Development and Application of Modular Bamboo-composite Wall Construction

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The objective of this study was to design and develop a novel type of modular bamboo-composite wall using bamboo bundle veneer/wood veneer laminated composite (BLVL) with excellent physical and mechanical properties. The physical and mechanical properties of the important component of the bamboo-composite wall, BLVL, were characterized and the thermal insulation properties of three types of walls composed of different thickness of structural layers were studied. The results showed that the physical-mechanical properties of BLVL-composite walls were excellent. For BLVL wall panels, parallel and perpendicular to the glue layer, the static bending strength and elastic modulus were 137.8 MPa and 124.1 MPa *vs.* 1.37 GPa and 1.06 GPa, respectively. The internal bonding performance of BLVL was 3.07 MPa, 3 times greater than the standard requirement. The total heat transfer coefficients for models I and II of the bamboo-composite walls were 0.46 and 0.43 W/(m^2·K), respectively, in line with the requirements of the "Public Building Energy Efficiency Design Standards" GB/T 50189-2005. The development of novel bamboo composite wall and its promotion and application in fabricated buildings have important market prospects and ecological and social values.

Keywords: Bamboo bundle/wood veneer lumber composites (BLVL); Novel wall materials; Structural design; Physical and mechanical properties; Thermal insulation performance

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INTRODUCTION

In China at present, buildings' walls are generally dominated by high-energy materials such as cement, brick, and steel. The use of environmentally friendly renewable resources from bamboo and other woods, to develop green building materials, is in line with national industrial policies. In developed countries and regions such as Europe, America, and Japan, wood is one of the main residential and commercial building wall materials (Liu and Liu 2008; Xu and Chen 2008; Susainathan *et al.* 2018; Figliola and Battisti 2019). The depletion of China's large-diameter high-quality grade timber resources, as well as the ban protecting natural forests, will affect the development of high-quality wooden wall panels.

Bamboo is widely used in the bamboo processing industry as a biomass material with abundant reserves in China. Bamboo engineering materials characterized by the use of bamboo scrimber have developed rapidly because the thermal conductivity of bamboo is much lower than that of other common wall materials (about 8% that of ordinary concrete, and about 11% that of reinforced concrete) (Jiang *et al.* 2002). In addition, bamboo has excellent physical, mechanical, and decorative properties, such that it could be used as an ideal wall material.

In recent years, bamboo engineering materials have gradually entered the construction industry. Bamboo mat laminated timber, bamboo curtain plywood, and bamboo scrimber were studied as bamboo wall materials. Fei and coworkers studied the shear properties of different cladding materials, finding that walls with bamboo scrimber as cladding have better shear strength, superior to bamboo curtain plywood and wood particle board (Chen *et al.* 2016; Li *et al.* 2016). Jiang and others used bamboo mats and bamboo curtain–laminated materials as the main raw materials to manufacture composite wall materials, studying their sound and thermal-insulation properties. The sound-insulation performance of bamboo walls was found to reach the Class III standard for building walls, and the thermal-insulation performance reached Level IV standard (Zhang *et al.* 2012).

Bamboo bundle veneer laminated composites (BLVL) are developed based on bamboo scrimber. BLVL are made of the whole bamboo bundle veneer laminated with artificial fast-growing forests such as poplar and eucalyptus by reasonable assembly and hot pressing (Hu and Pizzi 2013; Yu *et al.* 2014; Deng *et al.* 2015; Hai *et al.* 2015). BLVL have the advantages of good uniformity, high mechanical strength, good dimensional stability, and high utilization rate of bamboo based on advanced structural design and material processing technology (Zhu *et al.* 2007; Ibrahim *et al*. 2015; Ma *et al*. 2018), and can develop new products with diversified and performance design for the construction industry. In recent years, green building materials and prefabricated buildings have received increasing attention (Loss *et al*. 2016; Jean *et al*. 2017; Alwisy *et al*. 2018; Noh *et al*. 2018; Sonnick *et al*. 2018), and the application of bamboo-structured lightweight composite walls in fabricated building structures has broad prospects.

A novel modular composite for modular wall construction, with BLVL as the main component, was developed for this paper. The objective of the study was to evaluate the novel BLVL composite wall's mechanics, thermal-insulation performance and application for its use environment, aiming at providing technical support for the manufacture of wall structures using BLVL. Based on the results, thin BLVL applied to dianthus composite wall components will be identified as prospects for further research.

