Construction and Building Materials 411 (2024) 134158

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Towards reducing the capital cost of manufacturing Laminated Veneer Lumbers: Investigating finger jointing solutions

Benoit P. Gilbert [a,b,*], Thomas E. Davies [a], Robert L. McGavin [a,b], Chris J. Dowse [a]

[a] Queensland Department of Agriculture and Fisheries, Horticulture and Forestry Science, Salisbury Research Facility, Salisbury, QLD, Australia
[b] School of Engineering and Built Environment, Griffith University, QLD, Australia

ARTICLE INFO

Keywords:
Laminated Veneer Lumber (LVL)
Finger joints
Structural performance
Continuous LVL

ABSTRACT

The capital cost of setting up a Laminated Veneer Lumber (LVL) plant which produces continuous LVL billet products, through a continuous veneer assembly and hot-pressing processes, is significant. However, the utilisation of batch-type presses, similar to those employed in the plywood industry, could significantly reduce this initial cost and may provide new opportunities for small to medium scale operations. This process would produce shorter billet lengths which would need to be joined together to produce lengths viable for structural products. Scarf joints have been used commercially to join some veneer-based engineered wood products but have limitations, while finger joints are a common method for jointing sawn timber products and offer some key advantages but is not a common method to join veneer-based products. Consequently, this paper focusses on investigating the influence of key manufacturing parameters on the performance of finger jointed LVL. The effect of the joint orientation (horizontal or vertical), the finger length, the gluing pressure and the adhesive type on the joint strength and stiffness were investigated. The finger jointed LVL were tested in edge bending, flat bending and tension, and the results were compared to reference unjointed LVL. The bending performance of the finger jointed LVL was also compared to scarfed jointed LVL. In total 304 tests were performed. The results indicated that the average strength values of finger jointed LVL can reach up to 99% of the average strength of unjointed LVL and compares to scarf jointed LVL on flat bending. Horizontal joints, being more practical to produce for deep beams, performed similarly to vertical joints. The 25 mm joints were found to have no mechanical advantages over the 20 mm investigated finger joints. A gluing pressure lower than the Eurocode's recommended level for solid timber achieved sufficient bonding for the products to be utilised. The gluing pressure was also found not to influence the performance of the joint, for the range of pressures investigated. Both polyurethane and resorcinol-formaldehyde adhesives produced high performing products, with the latter displaying superior adhesive bond durability. The paper concludes that finger jointing LVL represents a viable solution to manufacture usable LVL lengths from short LVL billets, but have lower edge bending efficiency than scarf jointed LVL.

1. Introduction

The production of continuous Laminated Veneer Lumbers (LVL) requires a high initial capital investment due to the need for specialised equipment and machinery, such as continuous veneer assembly and hot-pressing lines [1–3]. Utilising batch-type presses, commonly used in the plywood industry, to produce LVL billets would require more accessible and rudimentary equipment, thereby reducing the capital cost of establishing an LVL plant and potentially providing new opportunities for small to medium scale operations. However, the use of such presses would result in billets of fixed dimensions, typically 2.4 m long, which would need to be joined together to create lengths that are more aligned with market demand for structural products, such as roof trusses, transfer beams or floor joists. To produce long LVL, the manufacturer can either joint the billets first and cut them into LVL of commercial depth or cut the billets into LVL products first and joint the products individually.

For this reason, Youngquist et al. [1] and Biblis et al. [3] looked at different ways of jointing LVL sections together. Youngquist et al. [1] investigated 28 mm long horizontal (Fig. 1(a)) and vertical (Fig. 1(b))

* Corresponding author at: Queensland Department of Agriculture and Fisheries, Horticulture and Forestry Science, Salisbury Research Facility, Salisbury, QLD, Australia.

E-mail addresses: benoit.gilbert@daf.qld.gov.au, b.gilbert@griffith.edu.au (B.P. Gilbert).

https://doi.org/10.1016/j.conbuildmat.2023.134158
Received 26 September 2023; Received in revised form 2 November 2023; Accepted 9 November 2023
Available online 30 November 2023

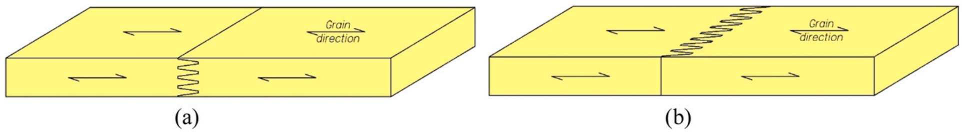


Fig. 1. (a) Horizontal and (b) vertical finger joints.

