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CASE STUDY

Application case of laminated bamboo lumber structure – Building of Sentai Bamboo Research Center

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Abstract: Laminated bamboo lumber (LBL) is an engineered bamboo product that provides consistent and reliable mechanical properties for structural applications while offering options for green, environmentally friendly and sustainable development. This paper presents a significant and novel case study highlighting different phases such as analysis, design and construction of a three story office building in which LBL has been used as the main building material. In this building, the main components are prefabricated and then assembled on site making the construction process fast and efficient. Hand calculation techniques were combined with finite element modeling to accurately and efficiently determine the dimensions of components. At present, the design of engineered bamboo structures is based on the standards of wooden structures, but with the gradual increase of engineered bamboo structures, it is important to develop design standards for engineered bamboo.

Keywords: Laminated bamboo lumber; Finite element model; Construction

1 Introduction

With the improvement of living standards and the global emphasis on green and sustainable development, the demand for environmentally friendly, lightweight, safe, and comfortable structures in the construction field is increasing day by day [1]-[3]. Bamboo has gained attention and research as a sustainable material that can be used as an alternative to traditional materials [4]-[8]. Bamboo family includes diverse species and can grow up to 15-30 meters within a short period of time, reaching the maximum strength within 3-8 years [9]-[11]. Harvesting time of bamboo is significantly shorter than that of wood; bamboo matures within only 3-5 years. In addition to the above advantages, bamboo offers higher strength-to-weight ratio when compared to other building materials. With a relative density of 0.55~1.01 g/cm^3, bamboo offers an average longitudinal tensile modulus of elasticity (MOE) of 8.99~27.40 GPa, and an average longitudinal tensile strength of 115~309 MPa [12]. It is worth noting that the tensile strength is equivalent to that of low-carbon steel and its strength and stiffness are higher

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than those of wooden products. Its strength-to-weight ratio is higher than that of wood, cast iron, aluminum alloy, and structural steel [13]-[15].

However, due to its natural limitations with size and structure, bamboo is not widely used in engineering applications. To overcome issues with its thin and hollow walls, researchers have developed various engineered bamboo products that offers superior and consistent material properties to be used in construction. LBL is one of the widely used engineered bamboo, which is made from raw bamboo through the process of splitting, peeling, gluing, hot pressing, etc., as shown in **Fig. 1**. LBL has attracted the attention of researchers due to its stable mechanical properties and machinable, and research on its various properties has been extensively reported. Relevant studies have shown that the flexural and compressive strengths of LBL changed with the height of the growth site of the raw bamboo [16]-[17]; the presence of bamboo nodes in bamboo strips affects the flexural, compressive and tensile properties of LBL [18]-[20], and both the species and density of bamboo have effect on the mechanical properties of LBL [19][21]. Despite the influence of the above factors, the average mechanical properties of LBL are comparable to or even exceed those of other bamboo-based materials and wood-based materials and can be processed into various types of structural components. Hence, LBL has a wider application space in the field of construction. For example, the office building located in Ganzhou, Jiangxi Province, completed in 2020 [4], and the facade renovation project located in Shaowu, Fujian Province, completed in 2023 [22], both used LBL as the main material, as shown in **Fig. 2**.

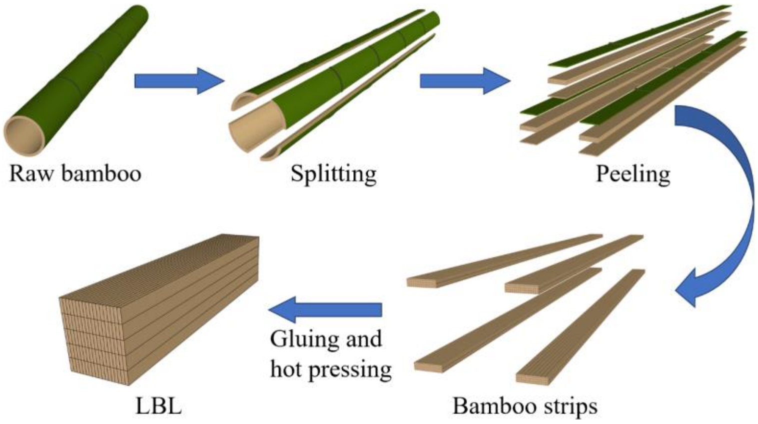


Fig. 1. Manufacturing process of LBL

(a) Office building of Sentai [4] (b) “Bamboo Cubic” [22]