MATERIALS AND METHODS

Materials

Moso bamboo (*Phyllostachys edulis*) was harvested from Xiaotao Town, Yong'an, Fujian in China. Bamboo bundles, obtained by splitting bamboo tubes longitudinally, were rolled and broomed with a self-developed untwisting machine. For details, see (Chen *et al.* 2013a,b; Li *et al.* 2015). Eucalyptus veneer with a thickness of 1.0 mm, spruce-pine-fir (SPF) timbers, and polyurethane insulation material were purchased from Fujian Heqichang Bamboo Product Co., Ltd. (Fujian Province, China); Phenolic (PF) resin adhesive with solid content at 52.4% was purchased from Taier Heavy Industries Co., Ltd. (Guangdong Province, China); bamboo liquefied-resin insulation material was self-developed (for details, see Liu *et al.* 2012; 2013; Zhang *et al.* 2016).

Preparation of Bamboo Bundle Veneer Laminated Composite (BLVL)

Several bamboo bundles were woven into one large BLVL using a rubber thread, then dried together with the eucalyptus veneer, to a moisture content of about 8%. The BLVL was immersed in a phenolic resin adhesive with a solid content of 25%, and the amount of adhesive was 15% to 18%. The eucalyptus veneers were coated on both sides by a rubberizing machine. The amount of glue applied was controlled at 320 to 330 g/m^2, and it was dried after dipping to a moisture content of 8% to 10%. The symmetrical structure was paved, in order from the outer layer to the core, as a double-layered horizontal bamboo bundle, a single-layer slatted wood veneer and a single-layer vertical bamboo bundle. BLVL was made by hot pressing, and measured at 2400 mm × 1250 mm × 12.5 mm. The hot-pressing parameters were: temperature 150 to 155 °C, pressing time 1.0 mm/min, pressure 4 MPa, and target density 1.1 g/cm^3.

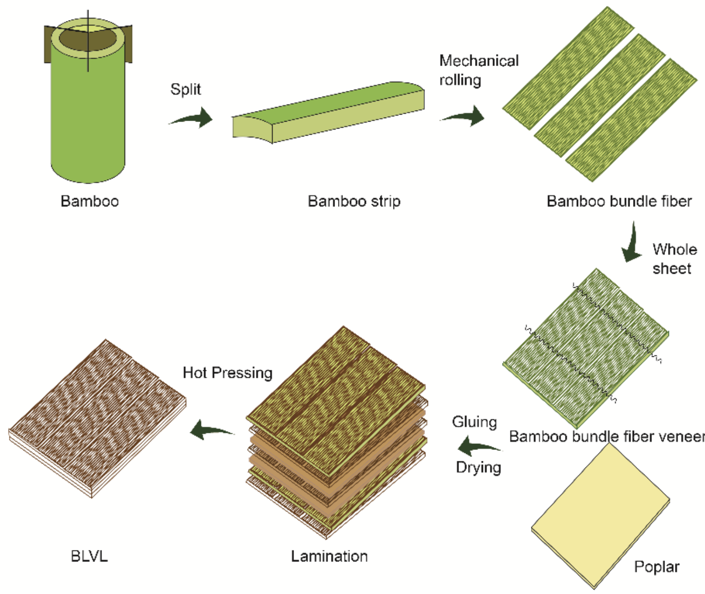

Fig. 1. Manufacturing flow chart for bamboo bundle veneer laminated composite (BLVL)

Preparation and Manufacture of Modular Bamboo-composite Wall

The total thickness of the wall material as designed in this study was 60 mm, according to the structural-design and thermal insulation–performance requirements for prefabricated houses. The material consists of three main components from the inside to the outside, namely BLVL, a layer of foam insulation, and a bamboo laminated timber decorative interior-wall layer, as shown in Fig. 2a. Three specifications were designed for evaluation of this bamboo composite wall material, in terms of thermal insulation performance at this thickness, and of the modular assembly requirements for bamboo-composite wall materials. The thickness of the structural level was shown in Table. 1.

Table 1. Design: Structural Layers in Bamboo-based Composite Wall Materials

Bamboo-based composite wall design	I	II	III
BLVL thickness (mm)	12	6	12
Core thickness (mm)	48	54	48
* The insulation in models I and II is a polyurethane foam material, and the insulation in model III was a liquefied bamboo–foam material.			