finger joints, as well as 159 mm long scarf joints, on 19 mm thick *Pseudotsuga menziesii* (Douglas fir) LVL. The scarf and finger joints were glued with phenol-resorcinol-formaldehyde and melamine-urea-formaldehyde, respectively. Samples were tested in tension only. The scarf joints outperformed the finger joints and achieved on average 95% of the strength of the control samples. In contrast, the horizontal and vertical finger joints exhibited average strengths equivalent to 71% and 83%, respectively, of the control samples. The authors also reported that machining the finger joints resulted in fast dulling of the cutters when compared to solid timber, especially for the horizontal joints for which the cutters wore at the locations of the gluelines. It was estimated that the cutters wore about 50 times and 8 times faster than solid timber for the horizontal and vertical joints, respectively. Nevertheless, with the improvement of tooling in the last 40 years, particularly the use of cemented carbide cutters when compared to high-speed steel cutters, wearing of the tools may be less of an issue than the 1984′s study by Youngquist et al. [1].

Biblis et al. [3] looked at finger joint orientation and wet-dry cycling on *Pinus taeda* (loblolly pine) LVL. The LVL were manufactured using either mature (50-year-old) or younger (20-year-old) trees. 38 mm × 89 mm samples were joined with 16 mm long finger joints and glued with a commercial aliphatic cross-linking adhesive. The finger joints were tested in three-point bending, both on edge and flat. Horizontal joints performed better than vertical joints on edge bending, while the opposite was true for flat bending. The average capacity of the samples manufactured from the mature and younger trees was equal to 55% and 88%, respectively, of the one of the control samples.

While the studies by Youngquist et al. [1] and Biblis et al. [3] offer valuable insights into the feasibility of jointing LVL and its ability to achieve mechanical properties comparable to unjointed specimens, key manufacturing information, such as the glue spread rate and gluing pressure, was not provided. Additionally, as the performance of finger joints on solid timber is affected by the gluing pressure to some extent [4–6] and by the finger joint length to a greater extent [5–9], it is important to understand the influence of these parameters of the mechanical properties of finger jointed LVL to optimise the manufacturing process. The choice of structural adhesive is critical in both manufacturing constraint and joint performance [7,8].

Additionally, while scarf jointing of veneer-based engineered wood products is used commercially, with the Australian and New Zealand standard AS/NZS 2269.0 [10] providing requirements to scarf joint plywood sheets together, finger joints are rarely used for such products despite representing a common jointing method for solid timber sections. Finger joints have manufacturing advantages over scarf joints: (1) they are wasting less material, being commonly between 8 mm and 25 mm long, opposite to scarf joints typically cut with a slope of 1:8–1:10 [10] and (2) they are faster to manufacture with a pressing time of a few seconds opposite to the full curing time of the adhesive for scarf joints. However, due to the tip gaps, they do not joint the full cross-section contrary to scarf joints. Investing the performance of finger jointed LVL and comparing it to the more accepted behaviour of scarf joints would provide essential decision-making data to a manufacturer willing to joint LVL sections.

Therefore, this study focusses at exploring the influence of key manufacturing parameters, including adhesive type, gluing pressure, finger length and finger orientation, on the bending and tension mechanical properties of finger jointed LVL. The bending performance of the finger jointed LVL was also compared to scarf jointed LVL. Investigations were performed on LVL obtained from two different companies and on two different LVL sizes. The bond durability of the finger joints was also investigated. The paper first presents the material used and methodology followed. The results are then discussed and compared to control samples consisting of unjointed LVL. The importance of controlling the investigated manufacturing parameters is examined. The characteristic design values calculated from the Eurocode EN 14358 [11] are also discussed. The paper only focuses on LVL, and cross-banded LVL are excluded from the study.

2. Materials and Methods

2.1. Materials

2.1.1. LVL

Two commercially produced LVL, from two different manufacturers (using continuous veneer assembly and hot-pressing lines), have been used in this study. These two commercial LVL types are referred to as Type 1 (T1) and Type 2 (T2). Type 1 LVL is composed of a mix of nominally 4.2 mm thick and untreated softwood and hardwood veneers, typically with two hardwood veneers through the cross-section, commonly positioned as the third veneers from the faces. Type 2 LVL is assembled from nominally 2.8 mm thick softwood H2 treated veneers [12].

