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Vibration Performance of Bamboo Bundle/Wood Veneer Composite Floor Slabs for Joist-Type Floor Coverings

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Abstract: Bamboo engineering materials are green, high-strength, tough, durable, and structurally safe, and have promising application prospects in various modern green and low-carbon buildings. To invest the vibration behavior of new bamboo bundle veneer -laminated lumber (BLVL) for use in floor slabs, this study designed two kinds of full-scale vibration tests under a pedestrian load: an extraction hammer impact test, and a static concentrated load test, it is expected to provide theoretical and data support for the application of bamboo bundle veneer laminated composite materials in the construction field. The results showed that the self-oscillation frequency and mid-span deflection of the BLVL composite met the requirements of multiple relevant regulations when used as the structural material of floor slabs. The BLVL floor slab had a higher flexural stiffness and better vibration-damping performance than the OSB floor slab. The first-order self-oscillation frequency of the BLVL composite floor slab was 13.769 Hz, the damping ratio of the first three orders of modalities was 1.262–2.728%, and the maximum static deflection in the span of the joist was 0.932 mm under a 1 kN concentrated load. The 1 kN static deflection of the BLVL was reduced by 22.33%, and the root mean square (RMS) acceleration of the walking load response was significantly lower than that of the OSB floor slab. The preparation of BLVL composite materials by homogeneous lamination of bamboo bundle veneer and wood veneer may help improve the vibration behavior of bamboo-wood structures such as floor slabs and walls.

Keywords: bamboo bundle veneer; bamboo bundle/wood veneer laminated composite; floor slabs; vibration performance; static deflection

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1. Introduction

China has the most abundant bamboo resources, the most advanced bamboo processing technology, and the most complete bamboo industry chain in the world. Bamboo has a fast growth rate (3–5 years to become timber), easy processability, high strength, and good toughness. In recent years, bamboo engineering materials, such as bamboo scrimber, laminated bamboo lumber, and bamboo LVL, have been used in outdoor flooring, household products, and building structural materials. The advantages of bamboo materials provide new options for materials used in green buildings [1–4]. Bamboo is a sustainable material, and its energy consumption is 1/8th of concrete and 1/50th of steel for the same building area [5–7]. Bamboo engineering materials show excellent vibration damping and vibration suppression properties due to their stiffness and damping effects [8,9], giving them wide application prospects for green low-carbon buildings. They also meet the requirements of sustainable development and circular economy.

Bamboo-wood composites applied for buildings such as assembled houses must consider the vibration, flexural stiffness, and other architectural applications characteristics for prefabricated composite floor slabs [10–12]. Hao et al. conducted an experimental study on the flexural performance of sprayed composite material-dense raw bamboo composite floor slabs. They explored the damage process, damage form, and damage mechanism of the composite floor slabs by observing the development of deflection of the composite floor slabs under various loads, the results show that the composite floor has good overall performance, and there is a good combination effect between raw bamboo and sprayed composite materials, which can provide high bearing capacity [13]. Xia et al. proposed a steel-wood composite floor slab made of cold-formed thin-walled steel sections connected by Populus euramevicana plywood. They studied the effects of steel plate thickness, plywood thickness, composite slab height, slab span, and other factors on the self-vibration characteristics and bending characteristics of the composite slab.The results show that Populus euramevicana plywood and thin-walled section steel can work well together, improve the thickness of section steel and plywood, significantly improve the bearing capacity and vibration comfort of composite panels, and the vibration performance and bending bearing capacity meet the requirements of building floors [14]. Zhou et al. conducted static deflection and vibration performance tests on a cold-formed thin-walled steel beam-OSB composite floor slab with different boundary conditions. The results showed that the midspan deflection of the composite floor slab under a 1 kN concentrated load with different boundary conditions was in the range of 0.6–0.9 mm. The self-vibration frequency under a dynamic load was higher than 15 Hz, which satisfied the requirements of domestic and foreign regulations [15]. The vibration performance and full-scale test data of bamboo composites for construction have not been reported, which limits their applications[16–19].

