Experimental Behavior of Laminated Veneer Lumber with Round Holes, with and without Reinforcement

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Laminated veneer lumber (LVL) is an engineered wood product that is commonly used for joists in wooden buildings. Holes in joists are often necessary to allow piping systems to pass through. Introducing a hole into an LVL joist remarkably changes the distribution of stresses in the vicinity of the hole. Tensile stresses occur perpendicular to the grain, and the capacity of the joist can be decreased accordingly. This study presents the experimental results of LVL joists with holes and reinforcement methods around the holes. The results showed that cutting a large enough hole contributed substantially to the strength reduction of LVL joists. Holes with a diameter-to-joist depth ratio of 0.4, 0.5, and 0.6 reduced the load-capacity 50.1%, 59.6%, and 68.8%, respectively. Glued plywood and glued-in threaded rods were both effective methods for reinforcing LVL joists with holes having a diameter-to-joist depth ratio of less than 0.5. The reinforcement effect of nailed plywood was relatively poor, increasing the load-capacity less than 30%. The reinforcement effect of all of the methods depended on the effective joint with the LVL. The thickness of the plywood, the number of nails, and the withdraw strength were also important factors.

Keywords: Laminates; Wood, Fracture; Hole; Strength

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INTRODUCTION

Laminated veneer lumber (LVL) is an internationally used generic descriptor for an assembly of veneers laminated with adhesive, in which the grain direction of the outer veneers and most of the other veneers is in the longitudinal direction, as described in AS/NZS 4357.2 (2006). Laminating distributes the natural defects of the wood and provides uniform structure, dimensional stability, and strength. As a result of these characteristics, LVL has become one of the most important engineering wood products used today. As a structural material, LVL is commonly used as a carrying component, such as in joists, and the structural strength is the focus.

Holes in joists represent frequent constructive requirements in buildings. Economical and architectural reasons often prohibit any constraints to room height, *e.g.*, caused by pipes for ventilation, water, and sewage (Aicher and Hofflin 2004). The pipes have to penetrate through the joists *via* holes located generally at mid-depth of the cross-section. The holes can be of considerable size, acting as stress concentrators and giving rise to greater tensile stresses perpendicular to the grain. Wood is very weak when exposed to tensile stress perpendicular to the grain. A large enough hole in the shear dominant region of the joist can change the failure mechanism to crack initiation and propagation around the hole (Ardalany *et al.* 2013b). Global strength is most often limited by perpendicular-to-the-grain fractures with crack initiation at the hole periphery and crack propagation along the grain direction. Hence, additional reinforcement should be given to joists with holes.

Studies of beams with holes and corresponding reinforcement methods have focused on glulam and I-beams (Johannesson 1983; Petersson 1995; Riipola 1995; Afzal *et al.* 2006; Pirzada *et al.* 2008). The reinforcement methods, described in the standard DIN 1052 (2008), use plywood and screws. Other reinforcement materials, such as steel bars, fiberglass, and self-tapping screws, were proposed and investigated (Hallström 1996; Aicher and Hofflin 2009). Formulas and design models for reinforced beams with holes are less.

Some research on LVL joists has been conducted recently. Ardalany *et al.* (2012) studied the effect of the location of a hole. The results indicated that the load-carrying capacity underwent a subtle change when the hole position was moved perpendicular to the grain, a slight difference when the hole position was moved to below the neutral axis, and a 10% positive difference when the hole position was moved to above the neutral axis in the compressed part of the joist. Additionally, in the three-point-bending test, the load-carrying capacity was nearly constant when the hole position was moved along the length of the joist, as long as there was enough distance that the hole is at least one beam height from the support and the loading location. Some reinforcement methods have also been tested by Ardalany *et al.* (2013a). The research showed a promising solution using glued plywood.

In the present study, LVL joists with holes of varying diameters (80 mm, 100 mm, and 120 mm) were tested for the purpose of evaluating the effect of opening diameter. Various options for reinforcement were investigated for the sake of proposing effective and convenient reinforcement methods. Nailed plywood, glued plywood, and glued-in threaded rods were used to reinforce LVL joists with holes and several variables not reported in the previous research were investigated.

EXPERIMENTAL

Materials

Laminated veneer lumber was produced from Douglas fir and manufactured by Weyerhaeuser (Seattle, WA, USA). There were 13 layers, averaging 45 mm in thickness, and all laminae were in the same direction. The mean density and moisture content, measured according to GB/T 20241 (2009), were 560 kg/m^3 and 7.7%, respectively. Other mechanical properties of the LVL are presented in Table 1. Tension strength perpendicular to the grain was a critical variable in this experiment, and the data were measured according to BS EN 408 (2012). The LVL was cut into test pieces with dimensions of 1500 mm × 200 mm × 45 mm, and round holes with various diameters were cut into these pieces according to the experimental program in Table 2.