For the finger jointed samples, all tested Type 1 LVL samples were cut from eight nominally 6.0 m (long) × 1.2 m (wide) × 38 mm (thick) billets, while the Type 2 LVL samples were cut from two nominally 5.7 m (long) × 150 mm (wide) × 45 mm (thick) and one 2.9 m × 400 mm (wide) × 45 mm (thick) LVL beams. Per investigated parameter, 12 Type 1 LVL and 14 Type 2 LVL samples were tested. The samples were grouped in 12 or 14 sets, with each set containing one sample of each analysed parameter. The samples within each set were cut in close proximity to each other to ensure they were manufactured from the same veneers, and as detailed in Sections 2.2.2 to 2.2.4, the samples to be used to investigate the influence of the joints on the mechanical properties were cross-cut in two parts which were jointed together. This process allowed a direct comparison between different parameters through consistent material between samples within a set. Reciprocally, the sets were cut as far away from each other as practically possible along the LVL billets and beams to ensure they were manufactured from different veneers, avoiding potential bias towards samples made from the same material.

A similar approach was followed for the scarf jointed samples, with the samples cut from another two nominally 6.0 m (long) × 1.2 m (wide) × 38 mm (thick) Type 1 LVL billets.

2.1.2. Adhesives

Two different adhesive types were used in the finger joint manufacture within the tested samples, while only one adhesive type was used for the scarf joints. They consisted of a 1-part 10 min polyurethane (PUR) (681.10) and a 2-part resorcinol-formaldehyde (RF) (950.82 resin with 950.85 powder hardener) structural adhesives. Both adhesives were manufactured by Jowat Universal Adhesives Australia Pty. Ltd.

The PUR was applied on one side of a joint at an average spread rate of either 430 g/m^2 (Stage 1 – see Section 2.2.2) or 630 g/m^2 (Stages 2 and 3 – see Sections 2.2.3 and 2.2.4, respectively). The RF was applied on both sides of a joint at an average spread rate of 500 g/m^2.

Note that the pressure to be applied for finger joints are commonly

Table 1
Samples manufactured and tested in Stage 1.

Label	Number of samples	Dimension - L (mm) × W (mm) × T (mm)	LVL	Finger joint Orientation	Cutter size (mm)	Glue type	Gluing pressure (MPa)	Loading type
St1_T2_OV_C20_PUR_P5.5_BE	14	980 × 45 × 45	Type 2	Vertical	20	PUR	5.5	Bending edge
St1_T2_OH_C20_PUR_P5.5_BE				Horizontal				
St1_T2_BE_Ref				N/A	N/A	N/A	N/A	
St1_T1_OV_C20_PUR_P5.5_BF	12	850 × 45 × 38	Type 1	Vertical	20	PUR	5.5	Bending flat
St1_T1_BF_Ref				N/A	N/A	N/A	N/A	

Fig. 2. Modified Festo Jointing Machine Combination FKV used in Stage 1 to press finger joints.

not provided by adhesive manufacturers, and as further developed in Section 3.1, the Eurocode EN15497 [13] can be used as a guide to calculate the required pressure versus finger length. However, while the pressure for face lamination is different to the one to be applied for finger joints, it is generally provided by adhesive manufacturers. These face lamination pressures are reported herein for reference only and are 0.6–0.8 MPa for the PUR and 0.7–1.0 MPa for the RF adhesives used.

2.2. *Methodology*

2.2.1. *General*

The experimental tests performed followed the best practice outlined by Gilbert et al. [14] and the research was performed in two incremental stages, consisting of:

- *Stage 1*: Type 1 and Type 2 LVL were cut to 45 mm (wide) × 38 mm (thick) and 45 mm (wide) × 45 mm (thick) samples, respectively. These samples were then cut in two and finger jointed in a commercial facility (EcoCottages, Cooroy, Queensland). They were used (1) as a benchmark for the finger joints manufactured in Stage 2, ensuring that this subsequent manual and laboratory-based manufacturing process best replicated commercial practices, and (2) to investigate the consistency of results between different LVL types (Types 1 and 2) and assess the influence of finger joint orientation.
- *Stage 2*: Finger jointed LVL samples were manufactured from Type 1 LVL products at the Queensland Department of Agriculture and Fisheries' Salisbury Research Facility, Brisbane. The LVL samples were cut and planed to 90 mm (wide) × 35 mm (thick) samples, ensuring dimensional uniformity which facilitated the manufacturing process. In this stage, the influence on the mechanical properties of (1) the finger joint length, (2) the adhesive type, (3) the loading type and (4) the gluing pressure was analysed.
- *Stage 3*: Scarf jointed LVL samples were manufactured from Type 1 LVL products at the Salisbury Research Facility, Brisbane. As in Stage 2, the LVL samples were cut and planed to 90 mm (wide) × 35 mm (thick) samples. The samples were used to compare the performance of finger jointed (Stage 2) to scarf jointed LVL.

