet. Contemporary architects, meanwhile, favor its structural expression and tectonic articulation, as it allows freedom in designing spaces enclosed beneath it and creates a profound impact to the spatial experience of the building user (Hebel and Heisel 2017; Crolla 2018).

A mostly used technique through which modern bamboo structures obtain longer span is the planar truss system. The Millennium Bridge at Green School (Figure 2a) uses a self-balancing structure of arched bamboo trusses to achieve a 23-metre span of bamboo bridge. The Mepantigan Auditorium at Green School (Figure 2b) functions as an open space for assemblies; its giant roof with only four points touching the ground is supported by two mega bamboo trusses of 19-metre span and 7-metre height.

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In constructing bamboo truss system, each member is placed within the structure in accordance to the forces that it needs to distribute and withstand, both vertically and laterally. When applying the system, on the one hand, a larger space can be obtained through a row of paralleling trusses. For example, the Bamboo Long House Restaurant (Figure 2c) creates a very deep space by 20 aligned symmetric trusses, all prefabricated with bent bamboo poles. The Bamboo Sports Hall for Panyaden (Figure 2d) uses prefabricated arch trusses with horizontal support connected to the upper chords; its maximum span reaches 17.2 metres and the depth reaches 36 metres. On the other hand, bamboo trusses can also be developed into dome. In the case of wNw Bar (Figure 2e), the architects use bow-shaped prefabricated trusses as the main structural units to form a 15-metre-span dome. In the Son La Ceremony Dome (Figure 2f), the trusses are configured in radial order, with a compression ring uniting all of the trusses while serving as a skylight, creating a 16-metre-span and 15.6-metre-high dome.

THE BAMBOO CANOPY PROJECT

Form

Bamboo Canopy is an outdoor stage canopy that hosts entertainment activities for both locals and visitors. In the heart of a conserved area of bamboo botanicals, the site offers a natural setting (Figure 3). On the site was an abandoned 1.2-metre-high outdoor concrete stage. Originally built in the 1990s, the existing stage was facing north to the groves of bamboo, with audiences sat on its rising seating. This however restricted the number of audiences and could no longer meet the requirements. To the south of the stage was an open lawn, which could accommodate a larger number of people. Therefore, the bamboo stage canopy had been set up on the existing foundation, facing south to the open space. In this way, the ascending stage defined a new territory, as surrounded by such a continuous forest of bamboo and deciduous trees, along with a creek, so that the direction and depth of the natural setting could be perceived.

FIGURE 2. a) Millennium Bridge at Green School; b) Mepantigan Auditorium at Green School; c) Bamboo Long House Restaurant; d) Bamboo Sports Hall for Panyaden; e) The wNw Bar; f) Son La Ceremony Dome.

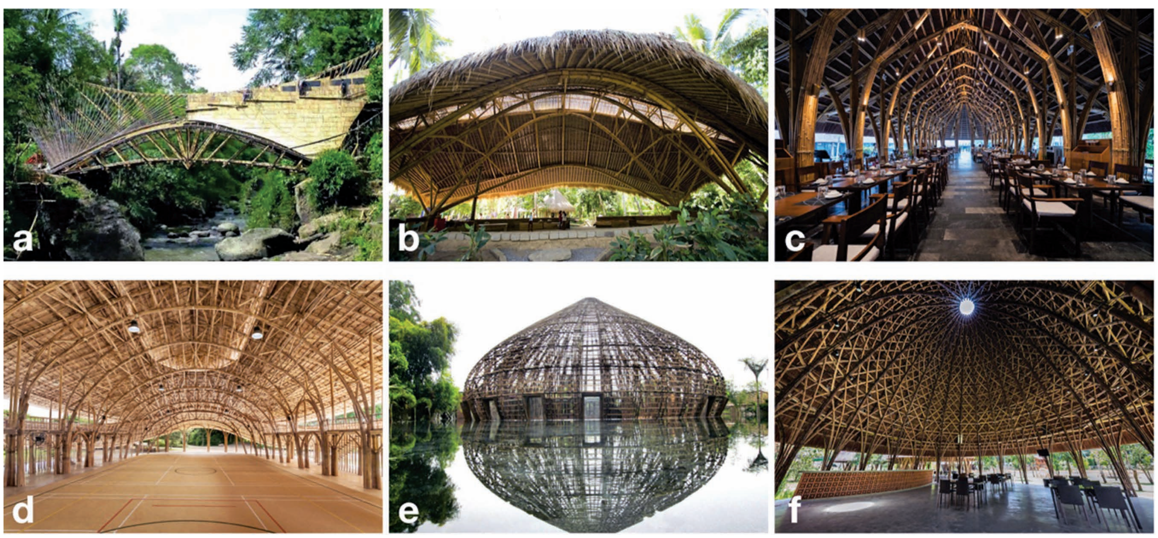

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FIGURE 3. Project site: Anji Bamboo Expo Park.

FIGURE 4. 'Weaving bamboo' as depicted in *the Garden for Solitary Enjoyment*.

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The design process for Bamboo Canopy involved a continuous dialogue between architectural thingness and structural performance of a natural material. We realized that bamboo had unique materiality which we attributed to Asian cultures—it could assume a poetic quality in the context of Chinese painting and literature. In his well-known painting, *the Garden for Solitary Enjoyment* (Figure 4), Qiu Ying depicted a space enclosed by a grove of bamboo 'like a canopy covering the sky', with a poet (owner of the garden) inside, 'lying, relishing, and lingering over this joy of contentment'. The bamboo, bound together near the top, was the only architectural element, blurring the dissimilarity of wall, column and ceiling. The making of such an ethereal place was completed with the ingenious gesture of 'weaving bamboo'. Inspired by this, we arrived at a concept that both the softness and toughness of bamboo should be brought to the extreme, by integrating its structural strength and materiality—the tangibility, smell, and acoustic qualities were merely elements of the language that we were obliged to use.