As a new type of bamboo bundle fiber recombination material for construction, bamboo bundle/wood veneer laminated composites retain the excellent physical and mechanical properties of traditional bamboo scrimber (high weather resistance, high strength, and toughness) and also improve the interfacial bonding properties by uniform lamination[20–23]. This reduces the density of the material, as well as the uneven density and high stress of bamboo scrimber[24–27]. In addition, it has been shown that the structural design of group blanks with two or more layers of high-impregnated bamboo bundle veneer on the surface can enhance the performance of bamboo laminated composites to different degrees[28–31]. Therefore, this study prepared a laminated composite with two layers of bamboo bundle veneer as the surface layer and multiple layers of wood veneer as the core layer. The vibration performance and static deflection of the joist-type BLVL composite floor slab were tested. In addition, the vibration performance and static deflection of the laminated bamboo veneer composite were compared with those of OSB, which was mainly used in lightweight wood structure building covers and wall panels. These results will provide theoretical and full-scale test data support for applying bamboo veneer laminated composites for green building materials.

2. Materials and Methods

2.1. Materials

Whole bamboo bundle into veneer: Four-year-old Moso bamboo (Phyllostachys pubescens) was harvested from Yong'an City, Fujian Province, China. The height and defect-free part was cut 1.5-2.5 m above the ground, bamboo wall thickness 10-12 mm. First, round bamboo with a diameter of not less than 100 mm at breast height was opened into several pieces of similar sizes by using a bamboo ramming machine. The bamboo green, yellow, and knotted parts were removed, and the bamboo pieces were thinned into loose net-like bundles of uniform thicknesses. The bamboo bundles were joined from the width direction to form a bamboo bundle fibrillated veneer with a length of 300 mm by using a self-developed bamboo bundle veneer weaving machine. Then, samples were air-dried to a moisture content of 8–12%, and a bamboo bundle veneer with an average light transmittance < 10% and mechanical stiffness > 900 N mm-1 was selected [19] and marked as B for further use.

Wood veneer: Poplar (Populus ussuriensis Kom.) over 10 years old was harvested from Cangzhou City, Hebei Province, China. Poplar trees had an average diameter at breast height of 50 cm and a tree height of 20 m or more. Poplar wood with no defects, no knots, and normal growth was selected and made into 1.2 mm-thick veneers by a rotary cutting machine, air-dried to 8–12% moisture content, and marked as P.

OSB was purchased from a market, with a thickness of 19 mm and a density of 0.65 g·cm-3. The elastic modulus (parallel) is 4.28GPa, and the elastic modulus (vertical) is 2.08GPa. OSB board is suitable for load-bearing and has a wide range of uses. It can be used for building exterior walls, floors and ceilings, it is a widely used wooden structural material[32,33].

2.2. Methods

2.2.1. Testing Equipment

An INV3020C signal acquisition analyzer, INV9314 test force hammer (sensitivity 50.5 μV·N-1), INV9828 piezoelectric acceleration transducer, ID-C150XB micrometer displacement meter (Mitutoyo), displacement meter stand (height 180 cm), and 1 kN weight made of cast iron.

2.2.2. Preparation of Bamboo-Wood Veneer (BLVL) Composite Flooring

Phenolic resin was diluted with water to a 30% solids content as an adhesive, and the bamboo veneer was dipped and dried twice to obtain higher adhesive absorption (4 min each time in the adhesive and dried to 8–12% moisture content in the mesh belt). The wood veneer was coated with 250–280 g·m-2 adhesive on both sides. Hot pressing was conducted at 135 °C for 40 min with a pressure of 10 MPa. The target dimensions were 2100 mm × 1900 mm × 19 mm (length × width × thickness). All sheets were placed in an indoor environment (temperature 20 °C, humidity 65%) for two weeks to equilibrate, BLVL density is 1.05 g·cm-3. The tensile strength and tensile modulus of BLVL were respectively 339.98 MPa and 26.33 GPa. The BLVL preparation process is shown in Figure 1

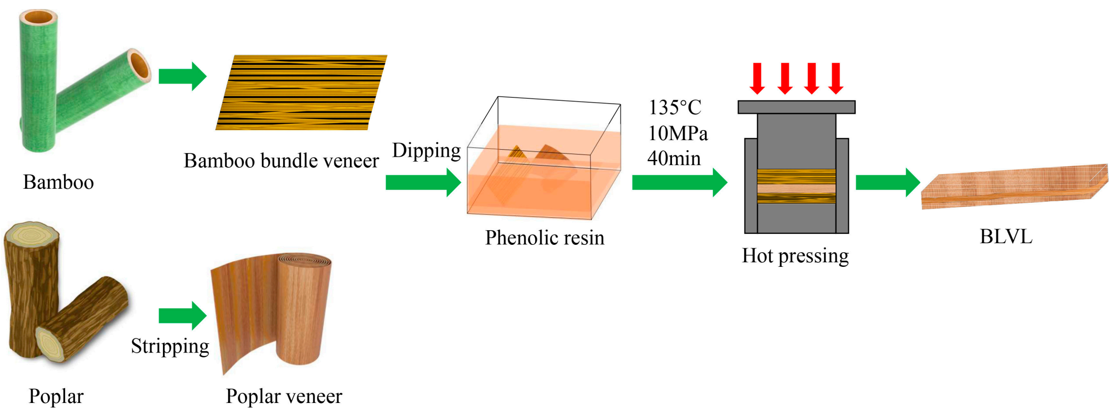

Figure 1. Preparation of BLVL.