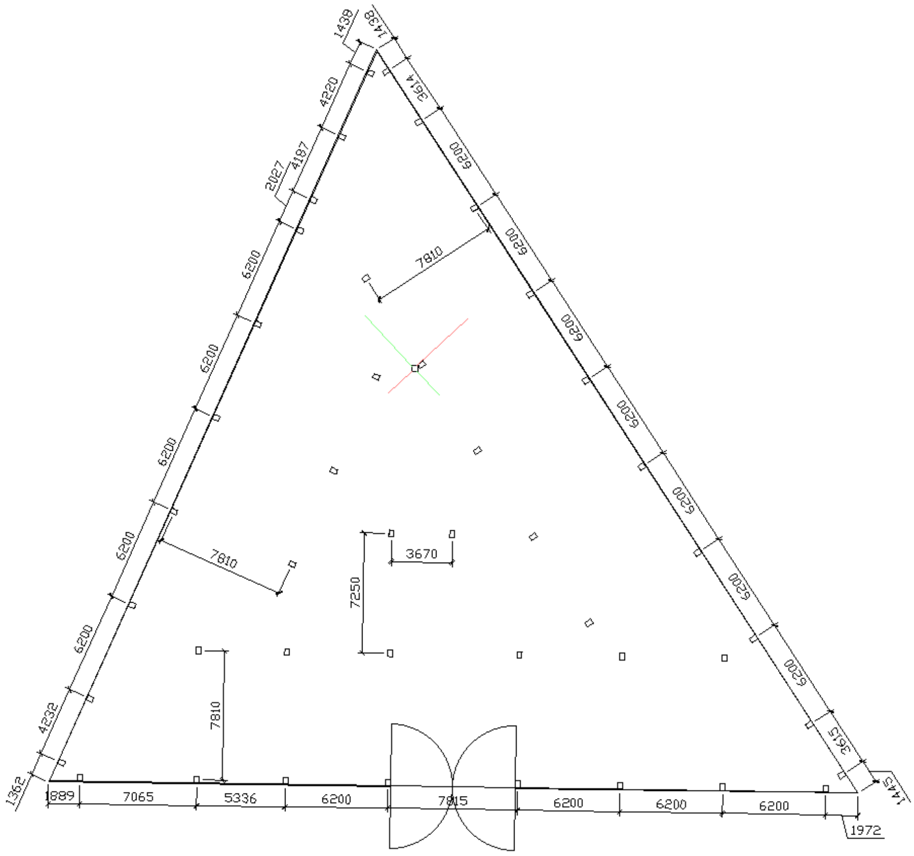
Fig. 2. Engineering applications of LBL

LBL is gaining recognition as an engineering construction material and more practical application examples of LBL have appeared in the construction field. This paper introduces an engineering case study of LBL, located in Ganzhou, Jiangxi Province. The building started construction early in 2023 and was completed in November, 2023. The structure is used as a research and development center for the bamboo industry.