The bamboo composite wall was made of BLVL as the outer wall board, the SPF specification material as the keel, and the bamboo laminated timber as the inner wall board. They were integrally connected with the isocyanate resin to form a lightweight wall. The process of manufacturing a lightweight wall material using BLVL is shown in Fig. 2b. The bamboo-composite wall material was made up of light SPF lumber with grade II as the keel frame, connected using a steam-driven nail gun to form the frame of the sizing module. At the four corners of the keel frame, special wedge-shaped blocks were used in order to enhance frame stability. The frame was coated with isocyanate adhesive, with the glue amount at 160 g/m^2 to 220 g/m^2. The aging was about 5 minutes. Then, the sanded bamboo laminated timber–inner wall panel and the BLVL–outer wall panel were placed on the keel frame and the foam insulation materials were placed into the frame. Then the composite wall was cold pressed and held for 12 h at 1.2 to 1.5 MPa. After the wall was formed, a high-speed opening machine was used around the keel section, to open a joint assembly groove with a width of 8 to 10 mm and a depth of 6 to 8 mm. Finally, the interior-wall panel was protected through treatment in a paint booth.

(a) structure of bamboo-composite wall material

(b) flow chart showing production of lightweight wall modules

Fig. 2. Structural design and manufacture of bamboo-composite wall materials

Mechanical Properties and Insulation Performance Test

In order to investigate the feasibility of using BLVL for the exterior-wall panels, research was done regarding the mechanical properties of BLVL, and insulation-performance properties of BLVL-composite wall materials. Investigation of mechanical properties was performed in accordance with Chinese-national standard GB/T 17657-2013 before and after humidity treatment (GB/T 17657, 2013). The dimensions of samples for the static bending strength (MOR) and elastic modulus (MOE) parallel and perpendicular to the direction of the glue layer were 300 mm (length) * 50 mm (width) * 12.5 mm (thickness) and 300 mm (length) * 12.5 mm (width) * 12.5 mm (thickness), respectively. The dimensions of samples for horizontal shear test was 60 mm (length) * 40 mm (width) * 12.5 mm (thickness) (parallel to the direction of the glue layer) and 60 mm (length) *12.5 mm (width) * 12.5 mm (thickness) (perpendicular to the direction of the glue layer). The immersion stripping rate test specimen size was 75 mm (length) * 75 mm (width). The impact test specimen size was 100 mm (length) * 21 mm (width) * 12.5 mm (thickness). The internal bond strength test sample size was 50 mm (length) * 50 mm (width)

A heat flow meter (JW-III) from Beijing Oriental Aoda Instrument Equipment Co., Ltd. was used for the insulation-performance properties. The calculation of insulation coefficient for wall materials was accorded to the Chinese-national standards for thermal design code in civil building (GB/T 50176, 2016).

RESULTS AND DISCUSSION BLVL

Study of BLVL's Physical and Mechanical Properties

The main component in bamboo-composite wall materials is the wall panel. Because the service life of the wall depends especially upon the physical and mechanical strength of the exterior wall panel, it is very important to evaluate these properties based on BLVL. The basic physical and mechanical properties of BLVL are shown in Table. 2. The static bending strength and elasticity modulus (MOE) of BLVL, on the grain and transverse to the stripes, were 137.8 MPa and 124.1 MPa, and 1.37 GPa and 1.06 GPa, greater than China's national standard for sheathing plywood for timber structures (GB/T 22349, 2008). Additionally, the screw-holding force was much greater than the relevant required standard (not less than 534 N). The bonding performance of BLVL was 3.07 MPa, three times that required in sheathing plywood for timber structures. No delamination phenomenon occurred, and the bonding performance was excellent. The mechanical properties exceeded the highest requirements of GB/T 22349-2008 (GB/T 22349, 2008).

Table 2. Basic Physical and Mechanical Properties of BLVL

Wall compo-nent	Bending strength (MPa)		MOE (GPa)		Shear strength (MPa)		Screw holding force (KN)	Impact tough-ness (KJ/m^2)	Immersion stripping rate (%)	Bond strength (MPa)
	Ⅰ	Ⅱ	Ⅰ	Ⅱ	Ⅰ	Ⅱ				
BLVL	137.8	124.1	1.37	1.06	11.59	7.40	2.68	93.00	0	3.07

Note: Ⅰ is parallel to the direction of the glue layer and Ⅱ is perpendicular to the direction of the glue layer.