2.2.3. Test Floor Slab Design and Construction

The test floor slab was composed of floor panels and timber joists built on a 1.85 m-high light timber wall with a nominal span of 6 m and a nominal length of 5.6 m. The wall frame structure was made of European red pine with a cross-sectional size of 38 mm×89 mm, and the wall panels were made of structural OSB with a thickness of 11 mm. The timber joist was connected by a tooth plate with a thickness of 1.0 mm, a tooth length of 10.5 mm, and a tooth density of 105–109 No·dm-2. The length × height of the timber joist was 6000 mm × 440 mm, the spacing between straight webs was 500 mm, and the diagonal webs were arranged in a herringbone shape, as shown in Figure 2a. A wooden combination joist was used as the joist (spacing 400 mm), and the lower end of the joist was nailed to the top plate of the wall with two 70 mm-long square head screws. The head joist was made of wood veneer laminated with a thickness × height of 38 mm × 438 mm, and 70 mm long screws were nailed to each end of the floor joist. The floor panels were made of BLVL and OSB, both placed perpendicular to the direction of the joist and screwed to the top chord of the wood joist. The construction process of the full-scale test floor vibration test platform with BLVL as the floor panel is shown in Figures 2b and 3.

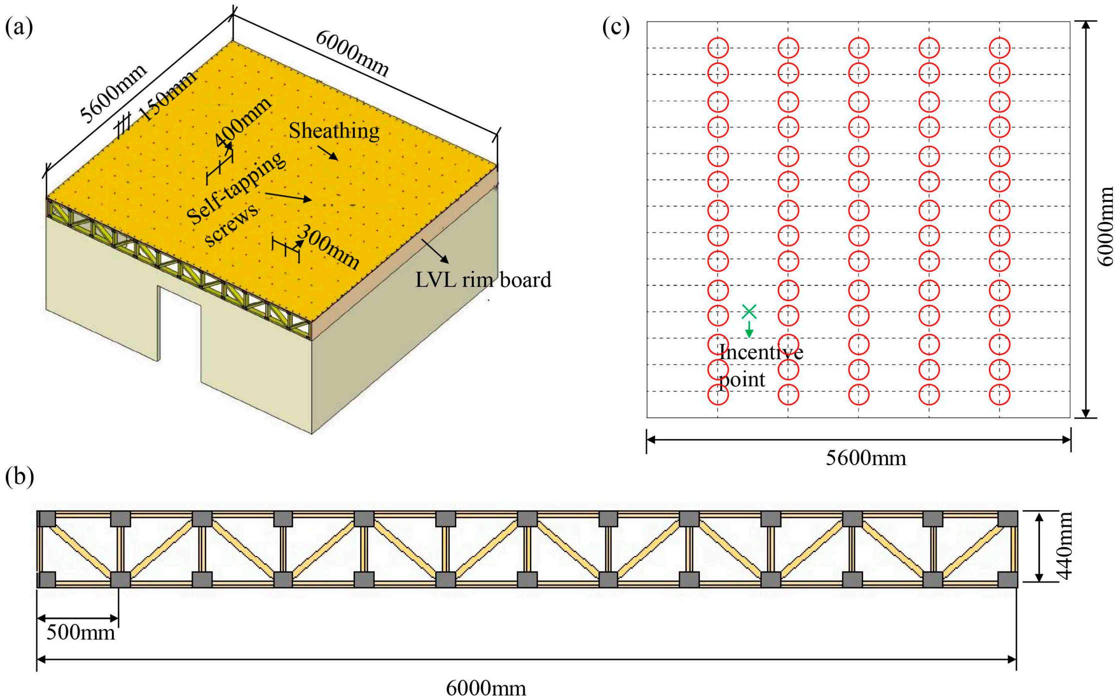

Figure 2. (a) Model of the test floor cover, (b) toothed plate connected parallel to the chord timber combination truss. (c) modal test measurement points.