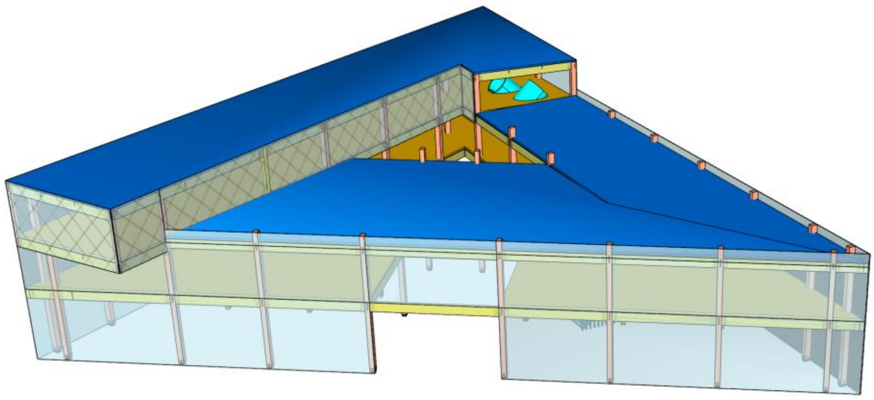
2 Layout and structural form of the case study building

The case study project is a three story LBL office building with a frame structure and a total area of 3000 m^2, which is located in Shangrao County, Ganzhou City, Jiangxi Province, China. The project is a triangular building with a cantilevered balcony on both the second and third floors. The primary material of the structure is LBL manufactured by Sentai Bamboo Co. Ltd. LBL components were connected by steel-filled plate-bolted connection; the floor slab is a lightweight steel concrete floor slab; and the wall is composed of glass panels to ensure sufficient natural lighting of the whole structure.

In this project, the shape design was carried out through CAD, SketchUp and other drawing software, and the shape schematic is shown in **Fig. 3**. A finite element model was developed and used in conjunction with manual calculation to determine the cross-sectional size of components. FE model was used to check whether the internal force and deformation of components meet the requirements of standards. If the requirements were not met, the section size and structural form were modified to ultimately determine the section size and structural form that can meet the internal force and deformation requirements.



(a) Layout of the first floor



(b) Mass model showing the complete building

Fig. 3. Schematic of the case study building

A large amount of LBL was used in this project. According to ASTM D143 [23], the mechanical properties of LBL were designed and tested. The basic mechanical properties obtained from test results of LBL are listed in **Table 1**.

Table 1. Mechanical properties of LBL [24]

	Compression parallel to grain	Compression perpendicular to grain	Tensile parallel to grain	Tensile perpendicular to grain	Shear parallel to grain	Bending
Strength/MPa	71.6	16.5	84.5	4.15	13.9	92.6
Elastic modulus/MPa	9680	1867	7013	-	8658	7999

3 Development of the Finite Element Model (FEM)

3.1 Material parameters

In FEM analysis, whether importing or constructing a 3D model, the first step is to define the materials used in the model. The main building material used in this project was LBL, which was an orthotropic material that is not readily available in the material library. Material characteristics were defined using input parameters such as mass density, weight density, three elastic modulus, three Poisson's ratios, and three shear modulus.

3.2 Section definition

The cross-sections of all LBL components were rectangular. The initial section sizes were defined in the corresponding section definition interface, and the structure was analyzed until the section size met all requirements and produced a sound structural design. This type of trial and error process was adopted for the whole building.

3.3 Load values

This project is located in Shangrao County, Ganzhou City, Jiangxi Province, with seismic fortification intensity of 7 degrees, design basic seismic acceleration of 0.10 g, and design seismic grouping of the first group. The building site category is Class II and the ground roughness is Class C. Based on the geographic location and the occupancy level of the building, the following loads were considered in the design process - the live load on the floor 3.0 kN/m^2, the live load on non-accessible roofs 0.5 kN/m^2, the live load on accessible roofs 2.0 kN/m^2, the basic wind pressure 0.45 kN/m^2 (once every 100 years), and the basic snow pressure 0.00 kN/m^2 (once every 100 years).

3.4 Load combination

When using FEM for structural modeling and calculation, the Chinese standards GB/T 50011 [25], GB 50009 [26] and GB 55002 [27] were followed to determine the relevant combinations of loads.

a) Standard combination of load effects: 1.0D+1.0L

b) Combination of dead load effect control: 1.35D+1.05L

c) Combination of live load effect control: 1.3D+1.5L

d) Combination with wind load: 1.3D+1.5L+0.9W

e) Combination with X-axis horizontal seismic action: $1.3D+0.65L+1.4Q_x$

f) Combination with Y-axis horizontal seismic action: $1.3D+0.65L+1.4Q_y$

Where D represents dead load, L represents live load, W represents wind load, Q_x represents the horizontal seismic action on the X-axis, Q_y represents the horizontal seismic action on the Y-axis.