For Stages 1 and 2, each different investigated set of variables was labelled in the following order:

- *Stage number*: "St1″ for Stage 1 and "St2″ for Stage 2.

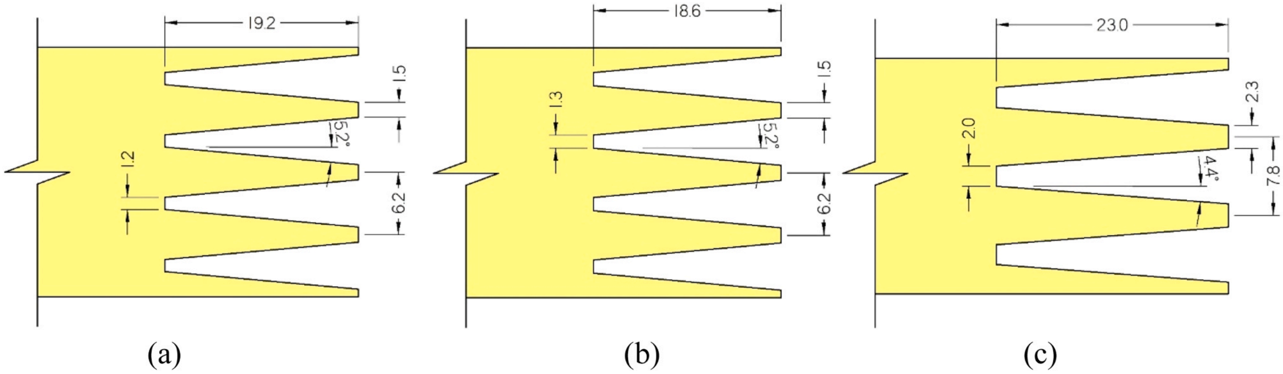


Fig. 3. (a) 20 mm finger joint used in Stage 1, (b) 20 mm finger joint used in Stage 2 and (c) 25 mm finger joint used in Stage 2 (dimensions in mm).

Table 2
Samples manufactured and tested in Stage 2.

Label	Number of samples	Dimension - L (mm) × W (mm) × T (mm)	LVL	Finger joint Orientation	Cutter size (mm)	Glue type	Gluing pressure (MPa)	Loading type
St2_T1_OH_C20_PUR_P3.7_BF	11[(1)]	750 × 90 × 35	Type 1	Horizontal	20	PUR	3.7	Bending
St2_T1_OH_C20_PUR_P5.5_BF	12						5.5	flat
St2_T1_OH_C20_PUR_P7.2_BF	11[(1)]						7.2	
St2_T1_OH_C20_RF_P5.5_BF	12					RF	5.5	
St2_T1_OH_C25_PUR_P4.5_BF					25	PUR	4.5	
St2_T1_ BF_Ref				N/A	N/A	N/A	N/A	
St2_T1_OH_C20_PUR_P3.7_BE	12	1850 × 90 × 35	Type 1	Horizontal	20	PUR	3.7	Bending
St2_T1_OH_C20_PUR_P5.5_BE							5.5	edge
St2_T1_OH_C20_PUR_P7.2_BE							7.2	
St2_T1_OH_C20_RF_P5.5_BE						RF	5.5	
St2_T1_OH_C25_PUR_P4.5_BE					25	PUR	4.5	
St2_T1_ BE_Ref				N/A	N/A	N/A	N/A	
St2_T1_OH_C20_PUR_P5.5_T	12	2000 × 90 × 35	Type 1	Horizontal	20	PUR	5.5	Tension
St2_T1_T_Ref				N/A	N/A	N/A	N/A	
St2_T1_OH_C20_PUR_P5.5_IB	12	750 × 90 × 35	Type 1	Horizontal	20	PUR	5.5	Internal
St2_T1_OH_C20_RF_P5.5_IB						RF		bond

[(1)] One sample out of the 12 was cut at the wrong dimensions and was not able to be used

Fig. 4. Custom-made laboratory press used in Stage 2.