Table 1. Material Properties of LVL

Shear Modulus of Elasticity (MPa)	Modulus of Elasticity (GPa)	Compression Perpendicular to Grain (MPa)	Tensile Strength Perpendicular to Grain (MPa)	Horizontal Shear Parallel to Grain (MPa)
862.07	13.79	5.17	0.83	7.34

Table 2. Experimental Program

Serial Number	Hole Diameter (mm)	Reinforcement Method	Plywood Thickness (mm)	Joint Method Between Plywood and LVL
1	No hole	—	—	—
2	80	None	—	—
3	80	Plywood	5	4 round nails
4	80	Plywood	5	8 round nails
5	80	Plywood	5	16 round nails
6	80	Plywood	5	4 screws
7	80	Plywood	5	8 screws
8	80	Plywood	5	16 screws
9	80	Plywood	9	8 screws
10	80	Plywood	12	8 screws
11	100	None	—	—
12	100	Plywood	9	8 screws
13	120	None	—	—
14	120	Plywood	9	8 screws
15	80	Plywood	9	Adhesive
16	100	Plywood	9	Adhesive
17	120	Plywood	9	Adhesive
18	80	Threaded rod	—	—
19	100	Threaded rod	—	—
20	120	Threaded rod	—	—

The plywood was made of fast-growing poplar grown in Siyang County of Jiangsu Province, China. Three common thicknesses of plywood in the Chinese market were selected (5 mm, 9 mm, and 12 mm) to compare the strengthening effect of plywood of varying thickness. The plywood, with dimensions of 1220 mm × 2440 mm, was cut to specimens with dimensions of 200 mm × 200 mm, and round holes of various diameters were cut into the specimens according to the experimental program in Table 2. The mean density and moisture content, measured according to GB/T 9846.3 (2013), were 0.43 g/cm^3 and 11.4%, respectively.

Plywood specimens were nailed or glued to both sides of the LVL joists with holes (Fig. 1). No adhesive was used when the plywood was nailed to the LVL to compare the reinforcement effects of nailed plywood and glued plywood. The adhesive was epoxy resin. Two kinds of nails were selected, round nails and screw nails, both with 40-mm length and 2.0-mm diameter. The main difference between them was the thread. Three configurations of nails (Fig. 1) were tested.

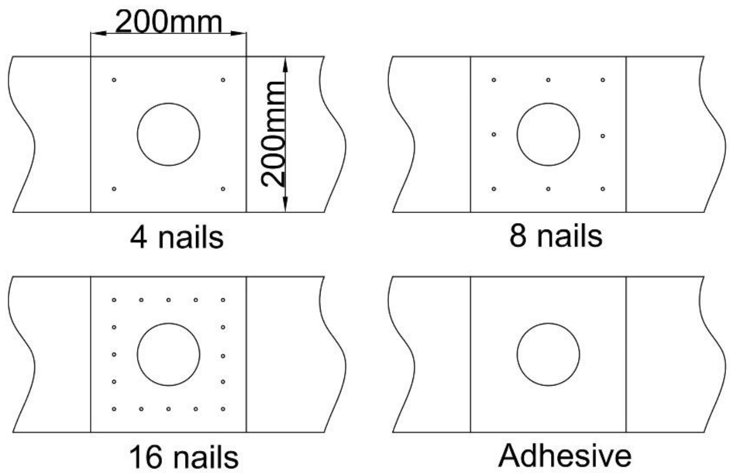


Fig. 1. Different joint modes between plywood and LVL

The threaded rods were made of carbon steel, with a strength grade of 4.8 (*i.e.*, the tensile strength was 400 MPa, and the yield ratio was 0.8), according to GB/T 3098.1 (2010). The length of the threaded rods was 250 mm, and the nominal diameter was 6 mm. Two threaded rods were glued and inserted into pre-drills on both sides of the hole (Fig. 2). The adhesive was epoxy resin. Two nuts and two washers were used to limit the rod from moving. Other criteria, such as pre-drill diameter and distance from the hole edge, should be complied with to prevent splitting in the surrounding wood. In this experiment, to minimize strength weakness caused by pre-drills, a diameter of 7 mm was chosen. To prohibit cracks around the hole caused by the pre-drill, a distance of 30 mm from the hole edge was chosen (Ardalany *et al.* 2012).