3.5 Definition of joints

In the modeling of LBL frames, the connection between the frame and the foundation was considered as a rigid connection, i.e., defined as a fixed support. The connection between components was made of steel filled plates and bolts. The shear force of the bolts in this joint and the local compression of the LBL components formed a torque that provided some rotational restraints to the joint. Although this bending resistance did not fully meet the requirements of a rigid joint, it can be approximated as a rigid joint.

3.6 Applied load

A uniform surface load of guide load to the frame was applied to the second and part of the third-floor slabs, the dead load was taken as the self-weight of the concrete floor slab plus the self-weight of the floor construction layer, and the live load was taken as 3.0 kN/m^2. Part of the third floor was an accessible roof and hence the live load value was taken as 2.0 kN/m^2. The roof was non-accessible, and therefore the live load value was taken as 0.5 kN/m^2. The exterior surface of this building was made of glass as the wall, which was subjected to wind loads.

4 Analysis and calculation

Due to the lack of corresponding bamboo structure standards, reference was made to the Chinese wooden structure design standard GB/T 50005 [28] for component stress and stability verification. The bending, compressive, tensile and shear stresses under load combinations were determined according to GB/T 50005 [28].

According to the provisions of GB/T 50005 [28], the strength design value and the elastic modulus should be adjusted under different usage conditions and design service life. The conditions that need to be considered for the LBL components in this project include: outdoor environment, use for bamboo structure, and design service life of 50 years. At the same time, the strength design value of LBL was determined according to the method provided in the standard, and required modification were made if required.

The relationship between the strength design value f_d and the standard value f_k is shown in equation (1).

$$f_{\mathrm{d}} = \frac{f_{\mathrm{k}} K_{\mathrm{DOL}}}{\gamma_{\mathrm{R}}} \tag{1}$$

K_{DOL}—The load sustained effect coefficient of LBL strength, based on existing research results, K_{DOL}=0.62;

γ_{R}—Partial coefficient of resistance.

According to the experimental statistical data, the coefficient of variation of material strength was obtained. The partial coefficient of bending strength for each grade of engineering bamboo was 1.32, the partial coefficient of compressive strength parallel to grain was 1.25, the partial coefficient of tensile strength parallel to grain was 1.45, and the partial coefficient of shear strength parallel to grain was 1.30. In addition, considering that the strength test data for engineered bamboo was not yet sufficient, and the engineering experience was slightly insufficient, the strength values were multiplied by a reduction factor of 0.9.

After substituting the data in **Table 1** into equation (1) to obtain the corresponding calculation results, the results were compared with the strength design values under the corresponding elastic modulus specified in Table 6.2.1-1 of the standard. If the calculated value was less than the specified value, the calculated value was taken as the strength design value of LBL. If the calculated value was greater than the specified value, the specified value was taken as the strength design value of LBL. The corrected results for the strength of LBL are shown in **Table 2**.