- *LVL type*: "T1″ for Type 1 and "T2″ for Type 2.
- *Finger joint orientation*: "OH" for horizontal and "OV" for vertical.
- *Cutter size*: Letter "C" followed by the cutter size in mm.
- *Glue type*: "PUR" or "RF".
- *Gluing pressure*: Letter "P" followed by the pressure value in MPa.
- *Loading type*: "BE" for bending on edge, "BF" for bending on flat, "T" for tension and "IB" for internal bond (adhesive bond durability).

For instance, "St1_T1_OV_C20_PUR_P5.5_BE" represents Type 1 LVL samples finger jointed in Stage 1, with the joints cut vertically and with a 20 mm finger joint cutter. These samples were glued with PUR adhesive at a pressure of 5.5 MPa, then tested in bending on edge.

For Stage 3, the scarf jointed LVL were labelled in the following order:

- *Stage number*: "St3″ for Stage 3.
- *LVL type*: "T1″ for Type 1.
- *Joint type*: "Sc" for scarf joint.
- *Glue type*: "PUR".
- *Loading type*: "BE" for bending on edge and "BF" for bending on flat.

The control (or reference) unjointed samples were labelled only with the stage number, LVL type and loading type, followed by "Ref", for instance "St2_T1_BF_Ref".

All samples were conditioned at 20 °C and 65% relative humidity before testing. A minimum of 7 days were also left between gluing and testing to ensure full curing of the adhesive. Immediately after testing, pieces were cut from selected samples and weigh to determine the moisture content at the time of testing following the methodology described in the Australian and New Zealand standard AS/NZS 1080.1 [15].

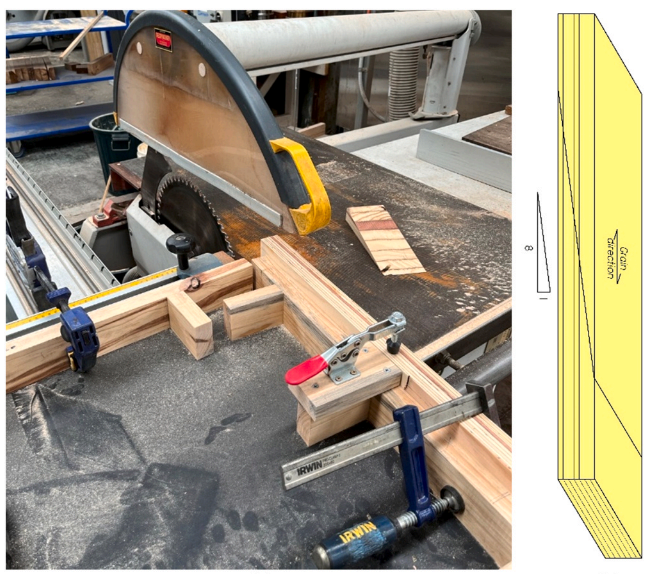
2.2.2. Stage 1

The parameters analysed in Stage 1, as well as samples sizes, are summarised in Table 1. The Type 2 LVL samples were used to compare the influence of the joint orientation and were tested on edge bending. The Type 1 LVL samples were manufactured with vertical joint and tested on flat bending. In this stage, all joints were cut using 20 mm cutters in a Festo Universal Profiler UP, which resulted in the finger joint dimensions provided in Fig. 3(a).

Samples were first cross-cut to their nominal length and then cross-cut in two sections. The joints were machined at the ends corresponding to the midpoint of the uncut samples. The two ends of a sample were then glued back together with PUR adhesive and pressed for 5 s at 5.5 MPa in a modified Festo Jointing Machine Combination FKV

Table 3
Samples manufactured and tested in Stage 3.

Label	Number of samples	Dimension - L (mm) × W (mm) × T (mm)	LVL	Joint type	Glue type	Gluing pressure (MPa)	Loading type
St3_T1_Sc_PUR_BF	12	850 × 90 × 35	Type 1	Scarf	PUR	1.1	Bending flat
St3_T1_ BF_Ref				N/A	N/A	N/A	
St3_T1_Sc_PUR_BE	12	1850 × 90 × 35	Type 1	Scarf	PUR	1.1	Bending edge
St3_T1_ BE_Ref				N/A	N/A	N/A	



(a) (b)

Fig. 5. (a) cutting the scarf joints on a panel saw and (b) sketch of resulted scarf joints.

(Fig. 2).