When using bamboo-composite wall materials, the bonding strength of each component is the key to ensuring the materials' safety. Table 3 shows the shear strength, internal bond strength, and immersion peeling test results, for inner and outer walls, under dry and wet conditions. The outer wall's horizontal shear strength, and that of the inner wall, under wet conditions, were 2.23 MPa and 1.89 MPa, respectively, which were slightly below the same values under dry conditions. However, the external wall's horizontal shear strength under dry conditions was 2.99 MPa, which was basically the same as that of the inner wall at 2.97 MPa, while the internal bond strength of the inner wall was 2.06 MPa, greater than the outer wall's 1.14 MPa. The failure mode of the wall end is shown in Fig. 3. Under the action of external force, there were two main failure modes at the end of the wall, which were the tearing failure of the wood and the pullout failure of the fixed nail. The bonding strength of both the inner and outer walls exceeded the highest requirements of GB/T 22349-2008 for internal bonding strength (greater than 0.8 MPa) (GB/T 22349, 2008). The wall showed no delamination phenomenon, and had good gluing properties.

Table 3. Basic Physical and Mechanical Properties of Bamboo-composite Wall

Wall		Horizontal shear strength（MPa）		Internal bond strength (MPa)	Immersion stripping rate (%)
		Dry state	Wet state		
Exterior wall	Upper end	3.54	2.51	1.01	0
	Lower end	2.50	2.18	1.12	0
	Side	2.92	2.00	1.29	0
Average value	-	2.99 (0.18)	2.23 (0.12)	1.14 (0.12)	0
Interior wall	Upper end	2.90	1.71	2.39	0
	Lower end	2.73	2.04	2.11	0
	Side	3.29	1.92	1.67	0
Average value	-	2.97 (0.10)	1.89 (0.09)	2.06 (0.18)	0

(a) Tearing of the wood **(b)** Pullout of the fixed nail

Fig. 3. Main failure modes of bamboo-composite wall materials

Insulation Performance of Bamboo-composite Wall Materials

Thermal resistance

Thermal resistance is a physical quantity that characterizes the heat transfer capacity of an envelope structure or a layer of material therein. The greater the thermal resistance, the stronger the material's capacity to impede heat transfer. It is calculated as follows (GB/T 50176, 2016).

$$R=\delta/\lambda \tag{1}$$

In the formula, R is the thermal resistance of the layer of material ($m^2 \cdot K/W$); δ is the thickness of the material (m); and λ is the thermal conductivity of the material, $W/(m \cdot K)$.

The wall materials were composed of the material elements in each part, so the total thermal resistance of the wall was calculated according to formula (2).

$$R=R_1+R_2+\cdots+R_n \tag{2}$$

The internal surface heat transfer resistance is 0.11 $m^2 \cdot K/W$, and the external surface–heat transfer resistance was 0.04 $m^2 \cdot K/W$.

The calculation results for thermal resistance in each layer of the bamboo composite wall, and those for the bamboo-composite wall panels' total thermal resistance, thermal resistance and heat transfer coefficient are shown in Table 4.

Design standard for energy efficiency of public buildings standard GB/T 50189-2005 stipulates that the thermal performance limit of Class A public buildings' envelope structures, in cold regions, is calculated as 0.50 of the heat transfer coefficient limit of the building envelope structure with an external body shape coefficient of ⩽ 0.3. The heat transfer﹣coefficient limit, 0.4 ⩾ external wall shape coefficient > 0.3, is 0.45 W/(m^2·K). The total heat transfer coefficients of bamboo-composite wall materials I and II were 0.46 and 0.43 W/(m^2·K), respectively, meeting the national standard–energy saving design requirements. The thermal insulation performance of wood and bamboo materials is better than that of concrete and hollow bricks. Under the same thickness conditions, the insulation value of wood/bamboo materials is 16 times higher than that of standard concrete and 3 times higher than that of hollow brick materials (Zhao 2007).

