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Experimental research on mechanical properties of laminated veneer lumber connected with wood dowels

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Abstract

Dowel laminated timber (DLT) represents a construction material consisting solely of dowels and laminated timber. It has the characteristics of green, low-carbon, and a high degree of prefabrication. Wood dowel connection is the forming method of DLT, and its joint design is the key to DLT. The properties of laminates affect the mechanical properties of both DLT and dowel-type timber joints. Laminated veneer lumber (LVL) is an engineering wood product made of veneer through laminated grouping and pressurized gluing, with excellent physical and mechanical properties. Dowel laminated veneer lumber (DLVL), a new type of engineering wood product, was developed by connecting small-thickness LVL with wood dowels. Double-shear tests of dowel-type timber joints were carried out to investigate the shear properties of dowel-type timber joints under different wood grain directions. The influence of loading direction on the flexural behavior of DLVL beams was also investigated by four-point bending tests. The study proved that DLVL was a feasible engineering wood product. The research results and analysis will provide theoretical references and design guidance for the engineering application of DLVL.

Keywords: Laminated veneer lumber (LVL), Dowel laminate timber (DLT), Wood dowel, Joint shear properties, Flexural behavior

1. Introduction

Wood has the advantages of sustainability, renewability, and efficient carbon sequestration, and is a kind of green building material with strong competitiveness [1-2]. Dowel laminate timber (DLT) is an engineered wood product composed of dowels and laminates, used as beams, walls, and floors [3]. DLT exhibits advantages, such as material efficiency, low carbon footprint, and a high degree of prefabrication. In the DLT, the laminates usually use softwood lumber, such as spruce-pine-fir (SPF), and the dowels use hardwood, such as beech [4]. The mechanical properties of dowel-type timber joints and DLT were related to the wood types of dowels and laminates, and enhancing the properties of wood dowels and laminates could improve the mechanical properties [5-6].

Laminated veneer lumber (LVL) is a kind of engineering wood product made of veneers through laminated grouping and pressurized gluing [7]. While meeting the requirements of structural strength and stiffness, LVL has the engineering value of using fast-growing and small-diameter wood [8]. However, the mechanical properties of LVL were affected by processing and adhesives [9-10]. External structural LVL usually uses phenolic resin adhesive with weather resistance, which has poor curing performance and needs to be hot-pressed for a long time when the veneers bond. The processing of LVL with large thickness has problems, such as complicated processes. Thus, using small-thickness LVL instead of SPF as the laminates of DLT can expand the engineering application of LVL and improve the mechanical properties of dowel-type timber joints and DLT.

Based on the DLT structure system and the LVL material characteristic, a new type of mass timber, dowel laminated veneer lumber (DLVL), was developed. On the one hand, carry out the shear properties of dowel-type timber joints under different loading directions by double-shear tests. On the other hand, investigate the influence of loading direction on the flexural performance of DLVL beams by four-point bending tests. Finally, summarize the main conclusions derived from the results alongside future work.

2. Materials and test methods

2.1. Materials

The laminates selected fast-growing larch (*Larix gmelinii(Rupr.) Kuzen*) LVL made with phenolic adhesives, and the laminate thickness was 20 mm. Beech (*Fagus*), a hardwood with high density and hardness, was used as the wood dowels, and the dowel diameter was 16 mm.

According to ASTM D2395-17 [11] and ASTM D4442-20 [12], the average density and moisture content of fast-growing larch LVL were 0.530 g·cm^{-3} and 12.4%, and the average density and moisture content of beech were 0.735 g·cm^{-3} and 11.5%, respectively.

2.2. Design and processing

In the double-shear tests of dowel-type timber joints, the variable was wood grain direction (JS-G). There were JS-GV and JS-GP groups with five repeated specimens in each group (**Figure 1**).