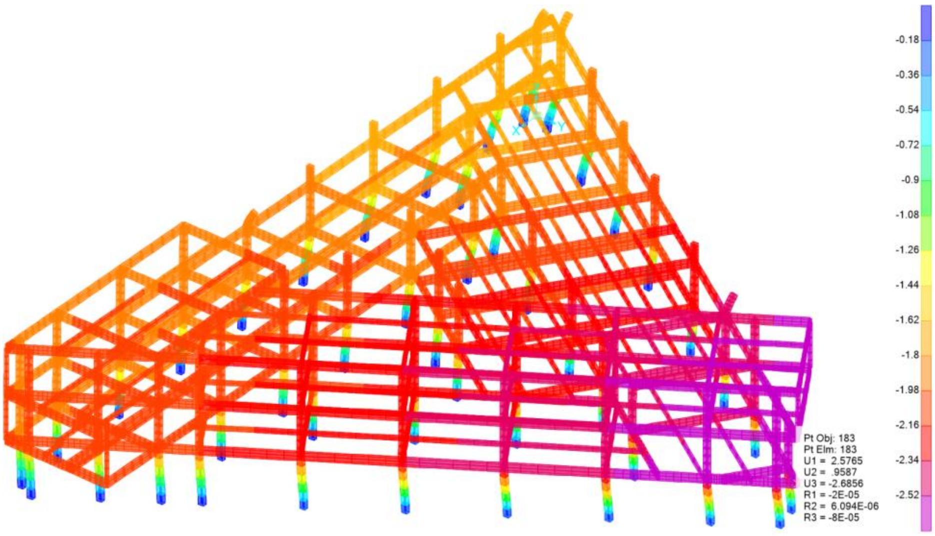
The strength of the component calculated according to GB/T 50005-2017 [28] shall not exceed the corrected allowable stress in **Table 2**.

The deformation contours obtained from the FE analysis of the LBL frame under various load combinations are shown in **Fig. 4**. Under wind load, the maximum deformation in the Z-axis direction of the frame beam occurred at the overhang of the second-floor slab as shown in **Fig. 4** (a), with the maximum deformation of 2.69 mm. At this point, the cross-sectional size of the beam was 580 mm × 200 mm, and the overhanging lengths of the two beams were 1800 mm and 1300 mm, respectively. The deformation of the frame in the X-axis direction under earthquake action is shown in **Fig. 4** (b), with the maximum inter story displacement of 18.2 mm, located at the top of the first-floor column. The cross-sectional size of the column was 400 mm × 300 mm, and the height of the column top was 4500 mm.

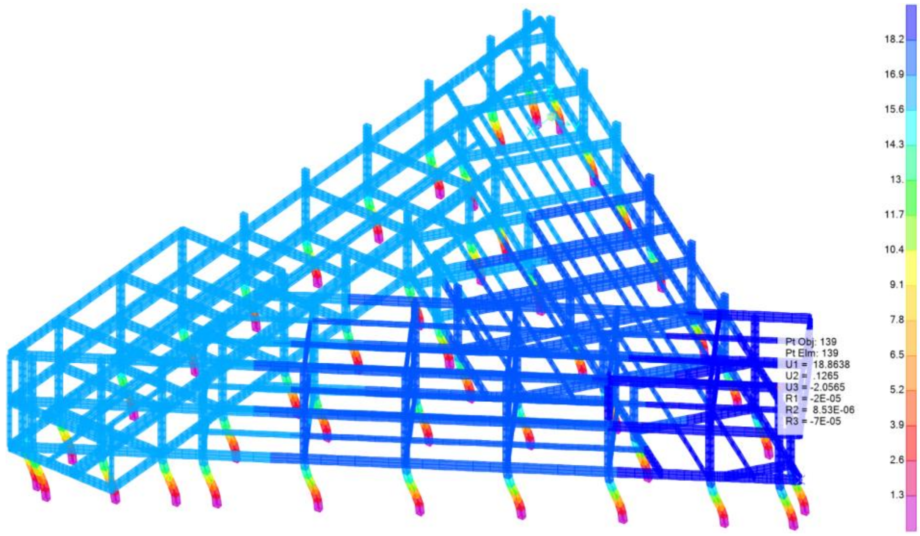
Table 2. Correction of strength and elastic modulus

Type	Use	Unmodified stress f_d (MPa)	Open-air [C_1]	For bamboo structure [C_2]	Design service life of 50 years [C_3]	Modified allowable stress f_a (MPa)
F_b	Bending	37.6	0.9	0.9	1	30.46
F_c	Compression	27.8	0.9	0.9	1	22.52
F_t	Tension	30.8	0.9	0.9	1	24.95
F_s	Shear	3.8	0.9	0.9	1	3.08
E_c	MOE	9680	0.85	1.0	1	8228

Note: C_1 is the strength adjustment coefficient for material in the open air; C_2 is the strength adjustment coefficient for material used in bamboo structures; C_3 is the strength adjustment coefficient for a design service life of 50 years.