Table 4. Calculation Results for Thermal Resistance of Each Layer of Composite Wall

Wall Materials	I	II	III
Core thermal resistance of surface thermal resistance of BLVL (m^2·K/W)	0.09	0.04	0.09
Polyurethane insulation material (m^2·K/W)	1.92	2.16	-
Liquefied-bamboo insulation material (m^2·K/W)	-	-	1.41
Total thermal resistance of BLVL (m^2·K/W)	2.01	2.20	1.50
Heat transfer resistance of BLVL (m^2·K/W)	2.16	2.35	1.65
Total heat transfer coefficient of BLVL (W/(m^2·K))	0.46	0.43	0.61

Thermal Storage Coefficient and Thermal Inertia Index

When a side of a single material of sufficient thickness is subjected to harmonic heat, the surface temperature will fluctuate according to the same period. The thermal storage coefficient of a material is the ratio of the heat flux amplitude to the surface temperature amplitude across the surface. The greater the value, the better the thermal stability of the material. The greater the value, the better the thermal stability of the material. The calculation formula for heat-transfer resistance in our walls was as follows (GB/T 50176, 2016).

$$R_0=R_i+R+R_e \tag{3}$$

Here, R_0 is the heat-transfer resistance of the composite wall envelope structure (m^2·K/W), while, R_i is the internal surface–heat transfer resistance (m^2·K/W). R_e is the heat-transfer resistance of the outer surface (m^2·K/W), and. R is the thermal resistance of the composite wall envelope structure (m^2·K/W).

Table 5, which is based on the national standards code for the design of civil buildings' thermal engineering (GB/T 50176-2016), shows the specific heat value and heat-storage coefficient of: bamboo bundle veneer laminated composites, with reference to plywood; liquefied-bamboo insulation material, referring to polyethylene foam; polyurethane insulation material–related indicators.

Table 5. Insulation Performance of Each Layer of Bamboo-based Composite Wall

Index	Density (g/m^3)	Specific heat (kJ/(kg·K))	Heat-storage coefficient ($W/(m^2·K)$)	Thermal Conductivity (W/(m·K))
BLVL	1.10	2.51	4.57	0.140
Polyurethane insulation material	0.11	1.38	0.36	0.025
Liquefied-bamboo insulation material	0.20	1.38	0.70	0.034

The thermal inertia index, *D*, is a dimensionless index that characterizes the extent to which an envelope structure attenuates temperature waves. The larger the *D* value, the faster the temperature wave decays therein, and the better the thermal stability of the envelope structure. It is calculated as follows (GB/T 50176, 2016).

$$D=D_1+D_2+\cdots+D_n=R_1S_1+R_2S_2+\cdots+R_nS_n \tag{4}$$

Here, R is the thermal resistance of each layer of material ($m^2·K/W$); the heat-storage coefficient of the material on the heat-transfer area S ($W/(m^2·K)$). The heat-storage coefficient of the air member is taken as S=0.

The thermal inertia index of the three types of bamboo-composite walls is shown in Table. 6. The best thermal stability for bamboo-composite walls was found in the Type-III structure, followed by Type I and then Type II. The thermal resistance and heat transfer coefficient of the composite materials showed good thermal insulation properties, and met the requirements of national standards. In general, Type I has the best insulation performance.

Table 6. Thermal Inertia Index *D* of Bamboo-based Composite Wall

Wall models	I	II	III
Thermal inertia indicator D	1.0829	0.9734	1.3799

Indoor Thermal Environment of Prefabricated Houses Using Bamboo-composite Walls

The bamboo-composite walls obtained by our experimental research were applied in building container houses. In this test, two container houses were prepared, one a traditional iron container house, and the other a container house using bamboo-composite walls. The size and space layout of the two houses were the same, and the indoor thermal environment–test performance of the two houses was investigated. The test site was located in Lulu Town, Wushen Banner, Ordos City, Inner Mongolia, China (latitude 38.60°, longitude 108.84°).

A comparative study of traditional container houses' thermal-insulation performance and that of the new bamboo container houses was obtained for the relationship between the desert climate of Inner Mongolia and the indoor environments, in order to guide the use and promotion of container houses in "bad" environments. By arranging the temperature and humidity meters as four-channel testers on the south and north walls of the house, the temperature and humidity of the indoor test-point and the outdoor test-point were determined. The data were collected every half hour over a test period of 68 days.

Fig. 4. BLVL composite house and iron house; temperature and humidity testers' distribution

The test data for the two houses are shown in Figs. 5 and 6. The outdoor temperature changes were the same on both the south wall and the north wall of the two houses, but the indoor temperature changes were quite different. As the outdoor temperature began to decrease, the temperature inside each house tended to decrease slowly. The indoor temperature drop rate of the traditional iron house was significantly higher than that of the bamboo house.

The relative-humidity test data of the two houses are shown in Fig. 7 and 8.