Our initial proposal was for a structure created primarily of bamboo, bringing together the material of the supporting frame and the overlay while using the simplest and lightest structure to complete the coverage for the existing concrete stage. For designing long-span bamboo structure, it was recognized that the planar truss system was commonly used through a description and comparison of several case studies mentioned above. The bamboo truss system has already been proved to be stable and well-performed. However, it often visually creates a sense of heaviness, as the trusses are formed by many triangular elements with a series of small members crossing each other, combined and repeated. In order to take advantage of bamboo's feature, flexibility, while emphasizing the lightness, we attempted to seek a breakthrough from

FIGURE 5. Conceptual design model evolution.

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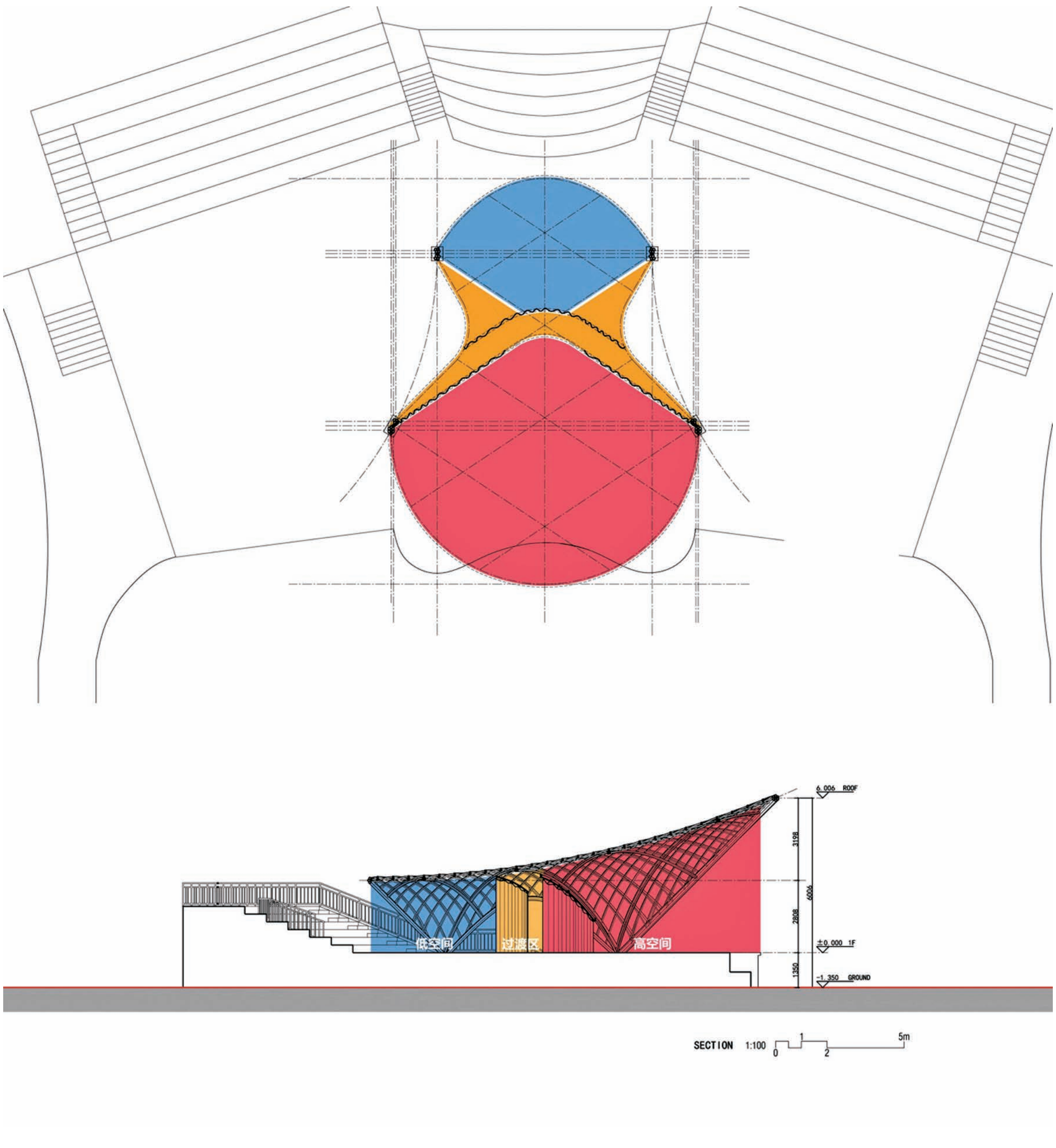
studying another type of structure, the gridshell. In the process of comparing multiple proposals (Figure 5), the woven latticed shell structure was selected as an optimized solution. The form of 'a woven bamboo gridshell' gradually became clear. It was a shell of openness and lightness. All the lines of the slender bamboo conformed to the clarity of the structure—both mechanically and tectonically. A raised stage and a seemingly floating canopy together created a space enclosed beneath bamboo for performance.

The canopy was designed as symmetrical, with a roofline that stretched all the way down to the ground to form partitions, and touched the ground with only four points. The required span for stage performance was obtained by sweeping arches made from bamboo, forming a

FIGURE 6. Architectural configuration and program for Bamboo Canopy.