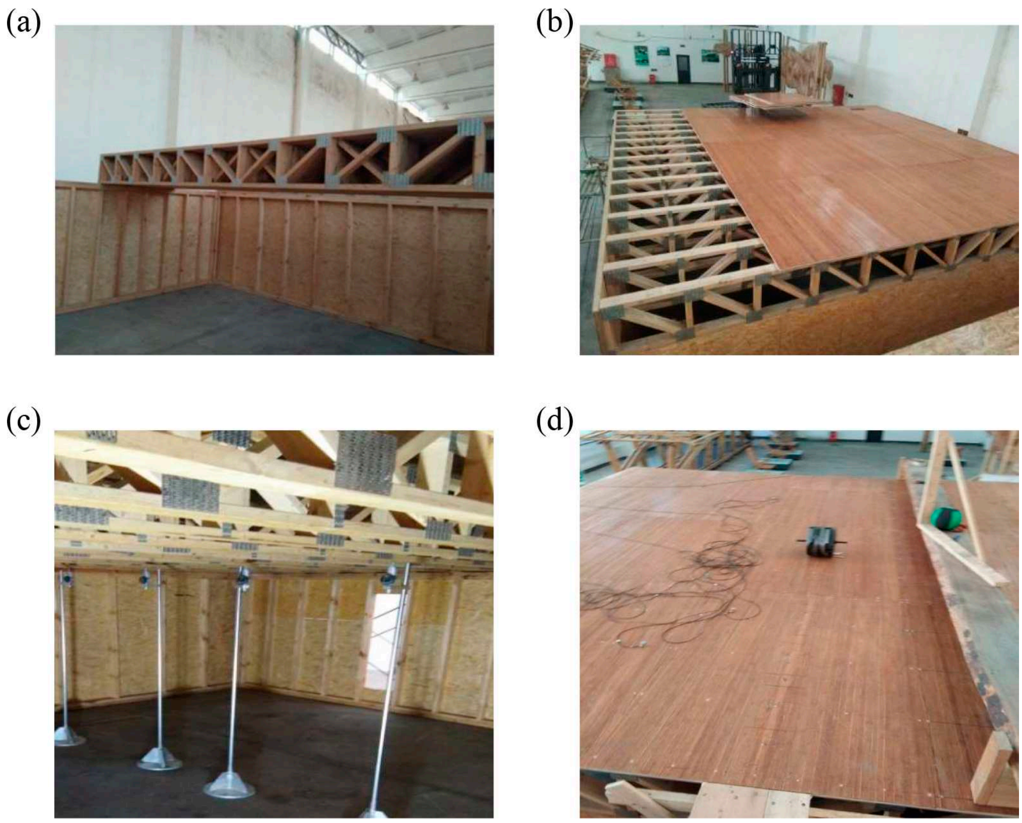

Figure 3. Construction and site layout of the test floor slab vibration test platform. (a) Construction of the vibration test platform of the floor slab. (b) Laying and fixing of the BLVL composite. (c) Micrometer displacement meter arrangement. (d) 1 kN static deflection test setup.

2.2.4. Vibration Performance Test on the Floor Slab

The vibration modes test was carried out with reference to international standard ISO 18324-2016, and the composite floor slabs were tested by the hammering method. The excitation response was analyzed by fast fourier transformation (FFT) transformation to obtain the first three orders of the self-oscillation frequency, damping ratio, and modal vibration pattern of the floor slab. The selected excitation point locations are shown in Figure 2c. The excitation points were fixed, and four acceleration sensors were arranged at measurement point positions 1–4. The fixed excitation points were repeatedly excited three times by a force hammer, and the accelerometer response was recorded by a signal acquisition analyzer. Then, the accelerometers were moved to measurement points 5–8, and the fixed excitation points were repeatedly excited three times, and the data were collected, and so on.

The 1 kN static deflection test was conducted with reference to the international standard ISO 18324-2016 and the National Forestry Industry Standard LY/T 3218-2020. The static deflection measurement point arrangement and field test are shown in Figure 4a. A micrometer displacement meter was fixed to the lower surface of the span position of the shelf fence through the bracket. First, a 1 kN weight was stationary on the upper surface of the floor slab at position P1, and the displacement value displayed by the micrometer was recorded. Then, the weight was stationary at position P2, and the displacement value was recorded, and so on.