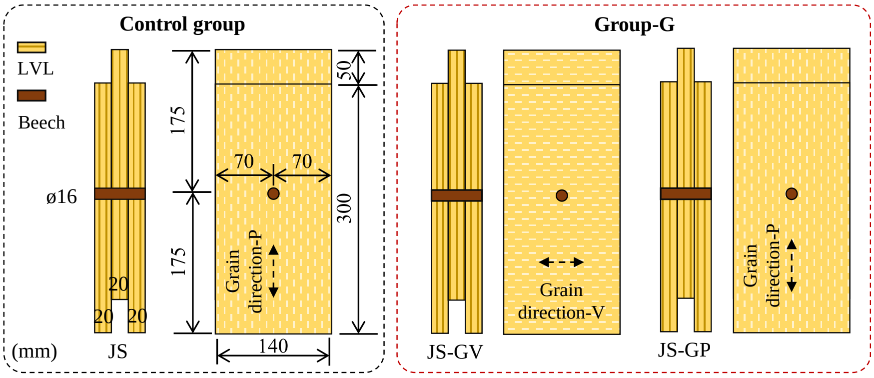


Figure 1: Specimen diagram of dowel-type timber joints

In the bending tests of DLVL beams, the variable was the loading direction (B-L). There were two groups with three repeated specimens in each group (**Figure 2**). The specimens were divided into B-LP and B-LV groups according to the loading direction parallel and perpendicular to the laminate stacking. Both DLVL beams had a cross-section of 120 mm × 120 mm (beam width b_B× beam height h_B), which were composed of six laminates with a cross-section of 20 mm × 120 mm (laminate thickness t_b × laminate width b_b).

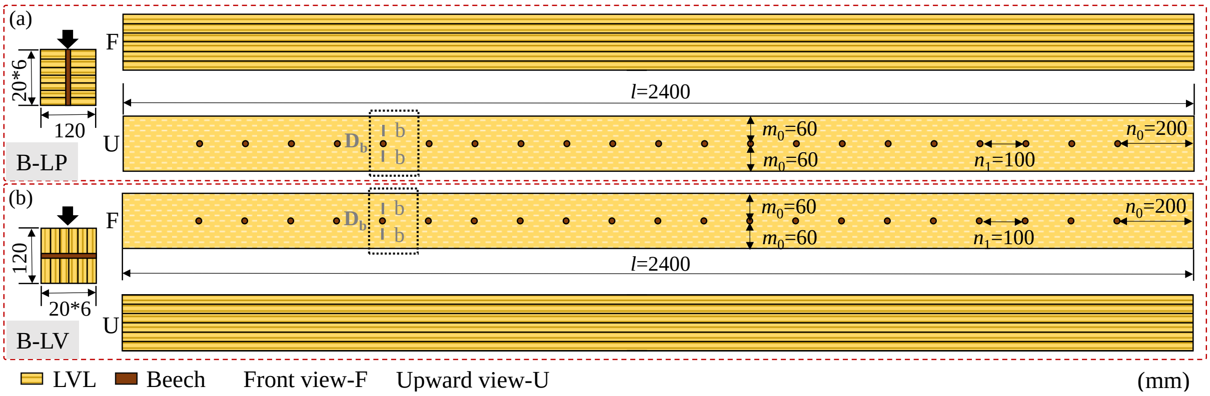


Figure 2: Specimen diagram of DLVL beams: (a) B-LP; (b) B-LV

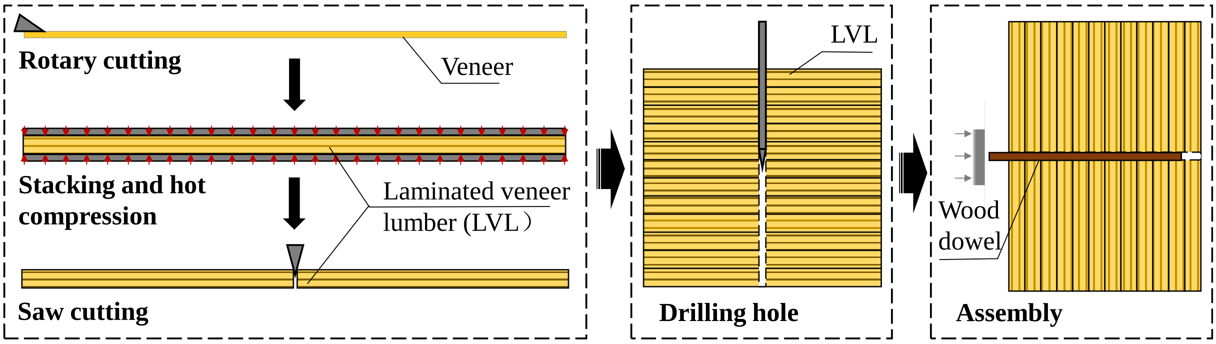


Figure 3: Specimen machining process

Figure 3 shows the specimen machining process. To ensure the unity of the connection between the wood dowels and the laminates as much as possible, the wood dowels needed to be dried when assembling the specimens. According to the preprocessing and pretest, determine the drying process conditions as oven temperature of 120°C and drying time of 45 min.