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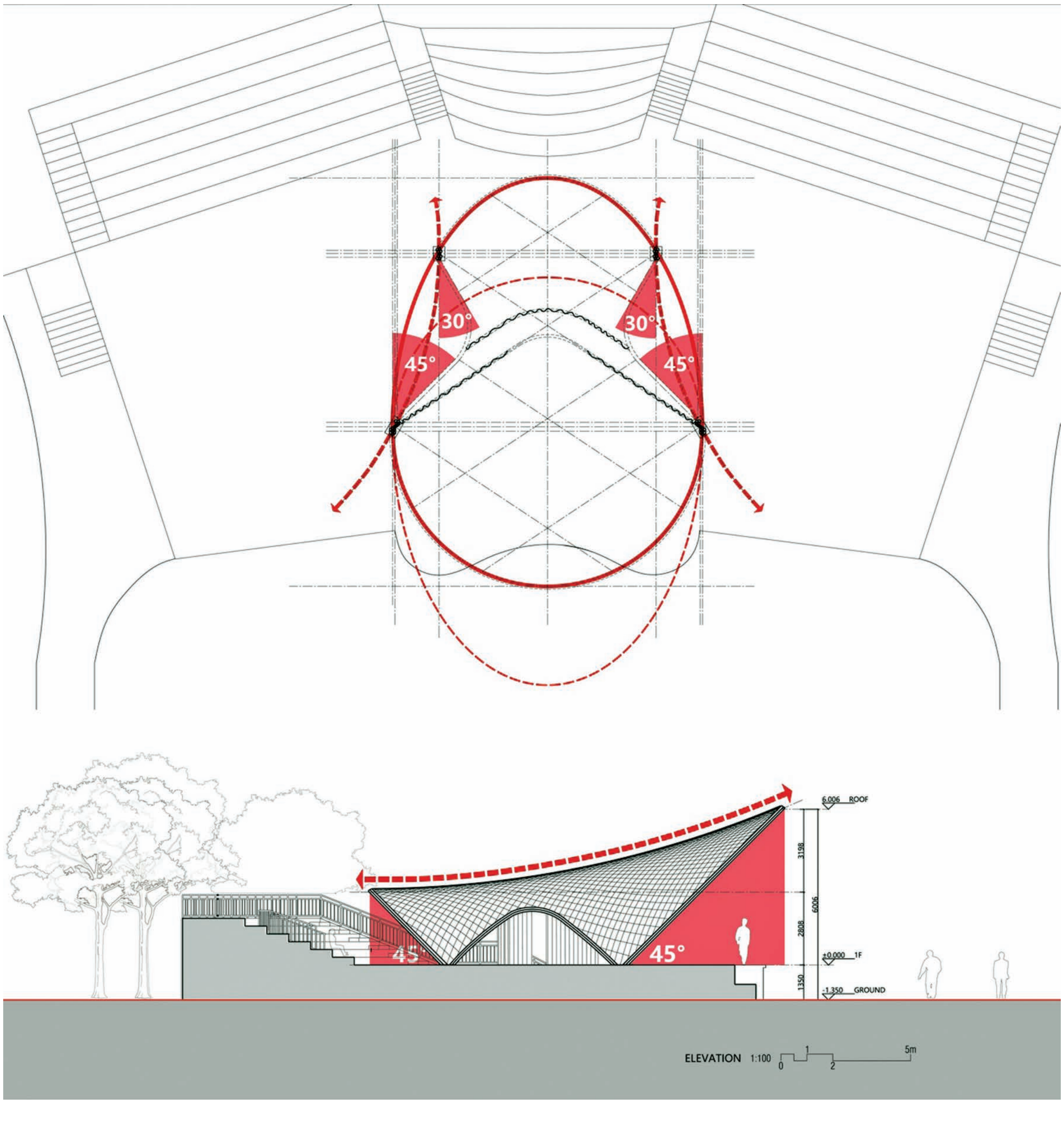
cantilevered canopy angled at 45 degrees. The form corresponded to the function of the stage, as its various parts—center stage, backstage and both wings—fell into areas identified by their differences in height. The tall and bright space was for the downstage, while the lower space was for the backstage. They were interconnected, yet not interfering with each other (Figure 6). Geometry of the plan consisted of a semi-ellipse and a semicircle, with their tangent intersection points combining the two, as the short axis of the ellipse was consistent with the diameter of the circle. Following a similar geometric rule, the form of the elevation was defined by an arc ridge (Figure 7). The overall shape resulted in smooth curves within the range of bending radius that bamboo could reach, which ensured the feasibility of fabricating with bent bamboo poles.

FIGURE 7. Generation of form for Bamboo Canopy.



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Structure

Once the form had been conceived from the perspective of architectural design, it was even more critical to develop the structural strategies for lightness. The pursuit of lightness meant precision and the ultimate in structural art, as was the case with Felix Candela's Los Manantiales Restaurant (Figure 8a), an experiment for light construction built in Mexico in 1958 that was known for a sense of lightness brought by the thin concrete shell structure. We were greatly inspired by the wing-like form of hyperbolic paraboloid that he used to create the roof. We found that the case of Luum Temple had taken cues from Felix Candela's catenary reinforced concrete shell work, making a five-sided bamboo structure with arched vaults that co-existed in structural dependency (Figure 8b). Although this case study provided very useful information in constructive aspects, it was not sufficient to solve several major problems we faced that were crucial to making the shell thinner and lighter: first, limit to the span of bamboo ellipse arch; second, the double-curve surface with upturned roofline instead of a standard hyperbolic paraboloid surface; third, the beams made of round bamboo canes instead of bamboo splits; fourth, the bamboo lattice woven together by a diamond-shaped pattern instead of a triangular pattern. These aspects led us to further explore the structural limits of bamboo in our design.