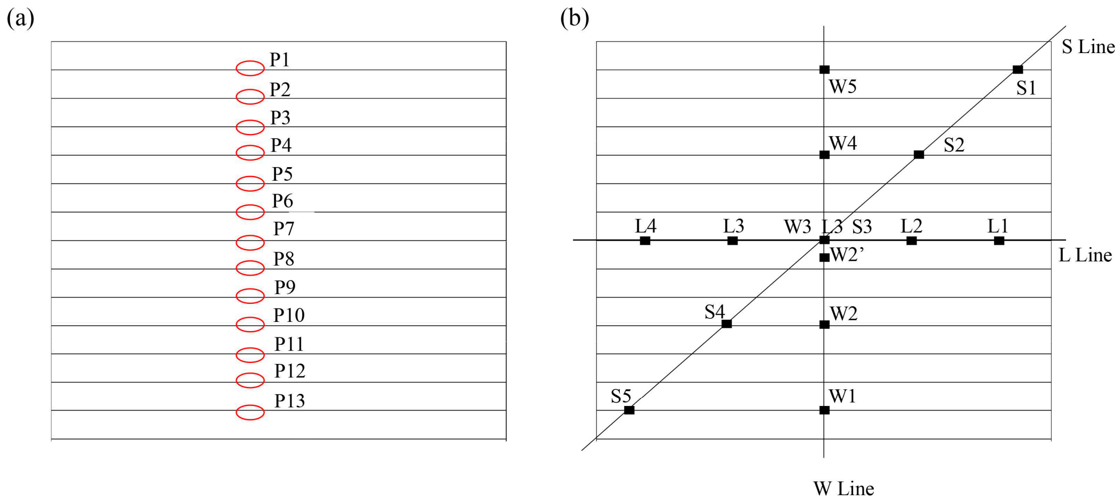

Figure 4. Static deflection and single-person walking test points. (a) Static deflection test; (b) walking load test.

The single-person walking load test was conducted with reference to the pedestrian load function model proposed by Tsinghua University[34]. The measurement point arrangement of the walking load test is shown in Figure 4b. The acceleration sensors 1–5 were fixed at W1–W5 of the building cover, respectively, and the measured weight of the tester was 89 kg. The walking load excitation was applied to the building cover along three paths of 600 mm width in the width (W), longitudinal (L), and slant (S) directions, respectively, using a metronome to adjust the step frequency to 2 Hz. The acceleration response time curve was obtained by a signal acquisition analyzer. Then, acceleration sensors 1–5 were fixed at positions L1–L5 of the building cover. The above test steps were repeated to obtain the acceleration response time curves. Finally, the test was repeated at positions S1–S5, and the integrated data were used to determine the peak acceleration and root mean square acceleration at the center of the building cover.

3. Results and Discussion

3.1. Vibration Modes

The first three orders of vibration modes of the BLVL composite floor slab and OSB floor slab are shown in Figure 5 The first-order vibration mode of the BLVL composite floor slab showed that the overall floor slab vibrated up and down and also displayed local irregular vibrations, while the OSB floor slab showed the largest vibration amplitude at the center, compared with bamboo bundle veneer laminated timber, OSB has a small modulus, and its modulus in the length direction and transverse direction are 4.28GPa and 0.28GPa respectively. Under the same section size, the stiffness, therefore, has a large deformation. In the second-order mode, the vibration was roughly divided into two parts in the direction of the width of the floor slab (vertical wood trusses), and the vibration direction was opposite and alternating，In the second-order mode, it is roughly divided into two parts (vertical wooden truss) in the width direction of the floor, and the vibration direction is opposite and alternating. This is a typical feature of second-order bending vibration. Under three constraints, the two parts of the vertical wooden truss show symmetrical mode under the constraint. The third-order mode vibration pattern was roughly divided into three parts along the width of the building cover. The outer two parts vibrated in the same direction, and the middle part vibrated in the opposite direction, showing V-shaped fluctuations.

(a)

(b)