(a) Z-axis deformation of frame under wind load



(b) Frame X-axis deformation under earthquake action

Fig. 4. Frame deformation contour diagrams

The model was analyzed using the developed FE model and the internal force values and corresponding deformations were determined under various load combinations; the members with the largest internal force and deformation were substituted into the corresponding calculation formulas to carry out strength and deformation calculations, and to verify whether the materials and sections selected for the project met the requirements and whether the design was reasonable. The verification results are shown in **Table 3**.

Table 3. Verification results

	f_c (MPa)	f_{cs} (MPa)	f_b (MPa)	f_t (MPa)	f_s (MPa)	Deflection (mm)	θ_{max}
Case	d)	d)	d)	d)	d)	d)	e)
Calculation	4.88	5.49	30.21	0.02	0.84	2.69	0.004
Allow	22.52	22.52	30.46	24.95	3.08	5.2	1/250
Result	Y	Y	Y	Y	Y	Y	Y

Note: Case corresponds to the load combination classification of Section 3.4. Y indicates that the calculation results meet the requirements. f_{cs} represents the compressive strength corresponding to the checking stability. f_{bs} represents the compressive strength corresponding to the checking stability. θ_{max} corresponds to Maximum interlayer displacement angle.

According to the verification results in **Table 3**, it is observed that the results of various mechanical indicators of the frame are all less than the allowable values specified in the standard, the deflection was within the range of L/250 specified in the standard, and the maximum inter story displacement angle was less than 1/250, indicating that the design and section selection of the frame were reasonable.

After FEM analysis and result verification, the cross-sectional dimensions that meet the strength and deformation requirements specified in the standard were obtained. The section size of the column was 400 mm × 300 mm, the section size of the main beam was 580 mm × 200 mm, and the section size of the secondary beam was 300 mm × 150 mm.

5 Construction

After determining the cross-sectional dimensions of each component based on the calculation results of FEM, steel-filled plate-bolt connection forms were designed at each joint. LBL components were prefabricated in the factory, and slotted and drilled holes at the corresponding locations of the components according to the size of steel filler plates and bolts at each joint as shown in **Fig. 5**. Prefabricated components were transported directly to the construction site for assembly.

Fig. 5. Prefabricated components

As the construction site was located in Jiangxi Province, the termite hazardous area level reached Z4, so it was necessary to implement various termite prevention and control measures in accordance with the relevant provisions of GB/T 50005 [28]. Before assembling the structure, it was necessary to level the ground of the building site. In this building, a foundation combining reinforced concrete and bricks was used to achieve the purpose of leveling the site, and met the requirement that the difference in height between the indoor and outdoor floors of the building should not be less than 300 mm, as shown in **Fig. 6** (a). At the same time, the steel connectors for fixing LBL columns were pre-installed at the column foot locations, and this connector was used as a cushion plate to achieve the purpose of waterproofing and moisture-proof at the base of the column. After the concrete had cured for 28 days and fully hardened, the LBL columns were lifted and fixed by bolts as shown in **Fig. 6** (b). Effective measures such as drainage, waterproofing and damp-proofing to prevent water and moisture intrusion from the ground were also required around the foundation.

(a) Foundation using concrete and bricks

(b) Installation of LBL columns

Fig. 6. Foundation and erection of LBL columns

After the columns were installed in place, a forklift was used to transport the components to the site, and then a small crane was used to lift the LBL beams to their corresponding locations where beam ends were connected using bolts; the whole process is shown in **Fig.7**. As the beam-column connection and beam-beam connection were in the form of steel-filled plate-bolt, the purpose of fireproofing of metal connectors can be achieved by blocking the bolt holes with wood plugs and filling the connecting joints with fireproof blocking materials according to the relevant provisions in GB/T 50005 [28].