Note that the applied pressure of 5.5 MPa used in the commercial facility was less than the recommended pressure of 8.2 MPa for a 20 mm joint in the Eurocode [13]. This pressure matched results from tests performed on 12 Type 1 LVL samples cut with 20 mm horizontal joints (same joint profile as in Stage 2, see next subsection). These samples were pressed with no glue and the size of the tip gap was observed. The joints completely closed (i.e., showing no tip gap) at an average pressure of 8.4 MPa. To ensure the presence of the tip gap for structural applications, the pressure recommended by the Eurocode [13] would therefore be likely too high and 5.5 MPa was used as the reference pressure in the study for the 20 mm joints.

2.2.3. Stage 2

Table 2 provides a summary of the parameters analysed in Stage 2, along with the sample sizes. In this stage, all joints were cut horizontally as this orientation only requires cutters as high as the thickness of the LVL, making it more practical for jointing deep LVL sections. Moreover, results from Stage 1 showed no specific mechanical advantages having vertical joints over horizontal joints (see Section 3.1 for more details). Joints were cut in a SCM T110 spindle moulder and pressed for 5 s in a custom-made press (Fig. 4). Due to laboratory manufacturing constraints, joints were first machined at both ends of the flat bending and internal bond samples. These samples were then cross-cut into two sections, and the two ends were jointed together. On the other hand, edge bending and tension samples were first cross-cut into two sections, and the joints were manufactured at the ends corresponding to the middle of the uncut samples, similarly to Stage 1.

The influence of different parameters on the mechanical properties were investigated as follow:

- *Finger joint length*: Samples were manufactured with 20 mm and 25 mm cutters, all glued with PUR and tested in both edge and flat bending. The longer the joints are, the less gluing pressure is to be applied [13]. As the 20 mm joints were glued at the reference pressure of 5.5 MPa, the pressure was decreased to 4.5 MPa for the 25 mm joints. This pressure was calculated by multiplying the pressure applied to the 20 mm joints by the ratio of the recommended gluing pressures for 25 mm and 20 mm joints in the Eurocode [13], i.e., a ratio of 0.82. The measured dimensions of the 20 mm and 25 mm joints are shown in Fig. 3(b) and (c), respectively.
- *Adhesive type*: Samples were manufactured with 20 mm cutters and glued with either PUR or RF at a pressure of 5.5 MPa. Samples were tested in edge and flat bending, and internal bond.
- *Gluing pressure*: Samples were glued with PUR at 3.7 MPa, 5.5 MPa and 7.2 MPa. The joints were 20 mm and the samples were tested in both edge and flat bending.
- *Loading type*: All 20 mm joints glued with PUR at 5.5 MPa were tested in edge bending, flat bending and tension, allowing comparison of joint performance between different loading types.

2.2.4. Stage 3

Table 3 provides a summary of the scarf jointed LVL investigated in Stage 3, along with the sample sizes. The samples were first cross-cut into two sections, and the scarf joints were manufactured at the ends corresponding to the middle of the uncut samples, similarly to Stage 1. Especially, the joints were cut through the thickness at a slope of 1:8

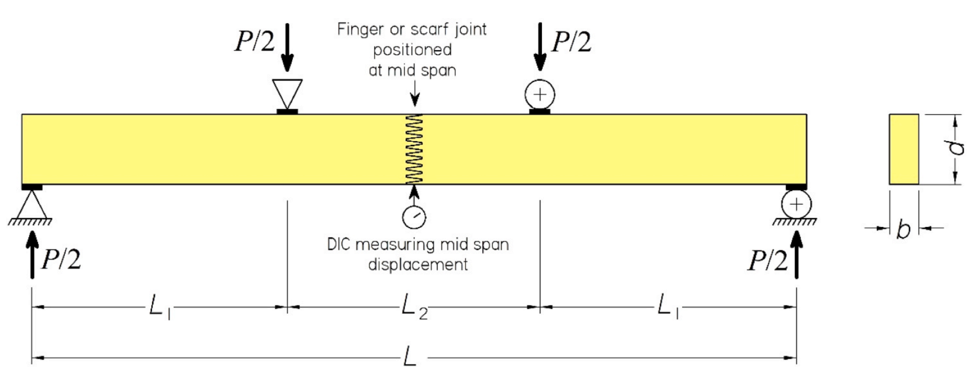


Fig. 6. Bending test setup.