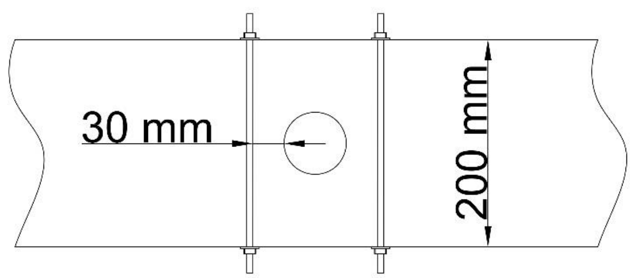


Fig. 2. Schematic drawing of reinforcement with threaded rods

Methods

The three-point bending test, following AS/NZS 4063.2 (2010), was carried out on all of the LVL joists, with a constant rate of 2 mm/min. The LVL joist was put on the roller supports of the WDW-300E mechanical testing machine (Jinan Wanyuan Test Equipment Co., Ltd., Jinan, China). Three steel plates (200 mm × 90 mm × 40 mm) were used on the roller supports and load point during the three-point bending test to avoid crushing the timber and ensure uniform loading. Four displacement sensors (W1, W2, W3, and W4, shown in Fig. 3) with an accuracy of ± 0.1 mm were used to measure deformations at the supports and global deformation and local deformation at mid-span. A load cell with an accuracy of ± 0.5 kN was used to measure the applied load.

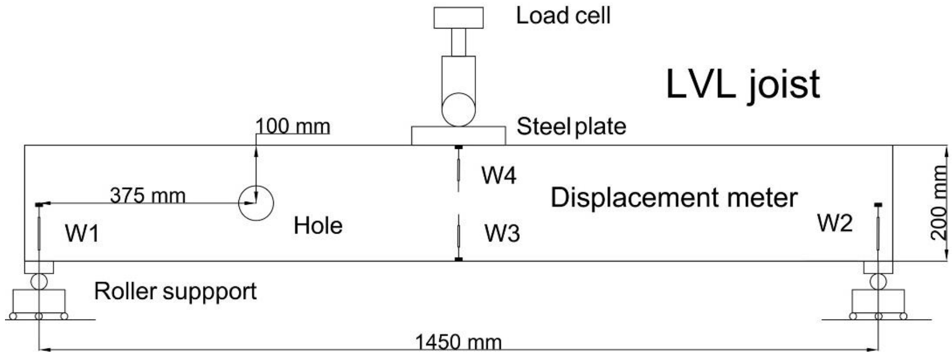


Fig. 3. Schematic drawing of experimental setup

The experimental program is presented in Table 2. Joists without holes, joists with non-reinforced holes, and joists reinforced with nailed plywood, glued plywood, or threaded rods were included. Three specimens were tested for each configuration.

RESULTS AND DISCUSSION

A typical failure scenario was observed for the joists with holes and without reinforcement that was characterized by two distinct major cracks, starting at the hole edge at the diagonally opposite location of the maximum tension stress, perpendicular to the grain, and extending parallel to the longitudinal direction (Figs. 4a, b). The ultimate load emerged when the crack appearing under the specimen arrived at the end of the joist, and shear fracture suddenly occurred (Fig. 4c).

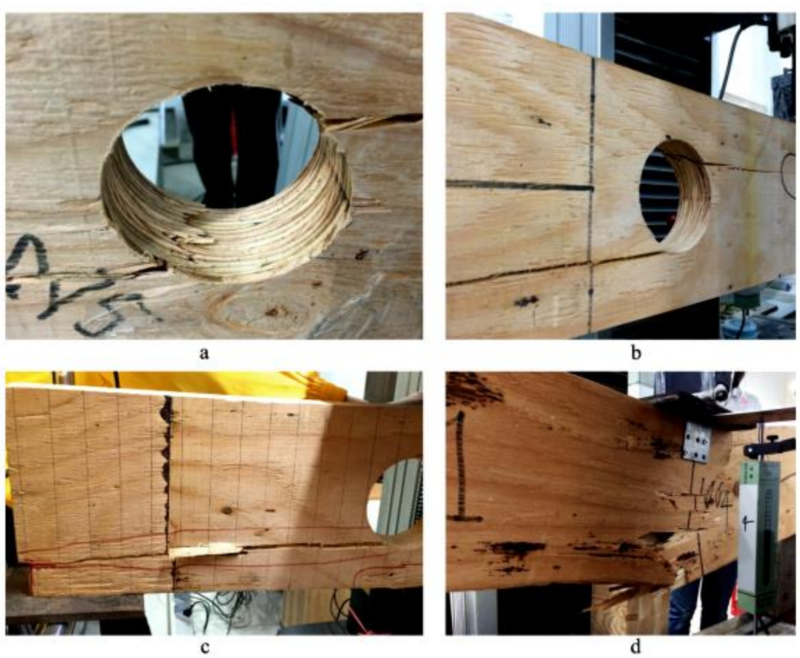


Fig. 4. Failure mechanisms of joists with and without holes: (a) two main cracks started at the hole edge; (b) cracks extended along the grain; (c) shear failure of the joists with holes; and (d) bending failure of the joists without holes