Bamboo is mechanically more efficient when it is compressed or stretched in the longitudinal direction, and the required diameter is relatively small. In contrast, it is less efficient under flexural strength and the required diameter is larger. In the choice of the bamboo canes of varying sizes, we separated different types of structural members based on force analysis. Each of the four arches stretching to the ground was constituted with either 7 or 4 canes of φ80 Moso bamboo (80mm in diameter) bound together (Figure 9). In doing this, the arch beams acquired a high bearing capacity, to guarantee proper transfer of bending force without kinking or buckling when they bore mainly the horizontal load (wind load and earthquake force) and partially vertical load (Figure 10). As the main arch beams leant outwards in opposite directions, a portion of their gravity loads could be balanced, thus a smaller diameter was sufficient for the other structural members, those woven with a diamond-shaped pattern. In this way, an unusual impression was given by the structural members contrasting in size. The largest one—the main ellipse arch which spanned over 12 metres with a 45-degree inclination, might seem very bold, dangerous and unstable as if it were going to overturn. This tendency was seemingly halted by a layer of slender bamboo that was quite thin. But in fact, once the bamboo shell was woven and formed, as a whole it bore the vertical gravity load and horizontal load with higher structural stability. In other words, it was both the inclining arches and the woven bamboo lattice interlaced in opposite directions that were resisting the forces.

FIGURE 8. a) Felix Candela and Los Manantiales Restaurant; b) Elevation of Luum Temple indicating the structural pattern.

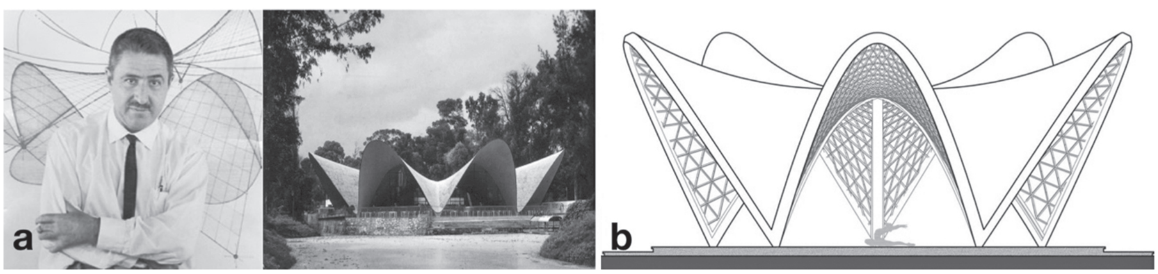

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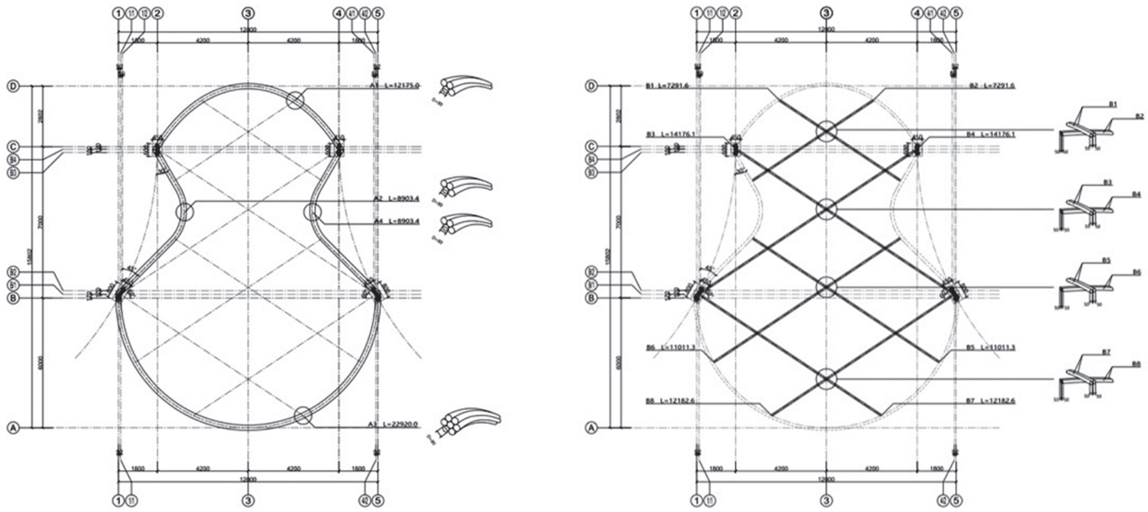
FIGURE 9. a) Plan showing the four arches, with sections through the bamboo beams; b) Plan showing the structural members, with sections indicating the joinery system.



Together those tightly-woven smaller members worked better than a sole larger beam. In order to optimize the span of bamboo arches, we took great advantage of the structural properties of gridshell, which were effective to provide cover for a large area with minimal use of material. With the help of the numerical simulation, deflection, stress and force flow analyses of the structure under different types of loading were studied (Figure 11). Comparing the numerical results, it was visualized and concluded that the structural performance is optimal with suitable arrangement of the woven lattice. Their relative value was crucial, through which we were able to figure out the distribution of load on the gridshell, and the portion of the load that every curve segment would have to resist. Instead of Moso bamboo, the Red Sheath bamboo (*Phyllostachys iridescins*), each of 50mm in diameter, was adopted for the woven bamboo lattice to achieve an optimum solution for increasing the lightness. These structural members were arranged in parallel at a distance of 500mm. Although a single cane of bamboo with such a small cross section had little lateral resistance in itself, when woven together in the structural form of gridshell, they were made the most effective use of to play a significant role in lateral resistance, as well as to avoid sliding off the beams in case of splitting. To further strengthen the woven bamboo lattice, the structural members were reinforced every 4.5 metres, with 2 canes of φ50 bamboo bound together, which were reliable for the maximum 12.4-metre span of the canopy. The two were placed flatwise so as not to increase the thickness of the shell. These structural members in smaller size made the construction process less complicated, as all bamboo pieces could be fabricated on-site, allowing each piece to be installed by the local builders without any equipment operation.