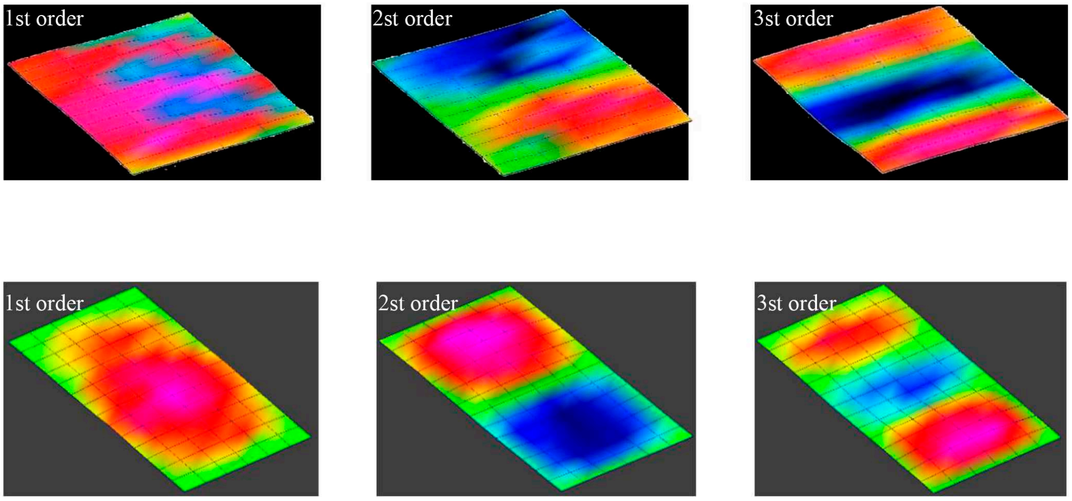

Figure 5. Modal vibration pattern of the first three orders of the floor slab.(a) BLVL; (b) OSB.

The self-oscillation frequency has been used as the main evaluation index when researching the vibration performance of building covers in relevant research around the world. The American Steel Design Guide (AISC/CISC, 1997) stipulates that the self-oscillation frequency of a lightweight floor slab should not be less than 8 Hz. The European Seismic Code (BS EN 1998-1, 2005) stipulates that the self-oscillation frequency of a floor slab should not be less than 9 Hz. The National Building Code of Canada (NBCC 2005) stipulates that the self-oscillation frequency of floor slabs should be more than 5 Hz. The Code for the Design of Steel Structure Houses (CECS 261-2009) stipulates that the self-vibration frequency of residential floor slabs should not be less than 8 Hz. In the present test range (Table 1), the first-order self-oscillation frequency of the BLVL composite floor slab reached 13.769 Hz, and the damping ratio of the first three modes ranged from 1.262% to 2.728%. The first-order self-oscillation frequency of the OSB floor slab reached 14.812 Hz, and the damping ratios of the first three orders of modalities ranged from 5.511% to 7.037%. The self-vibration frequency of the BLVL composite floor slab under excitation by an impact load met the requirements of various domestic and international regulations.

Table 1. Frequency and damping of the first three orders of BLVL and OSB floor.

Type	Order	Frequency (Hz)	Damping ratio (%)
	1	13.769	2.728
BLVL	2	19.533	1.337
	3	22.321	1.262
OSB	1	14.812	7.037

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	2	17.801	7.302
	3	21.034	5.511

3.2. Static Deflection

Foreign codes specify the deflection limits for floor slabs under a 1 kN concentrated load. The Swedish Code (Ohlsson, 1988) stipulates that the span deflection shall not be greater than 1.5 mm with a 1 kN concentrated load on the floor. The Australian Steel Code (AS3623, 1993) stipulates that the floor deflection should be less than 2 mm with a 1 kN concentrated load at any position on the floor. The Canadian Code (CCMC, 1997) stipulates that when the span of the floor slab is in the range of 3.0–5.5 m, the deflection in the span of the floor slab system should be less than 1.5 mm under the action of a 1 kN concentrated load. Within the scope of this test (Figure 6), the spanwise displacement of each joist of the BLVL composite floor slab in the width direction was an inverted V shape. The maximum static deflection in the span of the intermediate joist P7 was 0.932 mm at the maximum. In addition, the maximum static deflection of the OSB floor slab was 1.200 mm(Figure 6b) i.e., the 1 kN static deflection of the BLVL floor slab was reduced by 22.33%. Thus, the spanwise deflection of the BLVL composite slab under a 1 kN concentrated load met the requirements of foreign regulations and had good flexural stiffness.