Generally, the design of a beam is governed by its bending stress and deflection limits. However, for beams with holes, shear stress can be more important. Normally, the maximum shear stress appears at areas around the supports, and the holes lead to substantial shear stress concentration. In contrast, with the bending failure of intact joists, which is always accompanied by fracture perpendicular to the grain (Fig. 4d), the shear failure of joists with holes was characterized by sliding of the fibers (Fig. 4c), and was considered a brittle failure.

In addition to the changing failure mechanism, holes weakened the load capacity of joists dramatically. For a 200-mm depth joist, a hole of 80-mm, 100-mm, or 120-mm diameter reduced the failure strength by 19.5%, 39.9%, and 52.3%, respectively. However, the effect of holes on the stiffness of the joists was unobvious (Fig. 5a).

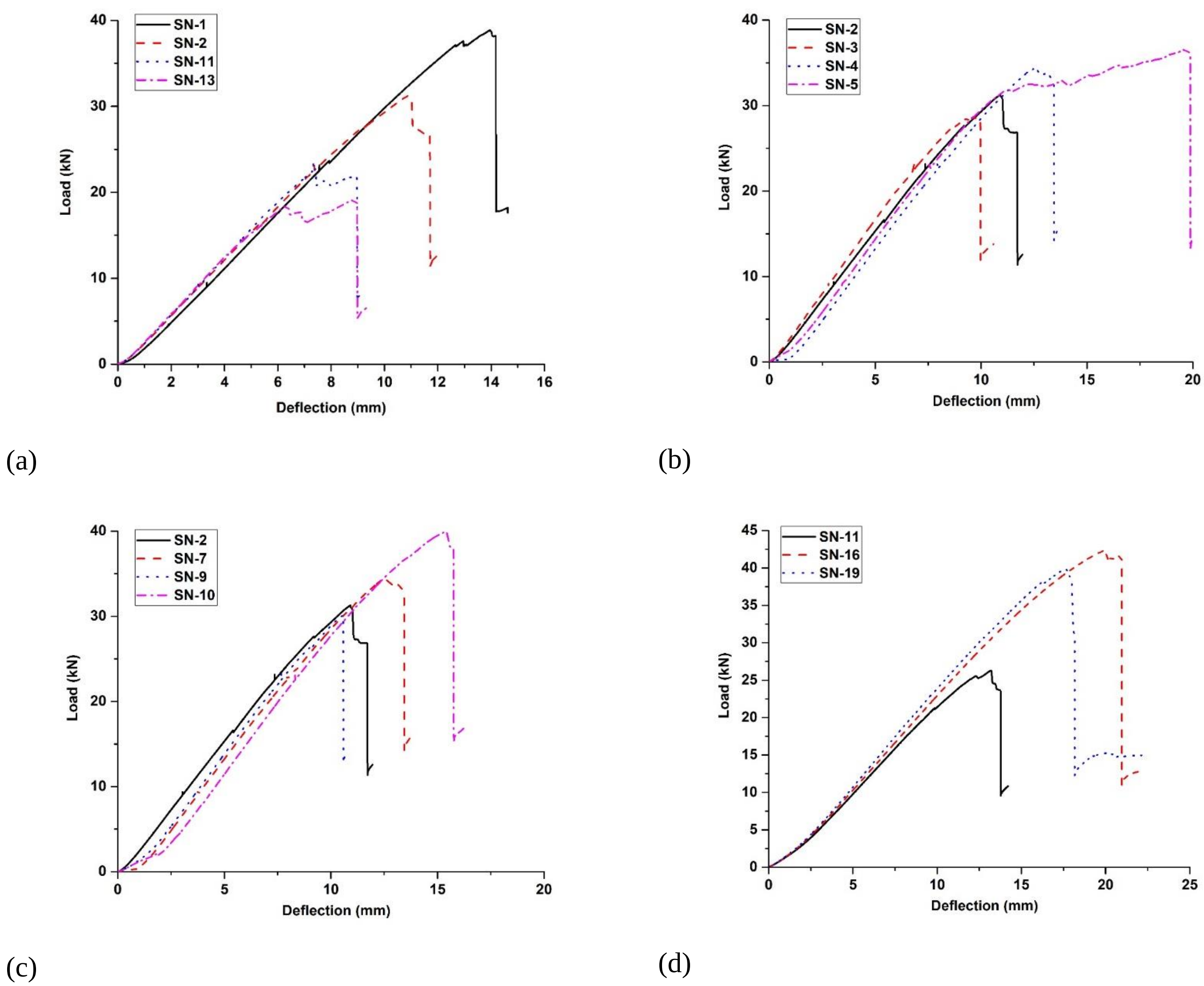


Fig. 5. Load-deflection curves for various test specimens for comparison of hole diameter (a), screw quantity (b), plywood thickness (c), and reinforcement method (d); SN is the serial number in Table 2, every line was an example of the corresponding serial.

For the joists reinforced with plywood, the results were influenced by the joint mode between the LVL and the plywood. For the LVL joists reinforced with nailed plywood, the failure mechanism was the same as the joists with holes and without reinforcement, *i.e.