The curved members were prestressed during the process of bamboo being bent into an approximate curve, which could introduce a tensile force while providing support to the shell roof. Flat sections of bamboo beams were bent on-site, and then screwed and strapped together to create the canopy. The four main arches at the edge of the shell were installed first, whose endpoints were the points that touch the concrete foundation. The anchor points to the foundations, with mortar being injected into them, increased the bending stiffness to gravity and horizontal forces. The other bamboo poles were installed subsequently by site workers, who were to determine the state of tension or compression at each bamboo pole end. After checking the

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FIGURE 10. Studies of reinforcement of the beam; buckling analysis (above) and stress analysis (below) shows that an optimized solution could increase the ultimate bearing capacity by 68.8%.

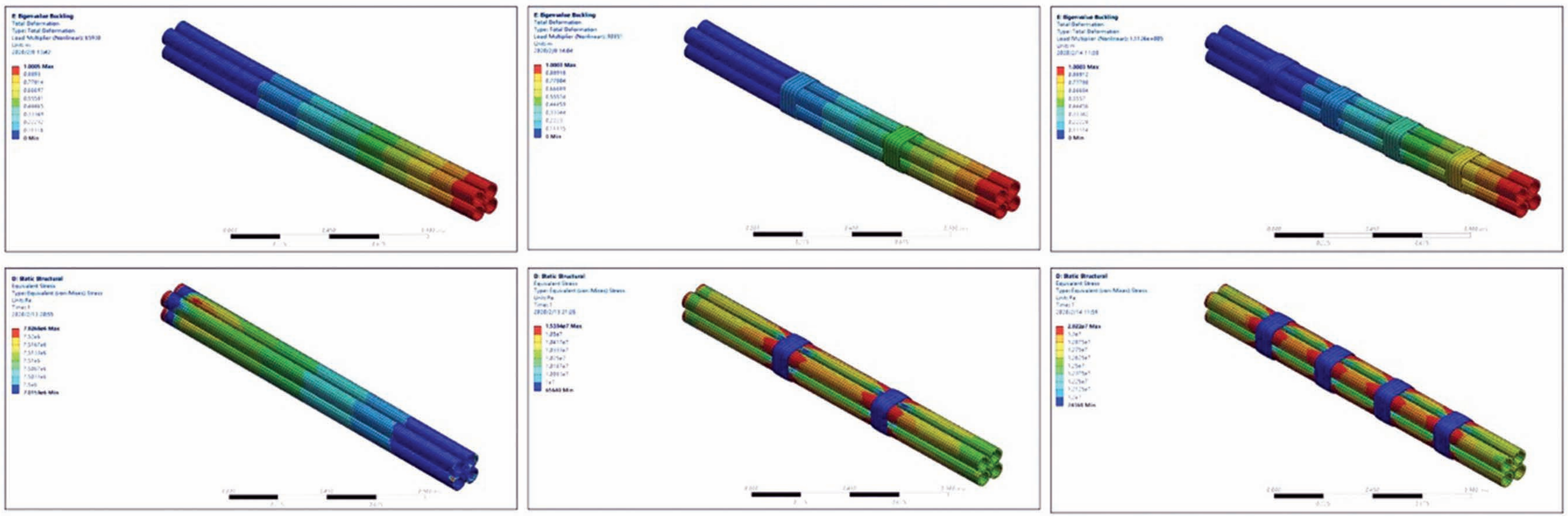

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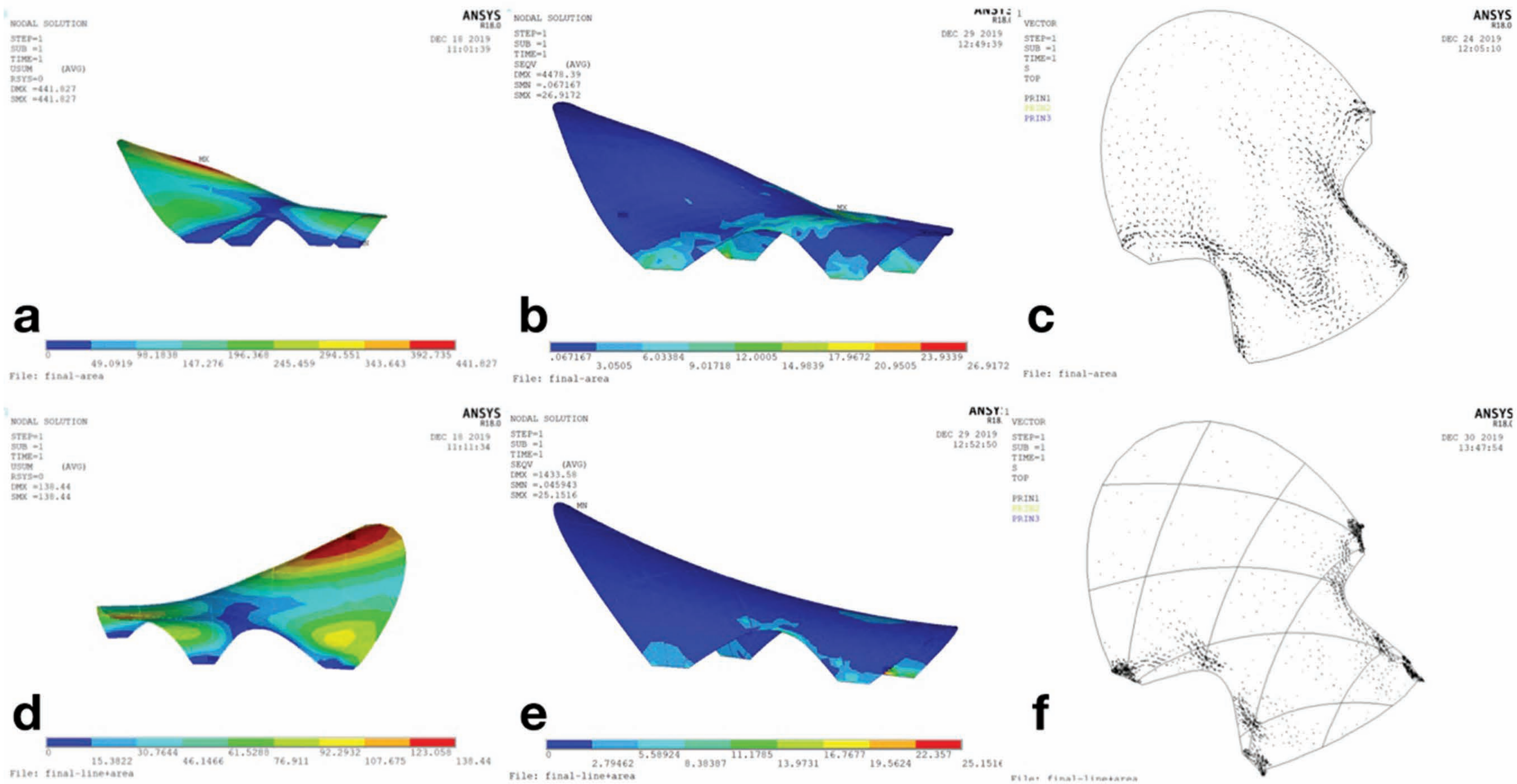
FIGURE 11. Comparative study between the double-curved surface (above) and the woven gridshell (below), with the deflection analysis (diagram a & d), the Von Mises Stress analysis (diagram b & e), and the force flow analysis (diagram c & f).