2.3. Test methods

Figure 4 (a) shows the loading device for the double-shear tests of dowel-type timber joints. According to the standard EN 26891-1991[13], the loading rate of the displacement control was 2 mm/min. The test ended when the wood dowel was damaged or the relative slip of the middle and side laminates was 15 mm.

Figure 4 (b) shows the loading device for the bending tests of DLVL beams. Shock-free loading by displacement control according to ASTM D198-21a [14]. Based on the pretest, the test loading conditions were calculated and determined (**Table 1**). The test ended when the laminates cracked and the whole specimen failed.

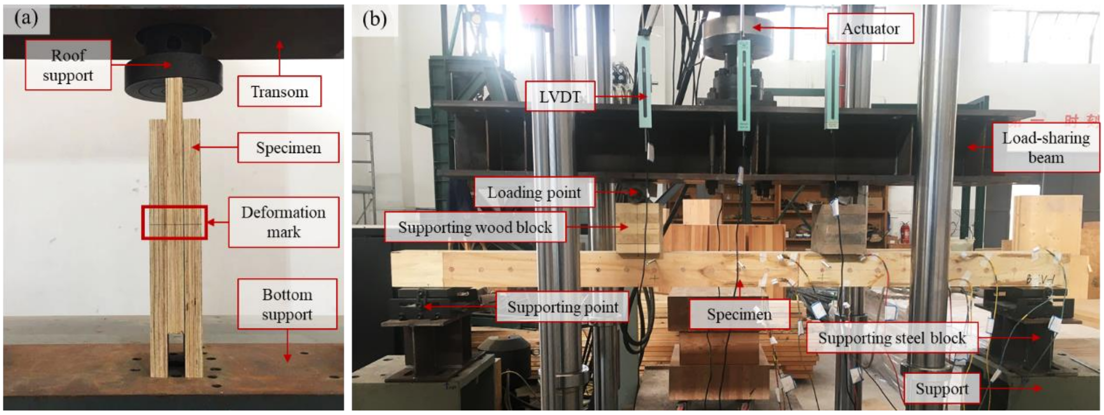


Figure 4: Loading device: (a) Double-shear tests of joints; (b) Bending tests of beams

Table 1 Test condition

Type	Group	Group number	l_0/mm	a_0/mm	Loading rate /mm·min^{-1}
DLVL beam	B-LP	1	2160	720	15
	B-LV	1	2160	720	5

Note: l_0 is supporting point spacing, a_0 is loading point spacing.

3. Test results and discussion

3.1. Shear performance of dowel-type timber joints

3.1.1. Failure modes

According to **Figure 5**, the failure modes of the two groups of dowel-type timber joints were similar, which showed that the wood dowels were damaged and a single plastic hinge occurred, while the laminate only had extrusion around the holes.

Figure 6 shows the load-deformation curves of dowel-type timber joints. The curves of the two groups of joints in the loading process could be divided into three stages: elastic deformation, elastoplastic deformation, and failure. However, there were differences, especially in the last two stages. 1) In the elastoplastic deformation stage, the joints of the JS-GP group appeared as yield platforms. The bearing capacity growth rate was slow, but the plastic deformation continued to increase, and the deformation growth ratio in this stage was more than 1/2. The joints of the JS-GV group also showed yield, but there was no yield platform. The plastic deformation at this stage accounted for only 1/5. 2) In the failure stage, the joints of the JS-GP group showed fracture failure. When the bearing capacity of the joints reached the peak, it decreased suddenly with a splitting sound. The joints of the JS-GV group showed softening failure. After reaching the peak, the bearing capacity decreased to about 2/3 of the peak load. The plastic deformation continued to increase until the end of the test, and the load remained stable.