*, two main cracks appeared diagonally opposite of the hole and extended along the grain. Failure occurred suddenly when the lower crack arrived at the end of the LVL joist, and the nailed plywood did not stop the propagation of the cracks. However, in the case of LVL joists reinforced with glued plywood, different phenomena were observed. In the tests of LVL joists with 80-mm holes, two tiny cracks initiated inside the holes, but they stopped when they reached the plywood. As the load continued, new cracks appeared at the bottom of mid-span and extended perpendicular to the grain. Finally, the joists fractured at mid-span, just like the intact joist. In the tests of LVL joists with 100-mm and 120-mm holes, the failure mechanism was same as joists with holes and without reinforcement.

As shown in Figs. 5b and 7a, the quantity and type of nails influenced the strengthening effect of nailed plywood. The plywood with 4 screw nails or round nails did not strengthen the joists but weakened them. This result may have been because the strengthening effect of this setup was minimal. More round nails or screw nails provided a greater contribution to the bond between the plywood and the LVL so that the stress could be transferred from the LVL to the plywood through these nails. Especially in the case of using 16 screw nails, the nailed plywood slowed the development of cracks around the holes, delayed the time to breakage, and provided a maximum load of 36.58 kN, which was close to the joists without holes. During the bending tests, it was discovered that the nailed plywood rotated and broke away from the LVL under the stress around the holes (Figs. 6a, b).

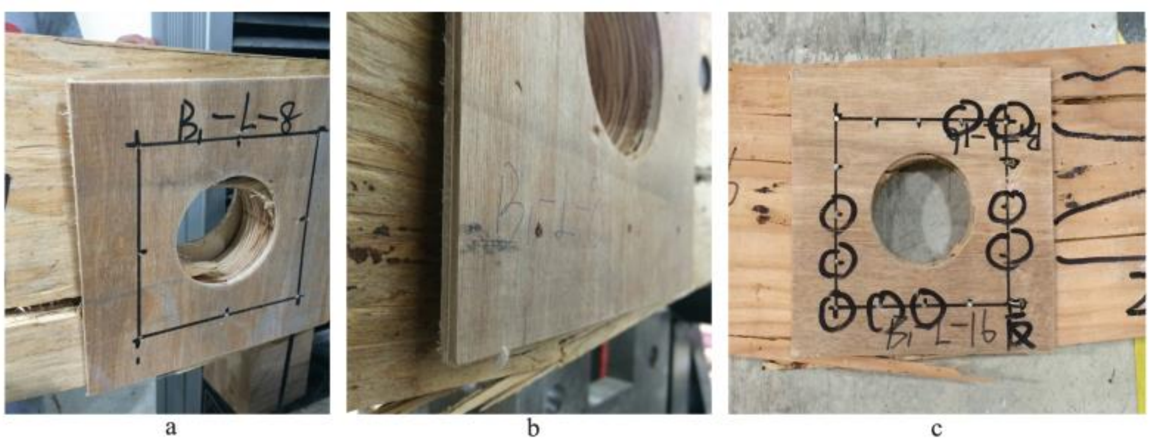


Fig. 6. Observations of nailed plywood: (a) rotation of the plywood, (b) separation between LVL and plywood, and (c) nails sinking around cracks

