

# Machine of Bamboo



Huimin Wu, Sicheng Zhou, and Xiaonan Li

**Abstract** The design philosophy is adopted as “Machine of Bamboo”. The systematic design and construction of this work are based on engineered bamboo, connected with metal joints. This approach can make the prefabrication of elements in the factory and installation of them on-site come true. This up-to-date design concept aims to develop and apply new materials and new technologies into green buildings.

**Keywords** Engineered bamboo · Lattice column · Construction · Prefabricated

## 1 Concept Design

The design philosophy is adopted as “Machine of Bamboo”. Engineered bamboo is adopted as one of the construction materials. Considering that the mechanical properties of raw bamboo culms, known as anisotropy, is greatly affected by its moisture content, therefore the durability of which is poor. To tackle these problems, engineered bamboo has been invented [1], which could be with mass production and application. Furthermore, mechanical performances of engineered bamboo under static and dynamic loading conditions have been studied by Xiao et al. [2], Zhou et al. [3, 4], and Wang et al. [5], showing that bamboo has great potential as a building material. A house is a machine for living in Corbusier [6]. “Machine” means prefabricated, reproducible and fast propagation. Bamboo material has the ability to meet the basic durability of the buildings, embodying the nature of the machine. It is a future-oriented ecological building material, which is more suitable for future sustainable development in the background of social industrial production.

The pre-specified dimension is based on a foundation of  $3\text{ m} \times 3\text{ m}$ . The works, the pavilion building, built on the foundation is 5 m height, with projected area of  $3.75\text{ m}$

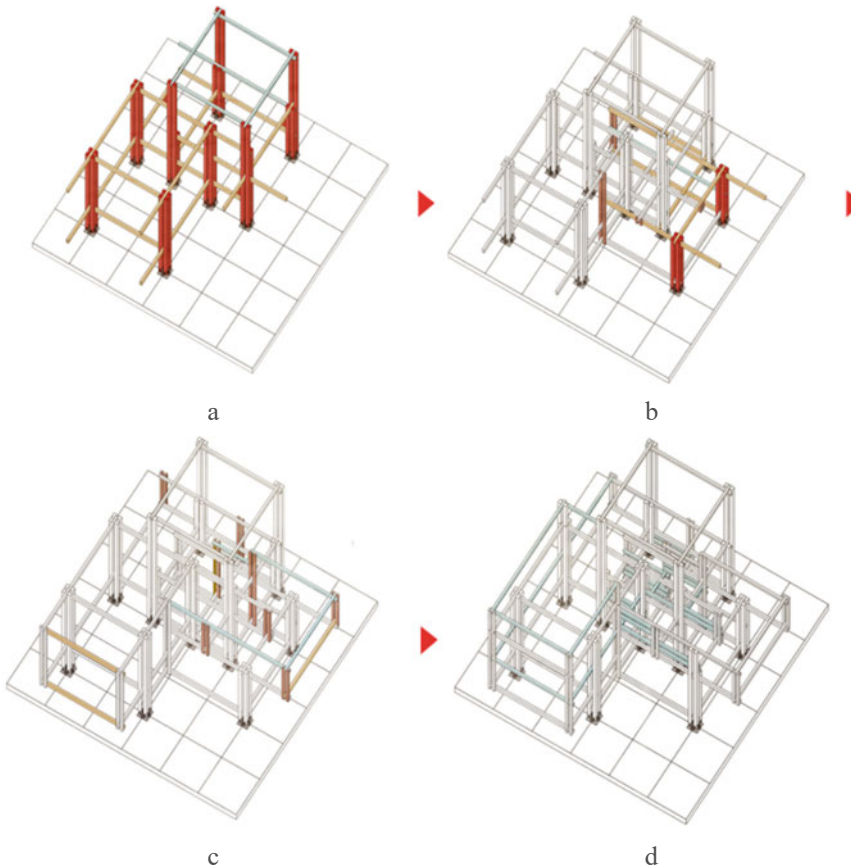
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H. Wu · X. Li  
School of Architecture, Nanjing University, Nanjing, China