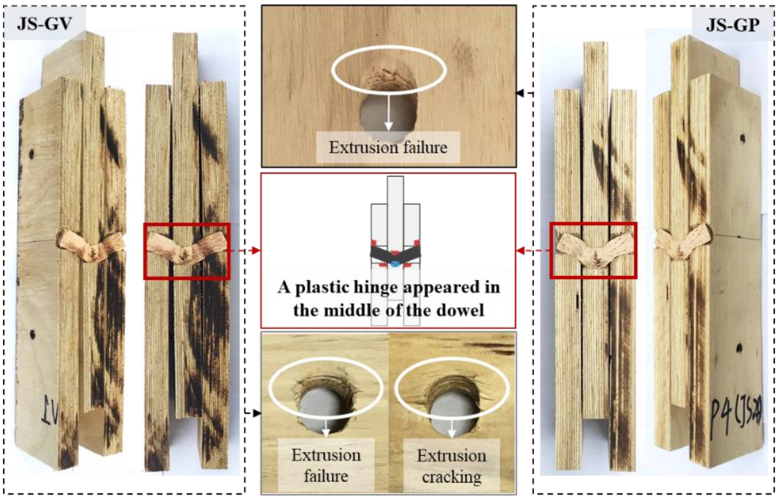
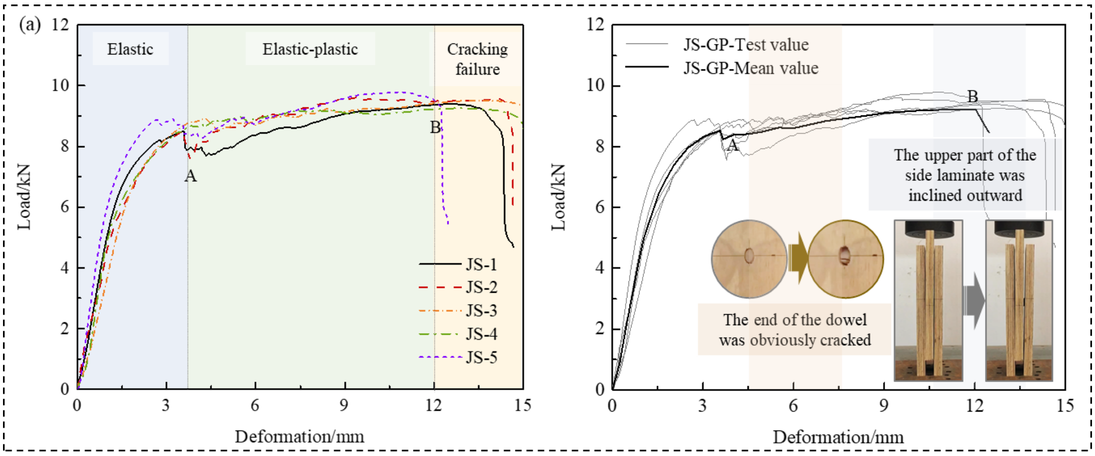


Figure 5: Failure modes of dowel-type timber joints



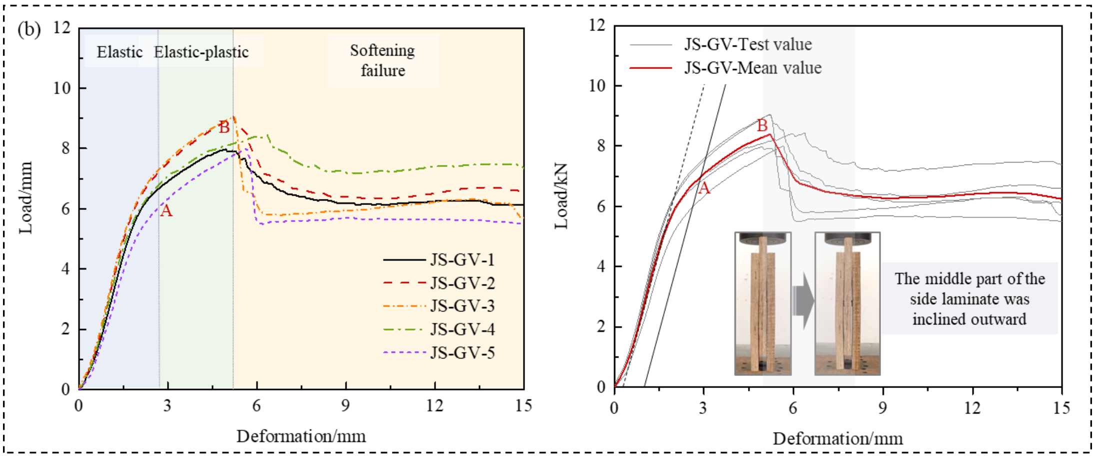


Figure 6: Load-deformation curves of dowel-type timber joints: (a) JS-GP; (b) JS-GV

3.1.2. Mechanical property indices

Table 2 shows the shear performance indexes of dowel-type timber joints. Take the slope value of the linear segment of 10~40% of peak load $F_{\text{max-JS}}$ in the load-deformation curves as the initial stiffness of joints K_{JS}. The ductility factor D_{JS} was the ratio of deformation corresponding to peak point B and yield point A ($U_{\text{max-JS}}/U_{\text{JS}}$). In **Table 2**, the average initial stiffness, shear capacity, and ductility coefficient of the joints of the JS-GP group were 5.43 kN·mm^{-1}, 9.52 kN, and 3.00, which are 43.8%, 12.0%, and 64.8% higher than those of the JS-GV group, respectively. The wood grain direction affected the shear resistance of the joints. Previous studies have shown that the shear performance of dowel-type timber joints was related to the dowel-bearing strength of wood dowel-LVL. Thus, properly strengthening the dowel-bearing strength could improve the shear performance of dowel-type timber joints.