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heights of the arched vault, they made adjustments to the contact edge of the pole, and drilled a hole into the key connection joints to the main arch beam: doing this exerted a compression strength on the resilient material. The intersection points of crossing members were installed onto one another, whose joinery depended on vernacular techniques of tying the poles with coir rope. Thus, the bending moment could be released from the hinge joints, which also contributed to reducing the size required for structural members. For such joinery, the unloaded woven arches had to be pre-cambered during construction, to avoid the appearance of sagging when loaded.

Details

Deviated from the sense of thickness and heaviness often found in thatch roof of bamboo architecture, we proposed to use the simplest and lightest construction to complete the coverage. The selected design had been developed through a series of studies that iteratively solved structural and spatial issues (Figure 5). At each step, internal bending forces were transferred continuously in between members until a greater level of structural slenderness and clarity was reached. The first models started with a trapezoidal set-up where a roof cover rests on a series of arches. By the following design iteration, operations had been intuitively introduced that broke with the typical procedural logic of scaling and subdivision; geometry was bent onto itself and enclosed in a more complex manner to gain strength. Finally, a rigid and strong result was achieved in which the structural system had transformed into a hybrid containing a diagrid doubly curved roof shell.

The shell's primary structure was envisioned to be braced and clad with a secondary bamboo diagrid. Both were generated by a diagonal plane grid, whose main axes were moved by equidistant translation, and then projected onto the double curvature surface to define the framework of the gridshell, thus replacing the commonly triangulated grid (Figure 12). Once the arches were raised, they were woven together by a structural diamond-shaped pattern and then further bound by a continuous layer of tightly woven bamboo lattice, interlaced in opposite directions for structural stability. The roof was actually ultra-thin, though it was made of a number of levels: bamboo mat, plywood, waterproof breathable membrane, and wood shingles

FIGURE 12. Installation process indicating the primary structure.

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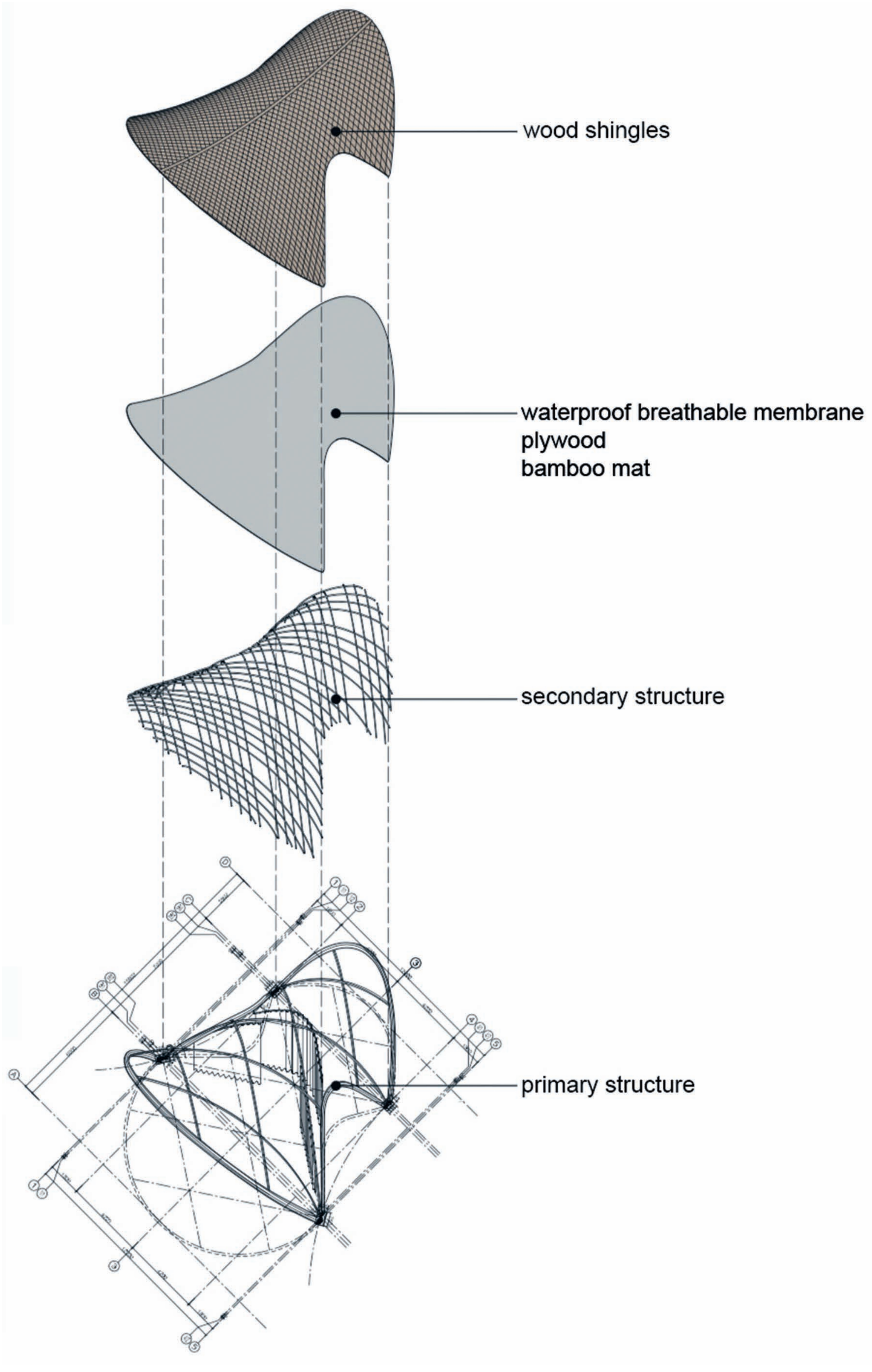
FIGURE 13. Construction of the roof.