S. Zhou (✉)  
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy  
e-mail: [sicheng.zhou@polimi.it](mailto:sicheng.zhou@polimi.it)

× 3.75 m. The building is made of engineered bamboo. According to its performance, industrial process, and module of engineered bamboo, 58 mm × 58 mm and 38 mm × 38 mm was adopted as sections of the main and the secondary bearing columns respectively. And 120 mm × 38 mm and 80 mm × 38 mm was adopted as sections of the main and of the secondary beams respectively. The cross-section size of 38 mm × 38 mm was selected as the section of auxiliary transverse members, such as the elevation fences. Based on the principle of the convenience of material processing and the maximization of material properties, the section size is finally determined through repeated tests, which fully embodies and makes the most of the longitudinal mechanical properties of industrial bamboo.

The main structure of the building consists of 3 frames, composed of 10 main columns. Two of the three frames are the main bearing parts, which are marked in red in Fig. 1a. And Fig. 1 shows the design logic, with different colors manifesting



**Fig. 1** Structure logic. Main structure (a); Accessory structure (b); Cantilever structure (c); Auxiliary component (d)



**Fig. 2** Model of main architecture structure

different components: main columns (red), secondary columns (orange), main beams (light yellow), and secondary beams (light blue). The design concept is that the structure regards two main frames, which have different top elevations, as the core. The third frame with a cantilever is implanted. Three frames of different heights make the whole structure rich in layering. The secondary columns, secondary beams, stair stringers, and ledges are used to set up auxiliary parts and improve the whole performance of the structure.

After the structure is designed, a manual model is made to simulate its loading conditions (shown in Fig. 2). The simulation shows that the connection of the two main frames is weak and one additional main beam (with the section of 120 mm × 38 mm) was attached to increase its stability.

## 2 Design Development

Considering that the base area is 3 m × 3 m, the layout scheme adopts 0.75 m as the basic module. The projected area of the structure is 3.75 m × 3.75 m. According to the limitation of the height (5 m), human accessible height is adopted as 3.6 m, with a local cantilever of 0.75 m (Fig. 3). The building consists of two main parts and one accessory part. The two main structural parts are divided into platform units and aisle units, connected with the accessory part. The platform units include two sightseeing zones (one inside at the elevation of 1.2 m (Fig. 4) and the other outside one at the elevation of 3.6 m (Fig. 5). A seating area is also set up at the elevation of 0.48 m of the accessory part.

The building plane is developed with 0.75 m × 0.75 m as the module and is composed of three major 1.5 m × 1.5 m units. The building facade is expanded with a modulus of 0.75 m × 1.2 m, with a human-accessible height of 2.4 m.

The facade is made of sunlight panels, as shown in Figs. 6 and 7, which are easy to install and ensure privacy and good architectural lighting. Two kinds of translucent and transparent sunlight plates were used in the main structure and the accessory corridor part respectively, strengthening the block sense of the whole building. Prefabricated steel-trellis plates were adopted as the floors and treads.