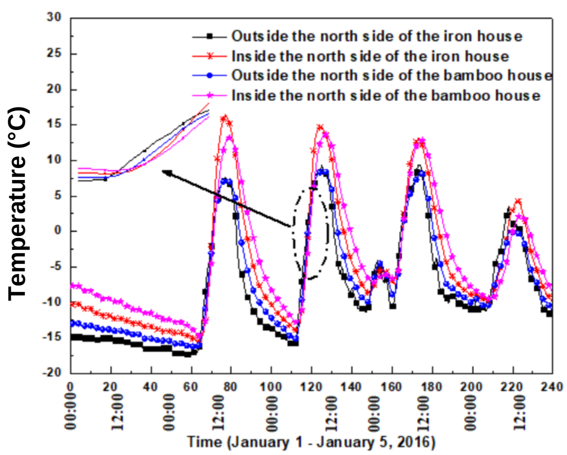

Fig. 5. Temperature comparison, north wall

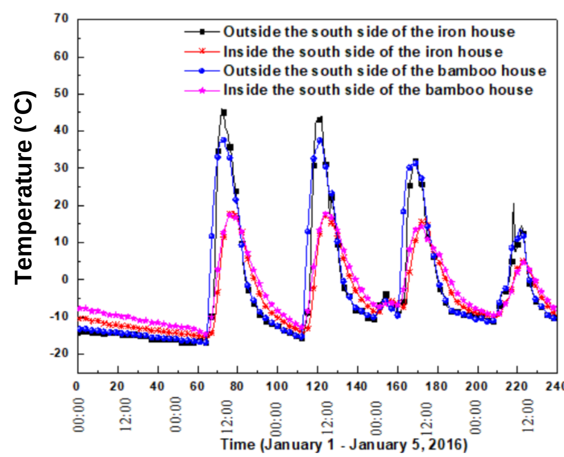

Fig. 6. Temperature comparison, south wall

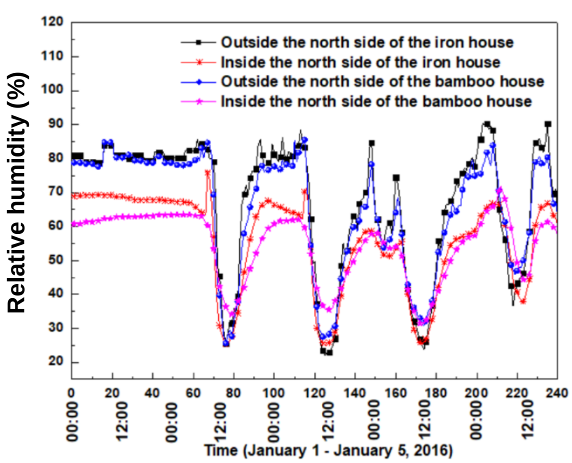

Fig. 7. Comparison of relative humidity, north wall

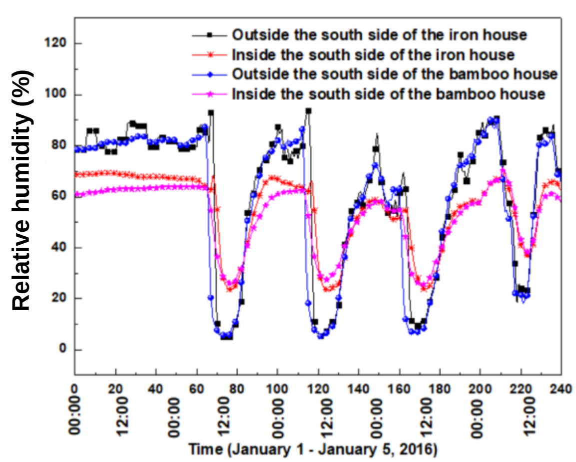

Fig. 8. Comparison of relative humidity, south wall

The range of indoor relative humidity in the traditional iron container house was significantly higher than that in the bamboo container house. The bamboo container house had a smaller range of temperature and humidity, more suitable than traditional container houses for use and promotion in the desert micro-environment.