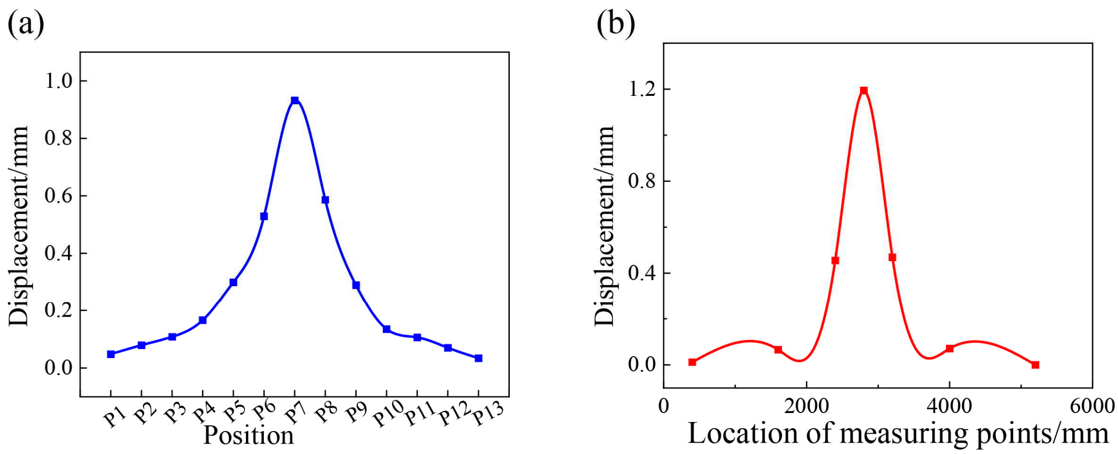

Figure 6. (a) Deflection variation curve in the span of each joist of a BLVL building cover. (b) Static deflection of OSB wooden structure floor.

3.3. Single-Person Walking Load

The peak acceleration and RMS acceleration curves collected by acceleration sensors W1–W5 (width), L1–L5 (longitudinal), and S1–S5 (slant) are shown in Figure 6. From Figure 7a,b, it can be seen that the peak acceleration and RMS acceleration gradually increased when testers walked along the width direction. When they walked along the longitudinal and slant directions, respectively, the peak acceleration and RMS acceleration were independent of the walking direction, and the peak acceleration and RMS acceleration were the largest at the center of the BLVL composite floor slab. Figs. 7c and 7 d show that the peak acceleration and RMS acceleration of the bamboo veneer laminated composite cover were independent of the walking direction when the testers walked along the width, longitudinal, and slant directions. The peak acceleration and RMS acceleration at the center of the bamboo veneer laminated composite cover were the largest. Figs. 7e and 7f show that the peak acceleration at S2 was the largest when walking along the width direction, and the peak acceleration at S4 was the largest when walking along the slant direction. This may have been due to the gradual accumulation of energy in the BLVL composite floor slab during walking. The peak acceleration and RMS acceleration at the center of the BLVL cover were the largest when testers walked along the longitudinal and slant directions.

In addition, the vibration RMS acceleration of the I-beam joist floor slab was less than 0.45 m·s^{-2}, according to Test Method for Vibration Performance of Wood Structure Floors (LY/T 3218-2020). As shown in Table 2, the RMS acceleration of the walking load response decreased significantly when the floor panel was a bamboo composite panel, indicating that the vibration performance of the BLVL floor slab was somewhat better than that of the OSB floor slab.