The nails around the holes were distorted and sank into the joists, particularly the nails around the cracks (Fig. 6c). Thus, these nails transmitted the stress from the LVL to the plywood and bore shear stress at the same time. The bond between the LVL and the plywood was tighter, the separation of the plywood was more difficult, and the failure time of the joists was longer with an increasing number of nails, and thus, the load-bearing capacity of the joists was better. Because of the higher withdrawal capacity in comparison with the round nails, the screw nails required more stress to distort and pull out, and thus, contributed to more load-bearing during the tests (Fig. 7a). The thickness of the plywood also influenced the reinforcing effect of the nailed plywood (Fig. 5c). The failure load of joists reinforced with 5-mm nailed plywood was 34.47 kN, but it was 40.88 kN for the joists reinforced with 12-mm nailed plywood, exceeding the failure load of the intact joist (38.86 kN). Limited by the size, the 5-mm plywood was more likely affected by the moisture content and more easily warped than the 12-mm plywood. Because of the discontinuous bond between the plywood and LVL caused by the nails, the effective connection areas of the warping plywood was much lower than that of the normal plywood.

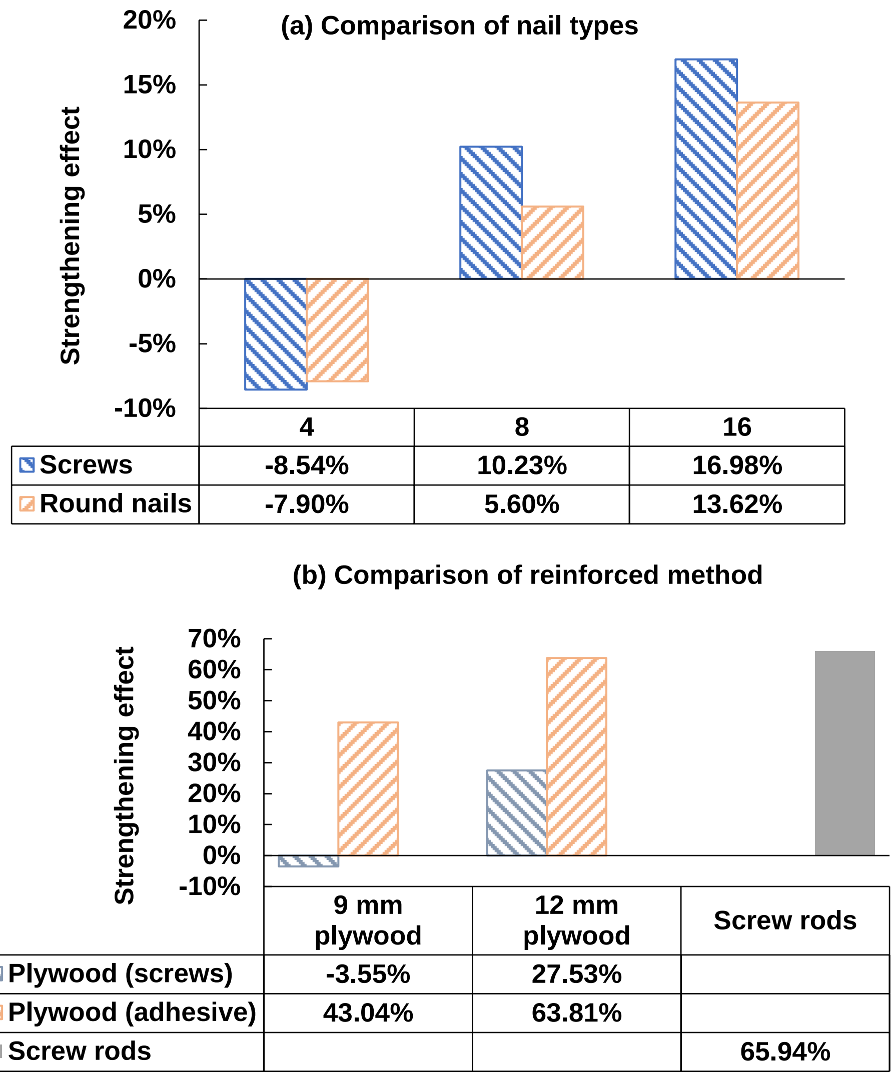
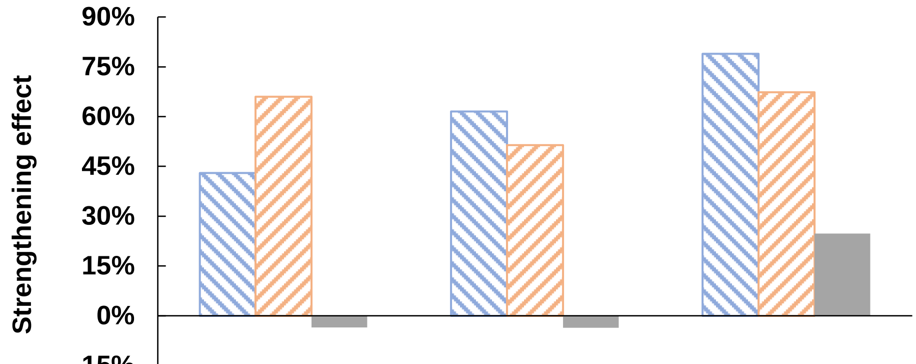