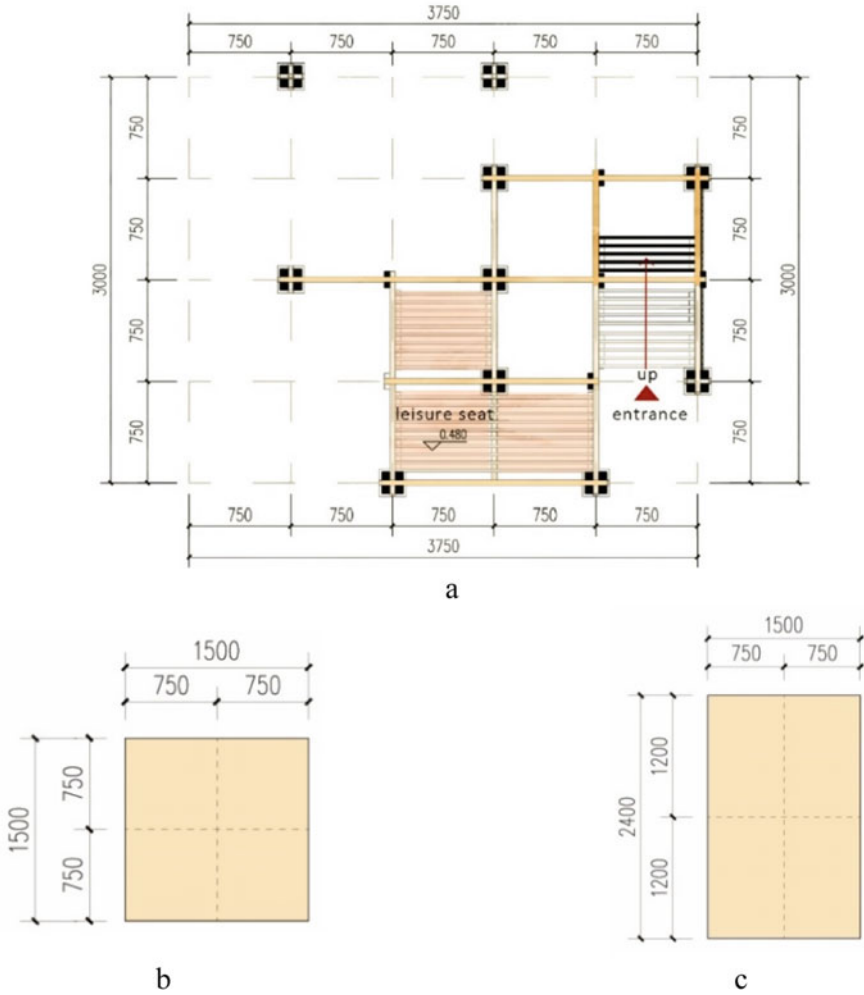


Fig. 3 Plane of 0.75 m in height (a); plan modulus (b); section modulus (c)

### 3 Construction

#### 3.1 Structural Details

Bolts are used as connecting members between industrial bamboo poles, and prefabricated metal parts are used to reinforce the main stress-concentration joints. There are two types of bolts used according to the design scheme: M8 and M10. In addition, M12 chemical anchor bolts are used to connect the columns with the base. According to the protection distance requirement, the hole diameter of M8 and M10 bolts on the