Prospect

Based on the research and development of the bamboo composite wall, the project team will develop a modular tone - bamboo composite wall component by the advanced material processing technology, structural design, and architectural principles combined with the high bearing characteristics of BLVL. The modular stone-bamboo composite wall component can fully exert the advantages of the natural inorganic material —stone with the high weather resistance (anti-mold, anti-insect, waterproof, moisture-proof, anti-discoloration, anti-freeze, wear-resistant, weather-resistant, *etc*.) and the natural organic material – bamboo possessed the high sound-insulation and weathering resistance. The thin-type bamboo bundle veneer laminated composite with high dimensional stability (below 6 mm) will be applied to the stone-bamboo composite wall with sufficient strength and reliable connection performance and stability to ensure the structural stability of the wall. The bamboo laminated timber will be used for the interior wall decoration board to give full play to the natural decorative effect of the natural organic material-bamboo which is comfortable and livable. In addition, the bamboo fiber foam material and nano-aerogel will be used for the intermediate layer of the stone-bamboo composite wall which could cut off the cold bridge layer and play a livable effect of heat preservation, heat insulation and sound insulation. Therefore, the industrialization and application of the novel stone-bamboo composite wall can give full play to the material advantages of both bamboo and stone, and integrate functional and decorative features. It has the characteristics of energy saving, environmental protection and comfort, and can be used for scenic spots housing, high-end business clubs, government office buildings, garden resort hotels and forest city buildings.

Fig. 9. Schematic diagram of the structure of stone-bamboo composite wall

CONCLUSIONS

1. Bamboo-bundle laminated veneer lumber (BLVL) and bamboo-composite walls have excellent physical and mechanical properties, and they can meet the requirements of national standards for wall panels and walls.
2. The heat transfer coefficient and thermal inertia index of each layer of bamboo composite wall, and of the wall itself, meet the requirements of national standards, and show good thermal-insulation performance. Comprehensively, bamboo-composite wall Type I has the best insulation performance.
3. Thermal-insulation performance, indoor thermal environment and comfort of the BLVL container house was superior to those of a traditional iron container house.
4. The stone-bamboo composite wall components by the abundant bamboo resources and cheap stone resources will be developed for outdoor performance assembled bamboo-wood structure buildings. It has important market prospects and social values for expanding the application of bamboo and promoting the optimization and upgrading of the bamboo industry structure.

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REFERENCES CITED

Alwisy, A., Hamdan, S. B., Barkokebas, B., Bouferguene, A., and Mohamed, A. (2018). "A BIM-based automation of design and drafting for manufacturing of wood panels for modular residential buildings," *International Journal of Construction Management* (4), 1-19.

Chen, F. M., Deng, J. C., Li, X. J., Wang, G., Smith, M. L., and Shi, Q. S. (2016). "Effect of laminated structure design on the mechanical properties of bamboo-wood hybrid laminated veneer lumber," *European Journal of Wood and Wood Products* 75(3), 439-448.

Chen, F. M., Jiang, Z. H., Deng, J. C., Wang, G., Zhang, D., Zhao, Q., Cai, L. P., and Shi S. Q. (2013a). "Evaluation of the uniformity of density and mechanical properties of bamboo-bundle laminated veneer lumber (BLVL)," *BioResources* 9(1), 554-565.

Chen, F. M., Jiang, Z. H., Wang, G., Shi, S. Q., and Liu, X. E. (2013b). "Bamboo bundle corrugated laminated composites (BCLC). Part I. Three-dimensional stability in response to corrugating effect," *The Journal of Adhesion* 89(3), 225-238.

Deng, J. C., Li, H. D., Wang, G., Chen, F. M., and Zhang, W. F. (2015). "Effect of removing extent of bamboo green on physical and mechanical properties of laminated bamboo-bundle veneer lumber (BLVL)," *European Journal of Wood & Wood Products* 73(4), 499-506.