Table 2 Calculation of shear performance indexes of dowel-type timber joints

Specimen	K_{JS}	Yield point A		Peak point B		Ductility factor D_{JS}
	/kN·mm^{-1}	U_{JS}/mm	F_{JS}/kN	$U_{\text{max-JS}}$/mm	$F_{\text{max-JS}}$/kN	
JS-GP	5.43 （25.54）	3.97 （11.40）	8.15 （5.98）	11.78 （13.01）	9.52 （2.11）	3.00 （18.07）
JS-GV	3.56 （7.86）	3.02 （2.33）	7.13 （6.59）	5.49 （10.16）	8.50 （6.23）	1.82 （11.17）

Note: Average value (Coefficient of Variance×100%)

3.2. Bending performance of DLVL beams

3.2.1. Failure modes

Figure 7 shows the failure modes of DLVL beams. The failure locations of all DLVL beams were in and around the loading point and midspan ranges. In **Figure 7(a)**, the beams of the B-LP group with the loading direction parallel to the laminate stacking showed vertical cracks in the tension zone at the bottom of each laminate of the beams, and the cracks expanded along the glue layer direction. At the end of the beam, the slippage between the laminates was obvious, and the wood dowels had shear deformation due to the sliding of the laminates. In **Figure 7(b)**, the beams of the B-LV group with the loading direction perpendicular to the laminate stacking showed vertical cracks at the bottom of the beams, and the cracks tore further along the direction of the wood dowel arrangement. There was no slippage between the laminates of the beams, and no deformation of the wood dowels.

Figure 8 shows the load-deflection curves of DLVL beams. The curves of the specimens showed the same trend, and the load increased with increasing deflection. Divide the process of DLVL beams into elastic, elastoplastic, and failure stages: 1) In the elastic stage, the compression zone and tension zone of the specimens showed linear elasticity, and the curves increased linearly. 2) In the elastoplastic stage, the wood fiber near the top of the compression zone had a yield trend, and the curves mainly presented a stepped ascent. When the load was close to the ultimate load, there was a modest decrease due to the failure of some laminates, but the whole still had a sufficient bearing capacity. 3) In the failure stage, the tensile side of the specimens in the pure bending areas cracked, and the cracks expanded rapidly, showing brittle failure.

Figure 7: Failure modes of DLVL beams: (a) B-LP; (2) B-LV

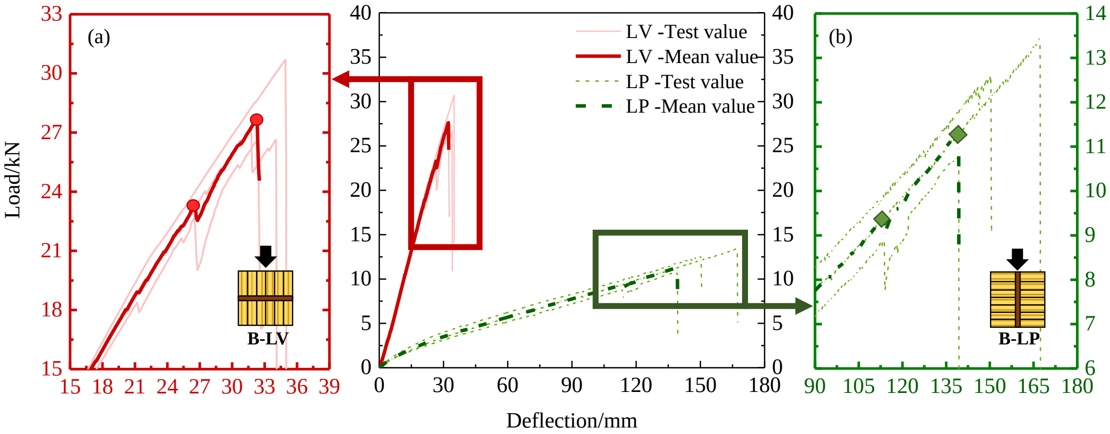


Figure 8: Load-deflection curves of DLVL beams: (a) B-LP; (2) B-LV

3.2.2. Mechanical property indices

According to standard EN 408 [15], analyze the flexural strength f_{B}, elastic modulus $E_{\mathrm{B\text{-}g}}$, and effective flexural stiffness $(E_{\mathrm{B\text{-}l}}I)_{\mathrm{ef}}$ of DLVL beams. The calculation formulas are as follows:

$$f_{\mathrm{B}} = \frac{F_{\mathrm{B-max}} l_0}{bh^2} \tag{1}$$

$$E_{\mathrm{B-g}} = \frac{a_0\left(3{l_0}^2 - 4{a_0}^2\right)\cdot \Delta F_{\mathrm{B}}}{48I\cdot \Delta w_{\mathrm{mid}}} \tag{2}$$

$$(E_{\mathrm{B-l}}I)_{\mathrm{ef}} = \frac{a_0{l_1}^2\cdot \Delta F_{\mathrm{B}}}{16\cdot \Delta w_{\mathrm{local}}} \tag{3}$$

$$I = \frac{bh^3}{12} \tag{4}$$

Where f_{B} is the flexural strength (MPa); $F_{\mathrm{B\text{-}max}}$ is the flexural capacity (N); l_0 is the clear span (mm); b is the section width (mm), that is, b_{B}; h is the section height (mm), that is, h_{B}; $E_{\mathrm{B\text{-}g}}$ is the modulus of elastic (MPa); a_0 is the spacing of the loading points (mm); ΔF_{B} is the load increment (N) and take the difference between 10% and 40% of $F_{\mathrm{B\text{-}max}}$; Δw_{mid} is the midspan deflection increment (mm) and take the midspan deflection difference corresponding to 10% and 40% of $F_{\mathrm{B\text{-}max}}$; I is the cross-section moment of inertia (mm^4); $(E_{\mathrm{B\text{-}l}}I)_{\mathrm{ef}}$ is the effective flexural stiffness (N·mm^2); l_1 is the distance of the pure bending areas (mm); $\Delta w_{\mathrm{local}}$ is the local deflection increment (mm) and take the local deflection difference corresponding to 10% and 40% of $F_{\mathrm{B\text{-}max}}$, where the local deflection is the difference between the average deflection in the midspan and the average deflection at 2.5h_{B} or 2.5h_{F} in the midspan.

In **Table 3**, the loading direction influenced the flexural strength, elastic modulus, and flexural stiffness of DLVL beams. The average flexural strength, elastic modulus, and flexural stiffness of the beams with the loading direction perpendicular to the laminate stacking were much higher than those with the loading direction parallel to the laminate stacking, which were 134.03%, 934.06%, and 713.66% higher, respectively.

Table 3 Calculation of flexural performance indices of DLVL beams

Specimen	$F_{\mathrm{B\text{-}max}}$ /kN	f_{B}/MPa	$E_{\mathrm{B\text{-}g}}$/GPa	$(E_{\mathrm{B\text{-}l}}I)_{\mathrm{ef}}$ / N·mm^2
B-LP	12.27 (11.24%)	15.34 (11.24%)	0.91 (12.71%)	26.50 (2.60%)
B-LV	28.72 (7.31%)	35.90 (7.31%)	9.41 (2.72%)	215.62 (7.45%)

Note: Average value (Coefficient of Variance×100%)

4. Conclusion

This study has demonstrated the development of DLVL, connecting small-thickness LVL with wood dowels. Double-shear tests of dowel-type timber joints were carried out to investigate the effect of wood grain direction on the shear properties of dowel-type timber joints. The influence of loading direction on the flexural behavior of DLVL was also studied by four-point bending tests. The main findings can be summarized as follows:

(1) The failure mode of dowel-type timber joints connecting small-thickness LVL with wood dowels was mainly plastic hinge failure. The wood grain direction affected the shear capacity of dowel-type timber joints by the dowel bearing performance.

(2) The load-deflection curves of DLVL beams composed of 20 mm thickness LVL laminates mainly showed the stepped ascent. The average flexural strength, elastic modulus, and flexural stiffness of the beams with the loading direction perpendicular to the laminate stacking were much higher than those with the loading direction parallel to the laminate stacking, which were 134.03%, 934.06%, and 713.66%

higher, respectively. DLVL showed a sufficient bearing capacity, but the failure mode was brittle. This aspect needs to be considered when exploring the possible fields of application.

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