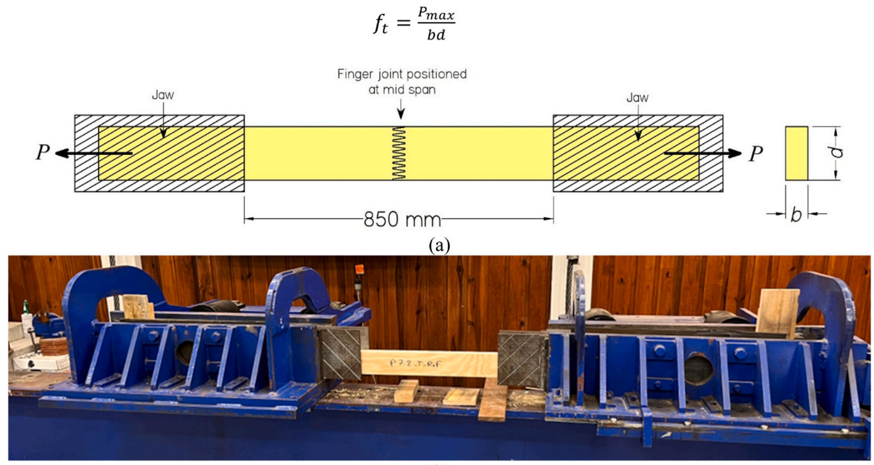
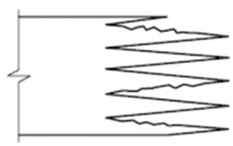
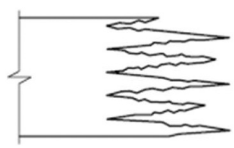
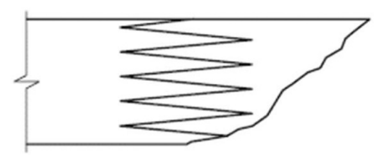
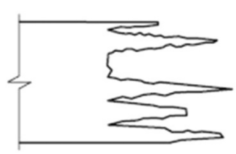
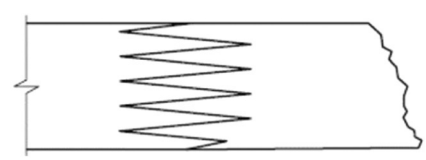


Fig. 7. Tension test setup (a) schematic and (b) photo.

Table 4
Finger joint failure modes of test specimens adapted from AS 5068 [17] in reference to ASTM D4688 [18].

Mode	Description	Example	Mode	Description	Example
1	Failure mostly along the bondline surfaces of the joint profile with poor wood failure of any kind (wood failure <70%)		4	Mostly tensile wood failure at the finger joint roots and with high overall wood failure. Little failure of any kind of the joint profile.	
2	Failure mostly along the bondline surfaces of the joint profile with good wood failure of any kind (wood failure > 70%)		5	Failure beginning at the joint (possibly to a stress riser) and progressing away from the joint. Essentially 100% wood failure.	
3	Failure mostly along the joint profile but with some failure at the finger roots. Good overall wood shear failure along the joint profile surfaces.		6	Failure away from the joint (not influenced by the joint) – all wood failure.	

[10] using a special jig attached to a panel saw (Fig. 5). The joints were then pressed using PUR adhesive under a pressure of 1.1 MPa for 40 mins.

The samples were then tested in edge and flat bending as detailed hereafter.

2.2.5. Edge and flat bending tests

Flat and edge bending tests were performed in four-point bending in accordance to the Australian and New Zealand standard AS/NZS 4063.1 [16]. The span L was equal to 18 times the depth d of the sample (with the depth corresponding to the dimension parallel to the applied load) except for (1) the scarf jointed samples tested on flat, for which L was equal to 780 mm to have the entire scarf joint located in the constant bending region and (2) the Type 1 LVL samples tested in Stage 1 on flat bending (d = 38 mm) where L was increased to 720 mm instead of 684 mm by inadvertence. Apart from these two exceptions, this resulted in L = 630 mm, 810 mm and 1620 mm for d = 35 mm, 45 mm and 90 mm, respectively. The distances L_1 between the supports and their nearest load application points, and L_2 between the load application points, were typically $L_1 = L_2 = L/3$, except for the scarf jointed samples tested on flat where $L_1 = 6d = 210$ mm and $L_2 = 360$ mm. A Digital Image Correlation (DIC) system was used to measure the vertical displacement δ at mid-span. The load P was applied by a Shimadzu universal testing machine fitted with a 100 kN load cell at a stroke rate to reach failure between 2 mins and 5 mins [16]. For all tests, the joint was positioned at mid-span. The test set-up is shown in Fig. 6.