Fig. 7. Strengthening effect of various reinforcement methods for joists with 80-mm holes. Comparison of nail types (a) and reinforced method (b)

The plywood that was glued to the LVL reinforced the joists substantially. As shown in Fig. 8, for joists with 80-mm, 100-mm, and 120-mm holes, 9-mm glued plywood increased the failure load by 43.0%, 61.5%, and 78.9%, respectively, compared to the joists with holes and without reinforcement. In some cases, the maximum load of the reinforced joists exceeded that of the joist without holes. However, the 9-mm plywood did not prevent the propagation of cracks. The failure mode of the joists was shear failure around the holes, and plywood on both sides of the joists also showed shear failure (Fig. 9b). For joists with

80-mm holes reinforced with 12-mm glued plywood, failure occurred at mid-span (Fig. 9a). The 12-mm glued plywood contributed more strength (approximately 20.81%, as shown in Fig. 7b) than the 9-mm plywood, and stopped the extension of cracks around the holes, successfully changing the failure mechanism. Therefore, the thicker plywood was able to bear more stress.



	Joist with 80 mm hole	Joist with 100 mm hole	Joist with 120 mm hole
Plywood (adhesive)	43.04%	61.51%	78.93%
Screw rods	65.94%	51.43%	67.32%
Plywood (screws)	-3.55%	-3.60%	24.74%

Fig. 8. Increase in failure load of joists with various reinforcement methods in comparison with joists with holes and without reinforcement

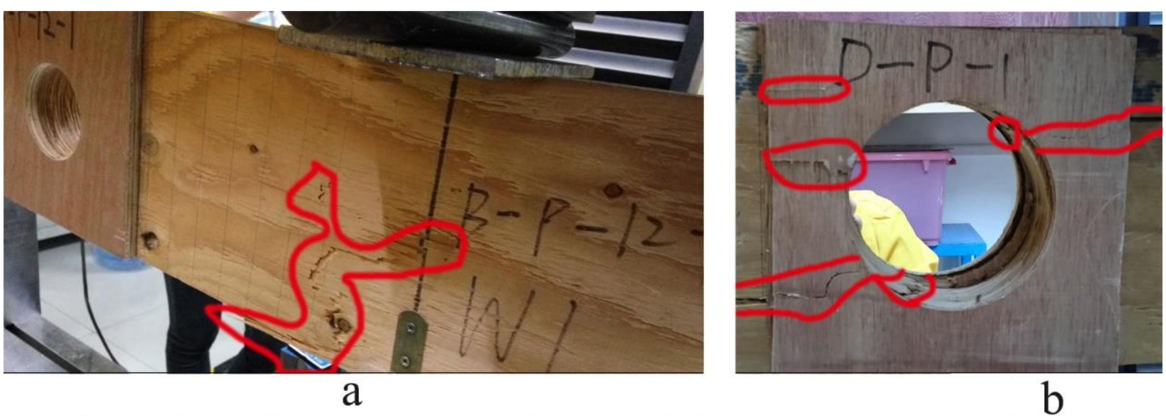


Fig. 9. Failure observation: (a) bending failure in mid-span of joists reinforced with 12-mm plywood and (b) shear failure cracks in 9-mm plywood

The strengthening effects and mechanisms of nailed plywood and glued plywood were quite different. The simple installation of the nailed plate was an advantage, while a disadvantage was that the bond between the plywood and the LVL was not continuous because of the nailing. Therefore, cracks can form and propagate. It was expected that more nails provided more reinforcing effectiveness, as the shear force is transferred through the nails from the LVL to the plywood. For the glued plywood, internal forces around the holes were decentralized through the adhesive layer, which prevented stress from concentrating. In this view, it was considered that the reinforcing effectiveness of glued plywood was governed by effective gluing. To ensure an effective gluing, 24 h are always necessary for adhesive curing. The glued plywood method was not expedited to allow for this.