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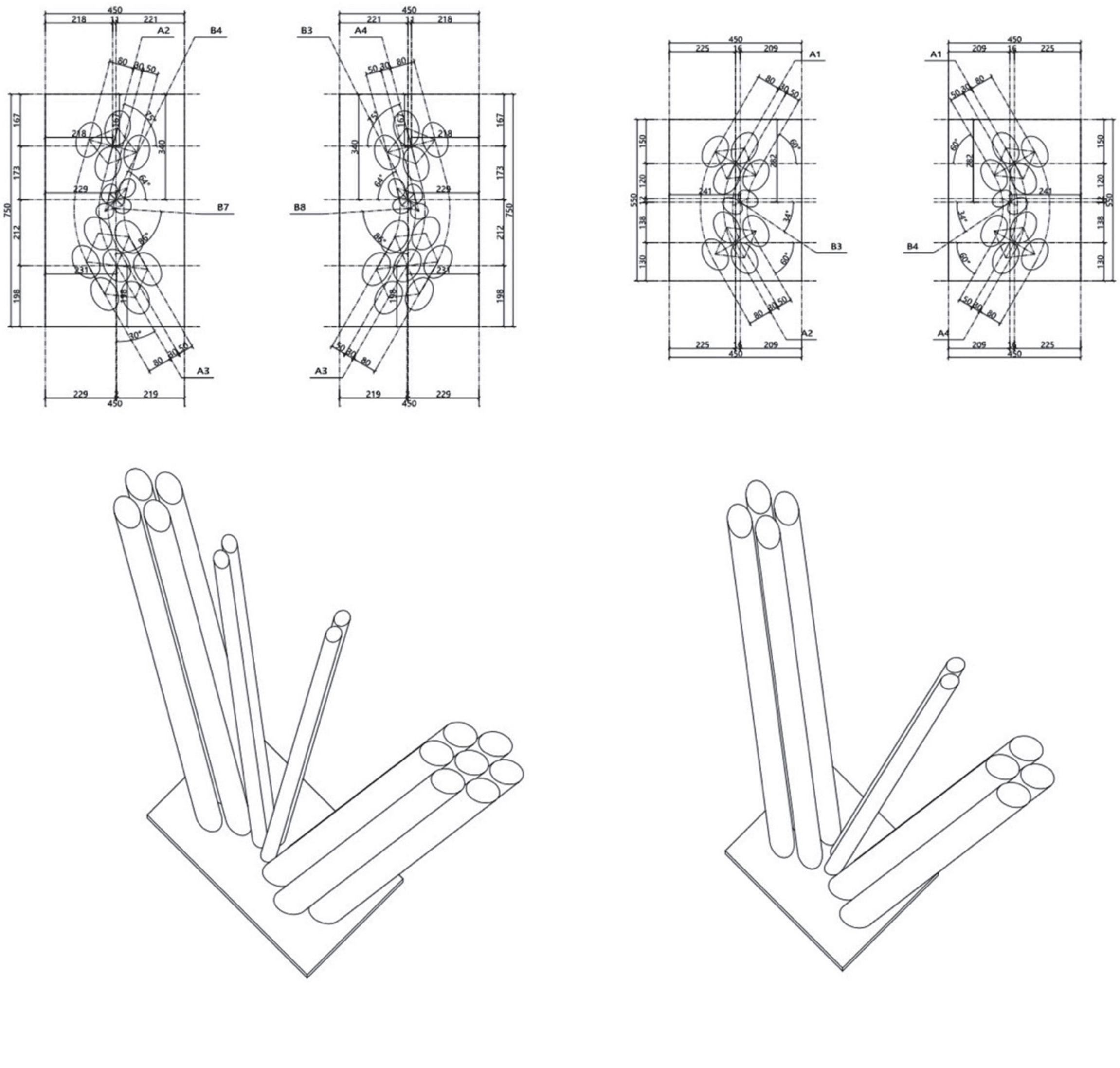
(Figure 13). The roof system emphasized the simple rule of geometry that was visible from both inside and outside. Inside, expressive geometry configurations were presented by the primary and secondary structural pattern, that used swooping lines and distorted grids. Outside, the wood shingles were also arranged in a diamond-shaped pattern, so that the roof covering corresponded with the configurations of its supporting structural members.