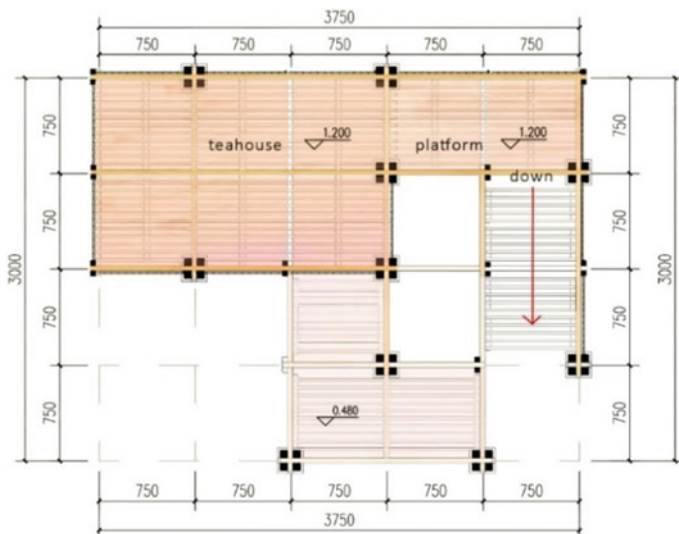


Fig. 4 Plane of 1.2 m in height

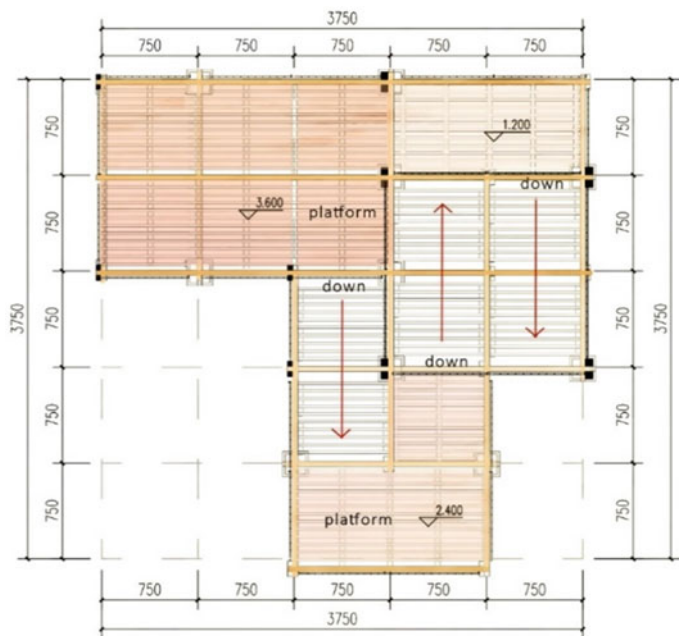


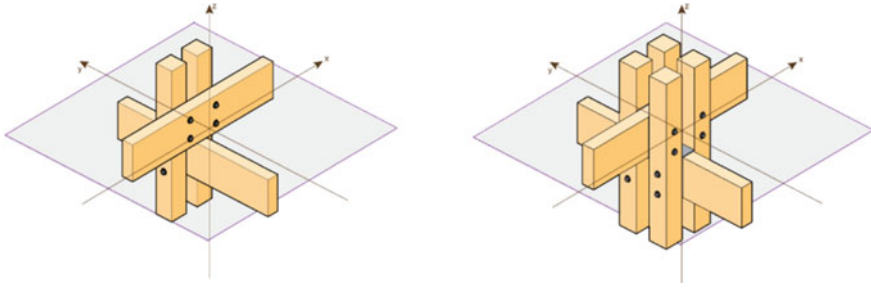
Fig. 5 Plane of 3.6 m in height



Fig. 6 Front elevation



Fig. 7 Side elevation



**Fig. 8** Details of engineered bamboo joints

rod are 9 and 12 mm, and the distance between the center points of the bolt holes is 60 mm, from the rod boundary 30 mm. Thus, the main beam with a section height of 120 mm can be connected with the vertical bar through 2 bolts, while the secondary beam with a section height of 80 mm can be connected with the vertical bar through 1 bolt. The details are shown in Fig. 8.

The steel-trellis plates are used as the building floor, and the structural connection is carried out by conventional industrial practice. The building facade is made of simple and economical sunlight plates as the enveloping, which is fixed with bamboo poles on the side by 2 mm thick angle aluminum and self-tapping screws, shown in Fig. 9.