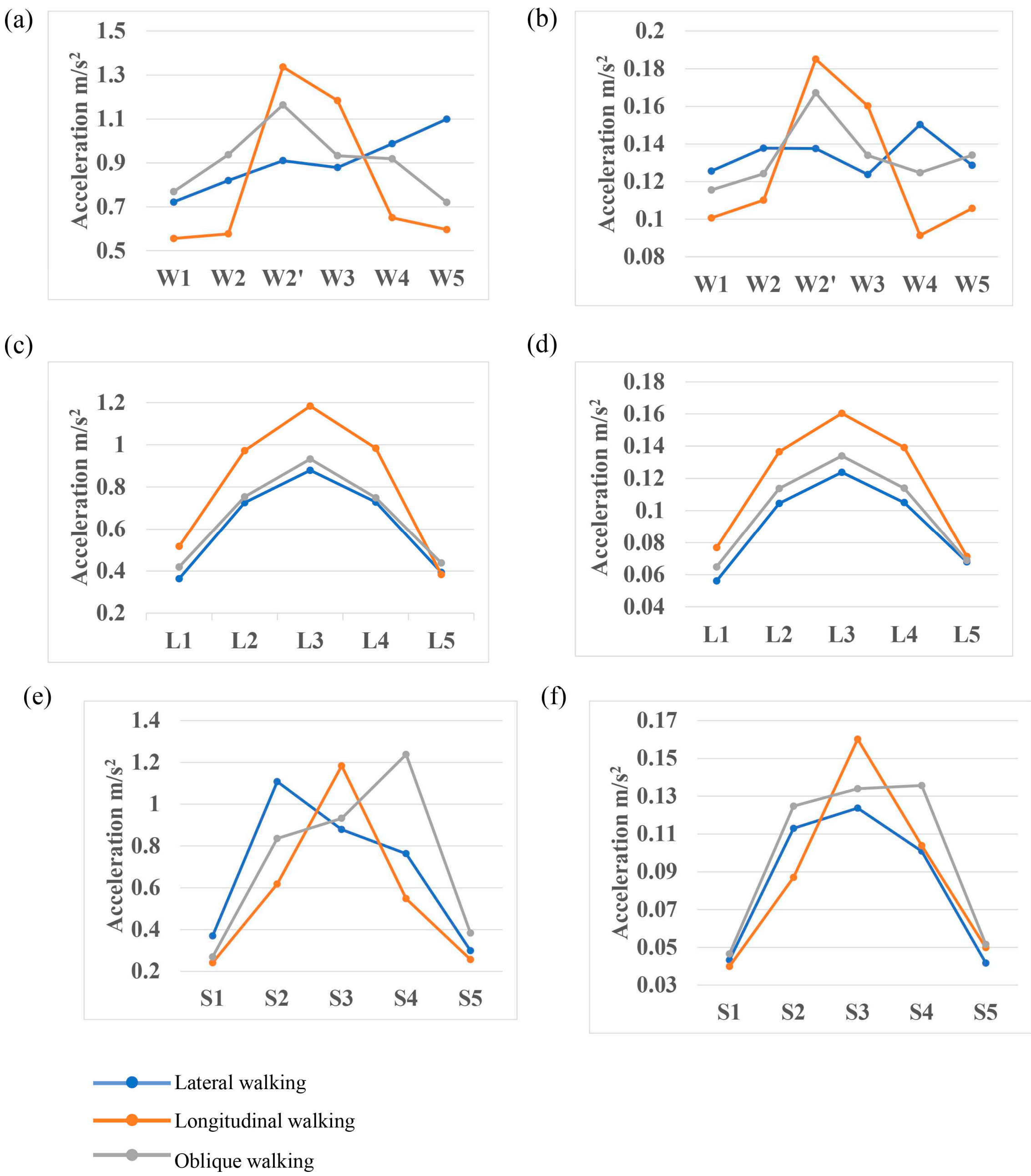

Figure 7. Peak acceleration collected by acceleration sensors W1–W5 (lateral), L1–L5 (longitudinal), S1–S5 (oblique), and RMS acceleration profiles. (a) Peak acceleration of W sensor. (b) RMS acceleration of W sensor. (c) Peak acceleration of L sensor. (d) RMS acceleration of L sensor. (e) Peak acceleration of S sensor. (f) RMS acceleration of S sensor.

Table 2. RMS acceleration and peak acceleration at the center of the two types of building covers.

Building cover types	RMS acceleration (m·s^{-2})			Peak acceleration (m·s^{-2})		
	S	W	L	S	W	L
OSB	--	0.138	0.263	--	1.62	2.13

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BLVL	0.134	0.124	0.16	0.933	0.879	1.184

Note: “-” indicates that no response data were obtained in the S direction.

4. Conclusions

The use of bamboo-wood composite materials as wooden floor slabs has resource, performance, and environmental advantages. The self-vibration frequency and mid-span deflection of the bamboo bundle veneer laminated composite (BLVL) developed in this test met the requirements of multiple domestic and foreign regulations for floor slab structures. Compared with the OSB floor slab, the BLVL floor slab had greater flexural stiffness, better vibration-damping performance, and better durability and environmental protection characteristics.

The vibration pattern of BLVL was similar to that of the corresponding OSB floor slab, but its first-order frequency was reduced by 8.2%, its second-order frequency was increased by 9.7%, and its third-order frequency was increased by 6.2%. The first-order damping ratio of the bamboo-wood composite floor slab was reduced by 61%, its second-order damping ratio was reduced by 81%, and its third-order damping ratio was reduced by 77% compared with that of the wooden floor slab. Compared with the OSB floor slab, the 1 kN static deflection of the BLVL composite floor slab was 22.33% lower and showed better flexural stiffness. Compared with OSB, the RMS acceleration of the walking load response of the BLVL composite floor slab was significantly lower, 45.07% reduction, and the vibration performance of the floor slab was improved to some extent.

Author contributions: L.C.: Data curation, Investigation, Writing - original draft. S.H.: Sampling, Trial. D.L. and J.D. : Supervision, Writing - review & editing. F.C.: Supervision, Resources. G.W.: Conceptualization, Project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All results from the data analysis needed to evaluate this report are available in the main text or in the tables and figures.

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Conflicts of Interest: The authors declare that they have no conflict of interest to report regarding the present study. The authors declare no conflict of interest.

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