The entire roof was supported by the foundations consisted only of four steel bases that held the hollow bamboo poles. While the bamboo was treated, the foundations were prepared on-site. Their main purpose, as ballast, was to hold the canopy onto the ground under the substantial uplift from wind forces. The light weight and long span gave an indication of the importance of the connection detail between the bamboo structure and the concrete foundation. For each of the four steel bases, eight chemical bolts were added penetrating the concrete slab. We designed the detail to fix the bamboo using steel plinths, protruding from the steel slabs, embedded into bamboo culms (Figure 14). Every plinth needed to be unique, tailor-made to incorporate the varying angles for each of the 50 culm ends. Its positioning was defined by the diagonal grid orientation. With three sets of control lines, the arrangement of the culm ends

FIGURE 14. Foundation positioning defines the axes.



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could be accurately positioned during construction. The 50 anchor points were arranged in a compact way to achieve a minimum area of the foundations. The total area of the four steel bases was 1.2 square metres only, dramatically contrasting with the span of the cantilever.

Traditionally, bamboo construction never bases itself on conventional plans or drawings. It is a high-speed, intuitive and imprecise construction method that follows a set of basic principles and rules of thumb. These allow craftsmen to respond to the varying material properties of bamboo and to differing site conditions (Crolla 2018). The challenge, here, was to take advantage of these properties, using natural bamboo canes of varying lengths, thickness, and bendability, as well as an approximative process, to materialize the precise plans and drawings in situ. The design team worked in close communication with local builders and an engineer who specialises in bamboo structures throughout the on-site construction. With the help of a 1:30 model, we were able to clearly communicate the geometry, curvature and form with the local builders. We worked together with them to find the reference points, axes and projection lines on the existing stage foundation. Some adjustments were made on-site during the process.

The design team also worked out the guide curves for flat sections of bamboo, whose geometry was drawn based on control points placed along the curvature, so that the bamboo poles could be accordingly bent to fit the precise shape. The local craftsmen had invented a curve ruler made of bamboo splits, with which we could draw perfectly smooth curves onto the ground. After the bamboo poles were accurately bent, they were placed behind one another and tied together to make up the long grid members. The builders made scaffolding according to the elevation of the control points, whose projection was previously marked on the ground. The bamboo poles were then pieced together and installed to the steel bases, allowing each piece to fit perfectly (Figure 15). Although there were no tools for numerically-controlled fabrication, the team and the builders arrived at a remarkably simple method in the span of a few days, which shed light on the field of relations between the knowledge of the academy and the knowledge of crafts.

FIGURE 15. Onsite installation by matching corresponding pieces.

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CONCLUSION

This essay began with the purpose of pushing the boundaries of bamboo—a material traditionally used in Chinese culture—to build a double curvature structure with a contemporary language. It recounted our experience with the design process, also involving the community in the construction process. It was a process that had been elaborated formally, technically and constructively, especially on how the work achieved a high level of structural slenderness and a sense of lightness.

The exploratory nature of the project is in the making of an abundant, versatile, resistant and ecological material—yet still little used in contemporary architecture—associated with a structural solution that allows large spans with few points of support, in which there is a refined balance between structural form, architectural space, and materiality. Another aspect of exploration lies in the explicit willingness to bridge and develop knowledge jointly among the actors involved: the university student team and local craftsmen.

The work is about the possibilities of bamboo as a material for architectural invention in the context given, characterised by low-tech, low-cost and labour-intensive properties. This is reflected in the resulting piece, which constructively engages with and builds upon local building culture. A high level of formal, structural and constructive simplicity is achieved. 150 square metres of the existing stage area is covered by the canopy while only 1.2 square metres of the area is actually grounding its surface, providing a 12.4-metre span and 6-metre length of cantilever, so that the architectural object is perceived as a shell of lightness, almost without weight, which perches on the ground in four points. It encourages spaciousness and possibilities for building with bamboo, which opens a promising area of opportunity to the locals and the sustainable bamboo industry as a whole.

FIGURE 16. Top view.

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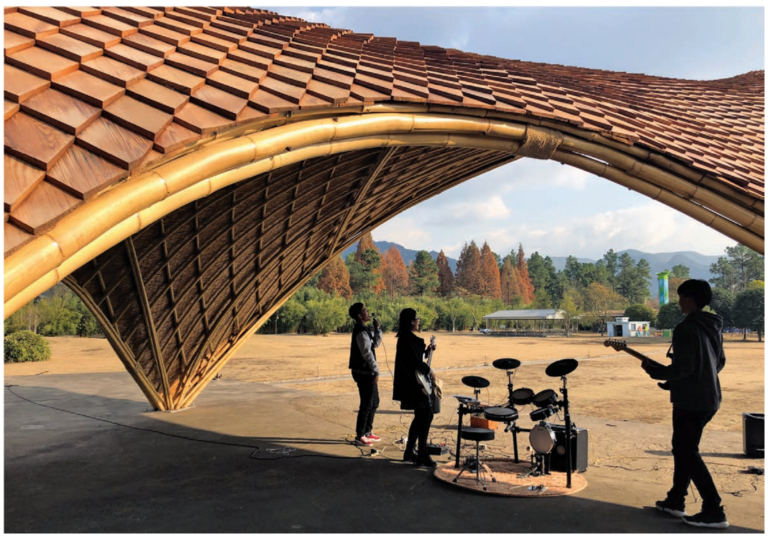
FIGURES 17–19. Exterior View.



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FIGURES 20–21. The project in use as a stage.

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Project credits

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Figure 4: Cleveland Museum of Art, 'The Garden for Solitary Enjoyment', accessed March 13, 2020, https://www.clevelandart.org/art/1978.67

Figure 8a: Spain Arts & Culture, 'Félix Candela, 1910–2010: A century', accessed March 13, 2020, https://www.spainculture.us/calendar/420/

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