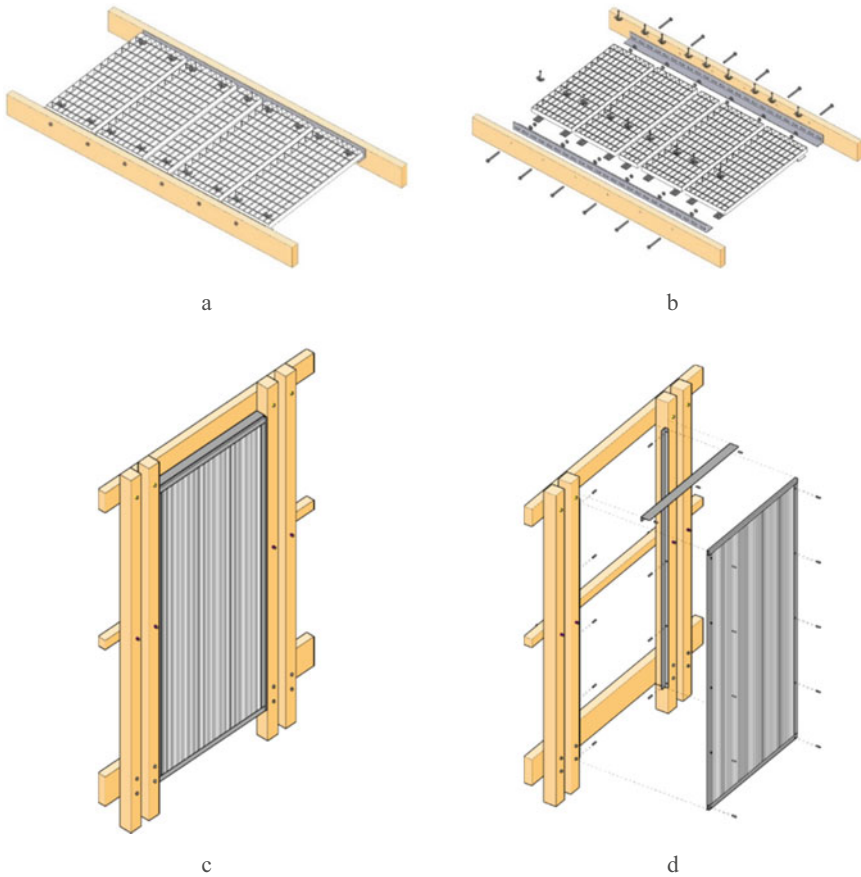
The structure was modeled, adopting information reported in Tables 1 and 2. Then, the structural system was analyzed by using SAP 2000 and the results are shown in Fig. 10.

Through the calculation, the stress and deformation limitation can be controlled under allowable value, and the structure meets the requirement of safety and serviceability.

### 3.2 Construction Procedure

The construction process is divided into two parts: pre-construction (Fig. 11) and on-site construction. The pre-construction was conducted in the manufacturing factory, to check the feasibility of the design scheme. It was done by workers in the factory, assembling the main structure. And the lattice columns were assembled and packed before transporting to the INBAR garden at the 2019 Beijing Expo.

The on-site construction was carried out by six students and two workers, taking three days. On the first day, the chemical bolts were anchored in the isolated footing. After the curing of the chemical glue, the main columns were set up and the perpendicularity was calibrated by the laser gradient. The connection component, angle aluminum, was installed, which was used to connect steel-trellis plates with main beams and connect sunlight panels with the main columns. Most of the beams and



**Fig. 9** Steel-trellis plates (a); exploded view of steel-trellis plates (b); PC sunlight panel (c); exploded view of PC sunlight panel (d)

secondary columns were assembled on the second day. During the last day, other components, including the steel-trellis plates and sunlight panels were installed. The procedure is shown in Fig. 12.

**Day 1 of the construction:** There are many problems in the construction of the foundation part: the uneven ground, the rough foundation construction, and the rain make it more difficult to put the chemical anchor and bolt reagent into the foundation, which directly leads to difficulties in the construction of the foundation on site. The chemical anchor and bolt could not be installed until the rain stopped.

The installation process (Fig. 13) includes four steps: (1) Layout the lines on a separate basis to determine the positions of the four chemical anchors on each base and to ensure that their X and Y directions are on the same line; (2) After curing at each anchor point, chemical anchor bolts were installed; (3) The top surface of the base was calibrated: double nuts are used to calibrate the plane and the level is used