Figliola, A., and Battisti, A. (2019). "Performative Architecture and Wooden Structures: Overview on the Main Research Paths in Europe," in: *Digital Wood Design*, Springer, Cham., pp. 937-969.
GB/T 17657. (2013). "Test method of evaluating the properties of wood-based panels and surface decorated wood-based panels," Standardization Administration of China, Beijing, China.
GB/T 50176. (2016). "Thermal design code in civil building," Standardization Administration of China, Beijing, China.
GB/T 22349. (2008). "Sheathing plywood for timber structures," Standardization Administration of China, Beijing, China.
Hai, F., Sun, H., Liu, W. Q., Wang, L., Yu, B., and David, H. (2015). "Mechanical performance of innovative GFRP-bamboo-wood sandwich beams: Experimental and modelling investigation," *Composites Part B* 79, 182-196.
Hu, J. B., and Pizzi, A. (2013). "Wood-bamboo-wood laminated composite lumber jointed by linear; vibration-friction welding," *European Journal of Wood & Wood Products* 71(5), 683-686.
Ibrahim, M. I., Abd Karim, S. R., and Salleh, A. H. (2015). "Physical and mechanical properties of hybrid laminated bamboo-wood veneer board (HLBWVB) for furniture components," *Advanced Materials Research* 1134, 143-146.
Jean, B., Mawulé, D., Zha, X., and Zhan, J. (2017). "Synthesis reaction and compressive strength behavior of loess-fly ash based geopolymers for the development of sustainable green materials," *Construction & Building Materials* 141(Complete): 491-500.
Jiang, Z. H., Wang, G., and Fei, B. H. (2002). "The research and development on bamboo/wood composite materials," *Forest Research – Chinese Academy of Forestry* 15(6), 718-725.
Li, H. D., Chen, F. M., Cheng, H. T., and Wang, G. (2016a). "Analysis of the mechanical properties of bamboo-wood hybrid laminated composite by off-axis tension tests," *Materials Review* 30(18), 159-163.
Li, H. D., Chen, F. M., and Wang G. (2015b). "Prepress densification technology for manufactured bamboo bundle laminated veneer lumber with continuous plate process and its properties," *Journal of Northeast Forestry University* 43(6), 103-106.
Liu, J. B., and Liu, X. Q. (2008). "Study on integral performance of a modern low-rise light-wood frame structure building," World Conference on Earthquake Engineering.
Liu, X. H., Fu, S. Y., Xu, Y. Z., Wang, C. P., and Chu, F. X. (2013). "Effect of acid curing agent on the foaming of liquefied bamboo-based resol resin," in: *Advanced Materials Research* 724, 231-235.
Liu, X. H., Zhang, M. M., Fu, S. Y., Li, S. H., and Wang, C. P. (2012). "Effect of bamboo powder on curing behaviors of liquefied bamboo-based resol resin," *Applied Mechanics and Materials* 204, 3914-3919.
Loss, C., Piazza, M., and Zandonini, R. (2016). "Connections for steel–timber hybrid prefabricated buildings. Part II: Innovative modular structures," *Construction and Building Materials* 122, 796-808.
Ma, X., Shi, S. Q., Wang, G., Fei, B., and Jiang, Z. (2018). "Long creep-recovery behavior of bamboo-based products," *Journal of Wood Science* 64(2), 119-125.
Noh, M. M., Ahmad, Z., Ibrahim, A., Kamarudin, A. F., and Mokhatar, S. N. (2018). "Static in-plane shear behaviour of prefabricated wood-wool panel wallettes," *Journal of Physics: Conference Series* 995, 012069.

Sonnick, S., Erlbeck, L., Schlachter, K., Strischakov, J., Mai, T., Mayer, C., and Rädle, M. (2018). "Temperature stabilization using salt hydrate storage system to achieve thermal comfort in prefabricated wooden houses," *Energy and Buildings* 164, 48-60.

Susainathan, J., Eyma, F., De Luycker, E., Cantarel, A., and Castanie, B. (2018). "Experimental investigation of impact behavior of wood-based sandwich structures," *Composites Part A: Applied Science and Manufacturing* 109, 10-19.

Xu, M., and Chen, F. X. (2008). "Discussion on deisgn method for framed wood structure residence," *Scientia Silvae Sinicae* 44(12), 105-111.

Yu, Y., Li, Q., and Yu, W. (2014). "Manufacturing technology of bamboo-based fiber composites used as outdoor flooring," *Scientia Silvae Sinicae* 50(1), 133-139.

Zhang, W., Fang, J., and Liu, L. (2016). "Research progress on liquefaction of bamboo phenol alcohol and its application," *World Bamboo and Rattan Newsletter* 14(2), 31-36.

Zhang, W., Wang, G., Yu, Z., Cheng, H., and Qiu, Y. (2012). "Effect of bamboo shape on properties of bamboo/wood LVL," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 36(5), 167-169.

Zhao, Y. (2007). "Research on energy-efficiency in light-frame wood residence and the wall heat transfer," Chinese Academy of Forestry.

Zhu, Y. X., Guan, M. J., and Fan, Y. K. (2007). "Prestressing effects of twisted bamboo bundle on the wood-bamboo laminated veneer lumber," *Journal of Nanjing Forestry University* 31(6), 16-20.

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