(a) Forklift transportation

(b) Crane lifting

(c) Fixation

Fig. 7. Beam installation process

The beam installation process was repeated until all beams and columns were in place, and the main framing arrangement was complete. In the next stage, the rotating staircase was installed at the pre-determined location using LBL, and a fire separation should be provided at the intersection of the first step tread on the top and bottom of the staircase and the floor cover. The floor slab was a light steel concrete floor slab composed of profiled steel sheets and concrete. The thickness of profiled steel sheet was 1.4 mm, and the total thickness of the concrete pouring was 120 mm. In floor slabs, the factory prefabricated profiled steel sheets were first laid on the beams and connected to the beams through self-tapping screws followed by 8 mm diameter rebar mesh placed on top of the profiled steel sheet as shown in **Fig. 8**. Afterwards, concrete was poured and left to harden for 28 days before self-tapping screws were driven from the profiled steel sheet face. Horizontal fire separation should be installed inside the floor and roof, and the length or width of the horizontal separation zone should not exceed 20 meters, and the area of the separation should not exceed 300 square meters.

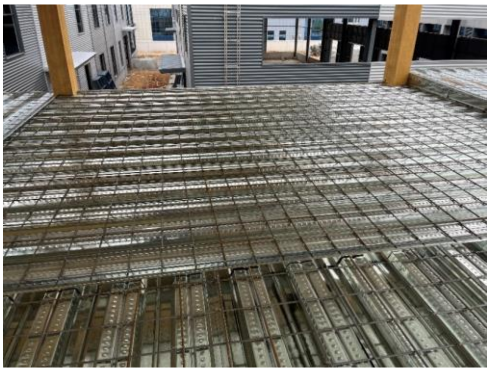


Fig. 8. Rebar mesh of the floor slab.

After the completion of the floor, the installation of the glass curtain wall and the internal wall of the building was carried out, in which the glass curtain wall was designed, produced, installed and accepted in accordance with the “Technical code for glass curtain wall engineering” (JGJ 102 [29]). After the wall panels were installed in place, the interior of the building was finely decorated, as well as the installation of wires and water pipes. Since the building was located in an area with termite hazardous area rating of Z4, surface treatment was carried out on all LBL components. The surface of the bamboo was cleaned to ensure that there was no oil, water, dust, etc. followed by application of varnish. Then, insect and preservative agents were applied to the surface of the components, and finally fire-resistant coating was applied. Finally, outdoor fire-retardant coating was applied. The application technology of outdoor fire-retardant coating referred to the relevant requirements of T/CECS 807 [30]. At this point, the construction of the three story LBL office building was completed. **Fig. 9** shows some typical photos of the entire construction process.

(a) Installation of columns

(b) Connection of beams and columns

(c) Main frame

(d) Rotating staircase

(e) Internal wall

(f) Entrance side

Fig. 9. Photos capturing the entire construction process of the LBL building

6 Conclusion

This article presented the modelling, design and construction of a three story LBL office building in China, which is a significant case study of LBL's application in structural engineering. The cross-sectional form of the component was determined through a combination of manual calculation and FEM. Due to the lack of corresponding engineering bamboo structure design standards, this project was based on design principles of the wooden structure design standards for strength and deformation verification of the component. The main components used in the entire structural construction process were prefabricated and hence a small number of workers and a few small equipment were needed during construction. The entire construction process was very effective in reducing labor and equipment costs. Therefore, this project is a significant milestone in showcasing the efficiency and convenience of the construction of engineered bamboo structures.

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CRediT authorship contribution statement

Xin Xue: Investigation, Formal analysis, Writing – original draft. **Haitao Li**: Conceptualization, Funding acquisition, Supervision, Investigation, Formal analysis, Writing – review & editing. **Zhenhua Xiong**: Funding acquisition, Writing – review & editing. **Mahmud Ashraf**: Supervision, Writing – review & editing. **Rodolfo** Lorenzo: Supervision, Writing – review & editing. **Sarah Shuchi**: Writing – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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