**Table. 1** Load analysis

Design load		
Load name	Load value (kN/m <sup>2</sup> )	Label
Dead load	1.0	<i>D</i>
Floor live load	1.0	<i>L<sub>f</sub></i>
Roof live load	1.0	<i>L<sub>r</sub></i>
Stair live load	1.0	<i>L<sub>s</sub></i>
Load combination		
Ultimate limit state	$1.35D + 1.4 \times 0.7 \times 1.0L_f$	
	$1.35D + 1.4 \times 0.7 \times 1.0L_r$	
	$1.35D + 1.4 \times 0.7 \times 1.0L_s$	
	$1.35D + 1.4 \times 0.7 \times (1.0L_f + 1.0L_r + 1.0L_s)$	
	$1.2D + 1.4 \times 1.0L_f$	
	$1.2D + 1.4 \times 1.0L_r$	
	$1.2D + 1.4 \times 1.0L_s$	
	$1.2D + 1.4 \times (L_f + L_r + L_s)$	
Serviceable limit state	$D + L_f + L_r + L_s$	

**Table. 2** List of elements

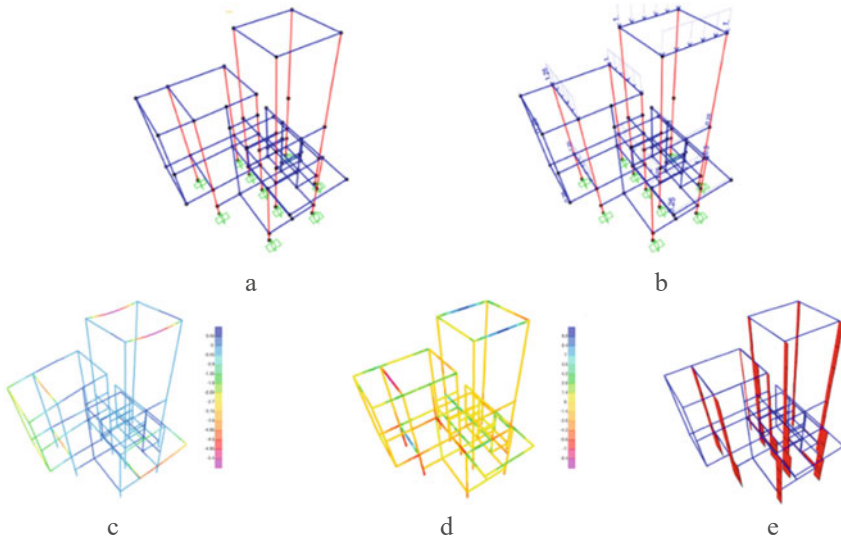
Section information	Unit: mm
Label	Size
Column 1	120 × 120
Column 2	60 × 120
Column 3	40 × 80
Beam 1	40 × 80
Beam 2	40 × 120

for measurement; (4) After the chemical anchor solidified, the main columns were installed.

**Day 2 of the construction:** According to the number of members, the main beams were installed. The frame of the whole building enhances the structural stability in the construction process. The bolts were not tightened, to adjust the construction error.

**Day 3 of the construction:** The main work of the last day was to install all the steel-trellis plates (Fig. 14a, b) and sunlight panels (Fig. 14c).

At the entrance of the building, two steps were made with red brick and slate (Fig. 15). Meanwhile, gravel blocks in the site were used to lay a stone road into the building, and red bricks were used to draw the edge.