Limited by the thickness of the LVL joists (45 mm), threaded rods with small diameters (6 mm) were selected. To minimize the influence of pre-drills on the effective section, the lowest possible diameter (7 mm) was used. During testing on the joists reinforced with glued-in threaded rods, the two characterized cracks also formed around the holes and extended along the grain. When the upper crack reached a threaded rod, it was stopped from further development. When the lower crack reached the other threaded rod, it was initially stopped, but as the load increased, the threaded rod slipped and bent under the shear stress. The crack propagated towards the end of joist, and shear failure occurred.

As shown in Figs. 5d and 8, the glued-in threaded rod was an effective method for reinforcing joists with holes. Similar to adhesive plywood, the use of glued-in threaded rods for holes up to 100 mm (0.5 of the joist depth) yielded excellent results in recovering the load-carrying capacity to that of intact joists. As for larger holes, *i.e.*, 120 mm, the failure load was increased by 67.32%. It was observed that the rod over the upper crack (Fig. 10a) was undamaged, while the other rod (Fig. 10c) was bent or broken, and the interface between the rod and the timber was fractured. Limited by the threaded rod, the upper crack could not extend over the boundary, and the tension stress could not be released through the development of the crack, which led to new cracks above the hole and a bulge of the timber in that area (Fig. 11).

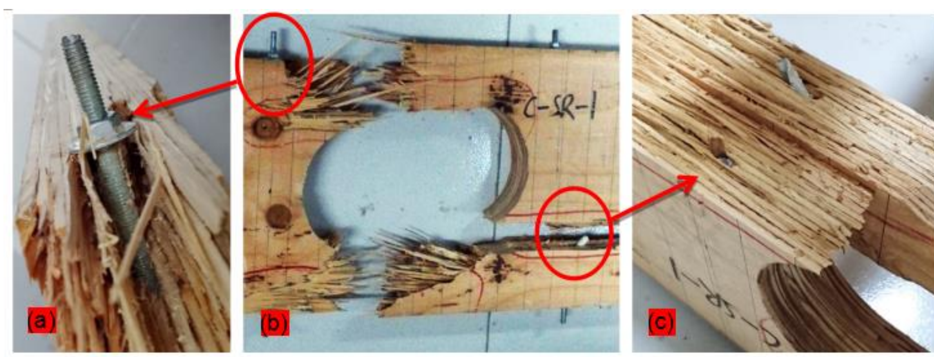


Fig. 10. Disassembly of the joists reinforced with glued-in threaded rods (b); the left rod was unharmed (a), but the right rod was broken (c)

Fig. 11. Cracks above the hole were confined within the two rods (a), and the wood under the washer was compressed (b)

Overall, glued-in threaded rods were an effective reinforce method for LVL joists with holes having a diameter-to-joist depth ratio less than 0.5. It was worth noting that threaded rods were not able to prevent crack development, *i.e.*, could not recover the typical bending failure mechanism, but were very effective at recovering the load-carrying capacity to that of the joist without a hole.

Holes can reduce the load-carrying capacity of timber joists dramatically and change the failure mechanism from bending failure to shear failure. The results showed that in a 200-mm deep joist, holes with diameters of 80 mm, 100 mm, and 120 mm (*i.e.*, with a diameter-to-joist depth ratio of 0.4, 0.5, and 0.6, respectively) reduced the load-capacity 50.1%, 59.6%, and 68.8%, respectively. For the sake of recovering the strength properties of joists with large holes, some reinforcement methods were proposed and tested.

CONCLUSIONS

1. Nailed plywood was the most convenient method of the three reinforcement methods. It minimally improved the strength properties of the joists with holes (less than 30%), and the effectiveness increased with increases in the withdraw capacity of the nails, the quantity of the nails, and the thickness of plywood. The latter two factors influenced the effective joint between the LVL and the plywood.
2. Glued plywood was an effective method for reinforcing LVL joists with holes having a diameter-to-joist depth ratio less than 0.5. It is important to note that gluing effectiveness was a determining factor in reinforcement. To ensure effective gluing between the plywood and the joists, suitable pressure was useful during gluing. The thickness of the plywood was also a crucial factor. The use of thin-glued plywood increased the load capacity remarkably but did not change the failure mechanism. The use of thicker glued plywood contributed more strength than thin plywood, prevented the development of cracks, and recovered the typical bending failure mechanism.
3. Glued-in threaded rods were able to change the distribution of stress on a small scale but did little in changing the shear failure. The reinforcement effectiveness of threaded rods was mainly reflected in the recovery of load-capacity.

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