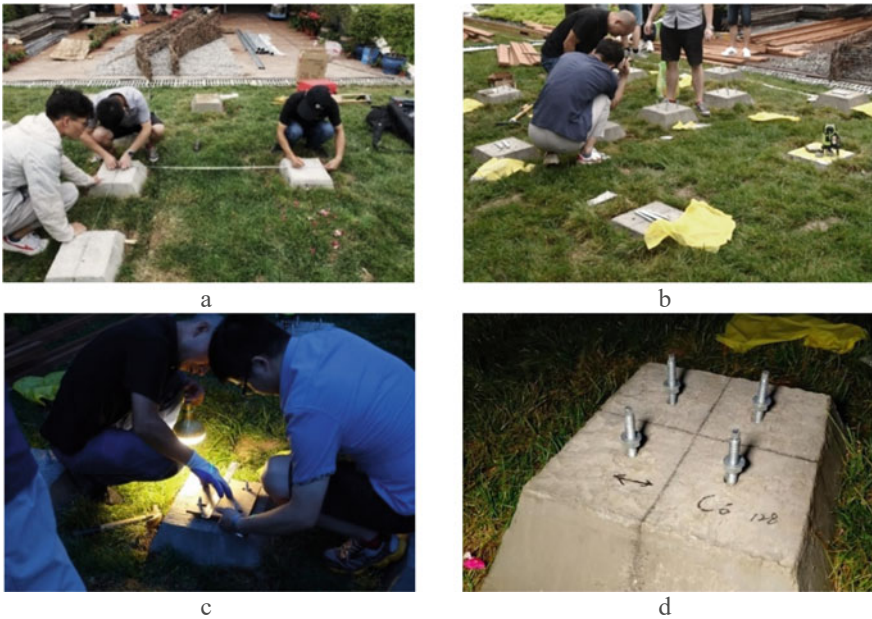
**Fig. 10** Structural analysis model set-up (a); applying loads (b); deformation (c); stress distribution (d); axial load distribution (e)



**Fig. 11** Pre-construction in the factory



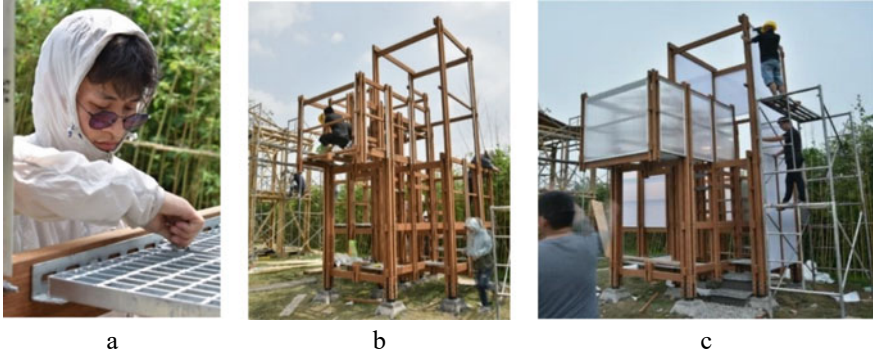
**Fig. 12** Different stages of assembling on-site. Day 1 (a); Day 2 (b); Day 3 (c)



**Fig. 13** On-site installation: lay out lines (a); drilling holes and installing bolts (b); calibration with the level (c); adjust double nuts (d)

## 4 Experience

The experience of three-days construction provides us a lot of harvest and feelings. The difficulties in the construction stage were different from those we encountered in the design stage. There were many unknown factors during the construction, such as the difficulty of multiple forms of elements, deficiencies of materials and tools,



**Fig. 14** Installing steel-trellis plates (a, b); installing PC sunlight panels (c)



**Fig. 15** Red brick drawing the edge at the entrance tread

complicated installation and etc. In addition, the rain also made our work tougher. However, as each member of us has a clear division of labor, everyone works very hard and earnestly so that we can overcome all the difficulties to complete the construction, which is our biggest advantage. It was a great experience for us to see our design from scratch, the rods, bolts, solar panels, and steel panels, to the final completion of an amazing building. Although there remained several points that needed to be improved, it had taken the first step of applying engineered bamboo as the main building structural material into practice, which is future-oriented. Next, the bamboo should be excavated at a higher height to build a higher level of the industrial bamboo building.

## 5 Renderings and Photos

Several renderings and photos of the real building are provided in Fig. 16. Figure 16a, b show the architectural rendering, which can be used as pavilions in the parks, scenic areas, etc. It is comfortable and enjoyable to have a seat and enjoy the sunshine, which shall be the top choice of a leisurely afternoon. Besides, Fig. 16c, d are the real photos of the architecture during the daylight and night. The original architecture is basically the same as the rendering.



a



b



c



d

**Fig. 16** Renderings in daytime (a); renderings at night (b); photo of the real building in daytime (c); photo of the real building at night (d)

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