If failure occurred between the load application points, the bending Modulus of Rupture (MOR) f_b was calculated from the maximum load reach P_{max} as:

$$f_b = 3\frac{P_{\max}L_1}{bd^2} \quad (1)$$

where b and d are the measure width and depth of the sample (Fig. 6). If failure did not occur in the constant bending moment region and at a distance L_f from the nearest load application point, the bending MOR was calculated as the bending moment at the location of failure [16] as,

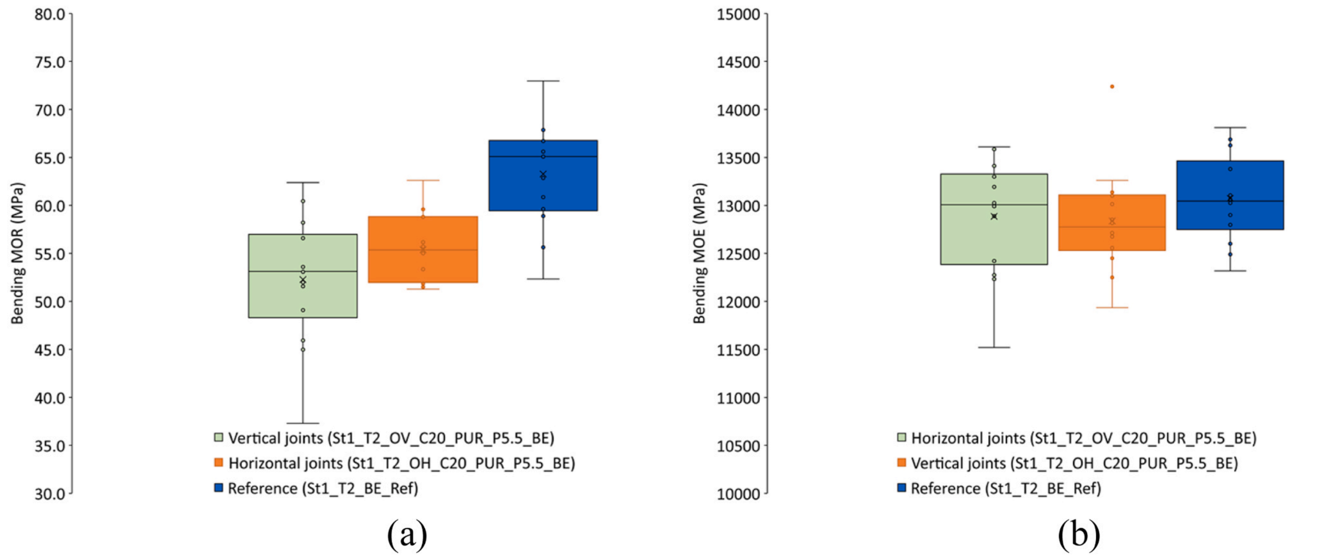


Fig. 8. Stage 1, bending test results for Type 2 LVL finger jointed samples tested on edge with either horizontal or vertical joints, (a) MOR and (b) MOE.

Table 5
Stage 1, test results for Type 2 LVL samples tested on edge bending with either horizontal or vertical finger joints.

Label	Experimental results			Performance ratios relative to reference		
	Average f_b (MPa)	Characteristic f_b (MPa)	Average E_b (MPa)	Average f_b	Characteristic f_b	Average E_b
St1_T2_OV_C20_PUR_P5.5_BE	52.3	38.9	12,887	0.83	0.73	0.99
St1_T2_OH_C20_PUR_P5.5_BE	55.4	48.7	12,838	0.88	0.91	0.98
St1_T2_ BE_Ref	63.3	53.1	13,074	–	–	–

$$f_b = 3\frac{P_{\max}(L_1 - L_f)}{bd^2} \tag{2}$$

The apparent bending Modulus of Elasticity (MOE) E_b was calculated as,

$$E_b = \frac{L_1}{4bd^3}\left(3L^2 - 4L_1^2\right)K \tag{3}$$

where K is the slope of the linear part of the load P-displacement δ curve, calculated by performing a linear regression between 20% and 70% of the maximum load.

2.2.6. Tension tests

The tension samples were tested in a custom-made tension rig fitted with a 200 kN load cell. The samples were first clamped between the jaws and tested in tension at a computer driven load rate of 25 kN/min, reaching failure between 6 mins and 8 mins. The span between jaws was equal to 850 mm. Fig. 7 shows the test set-up. The finger joints were positioned as mid span. The tension MOR f_t was calculated from the maximum load reached P_{max} and measured cross-sectional dimensions as:

$$f_t = \frac{P_{\max}}{bd} \tag{4}$$

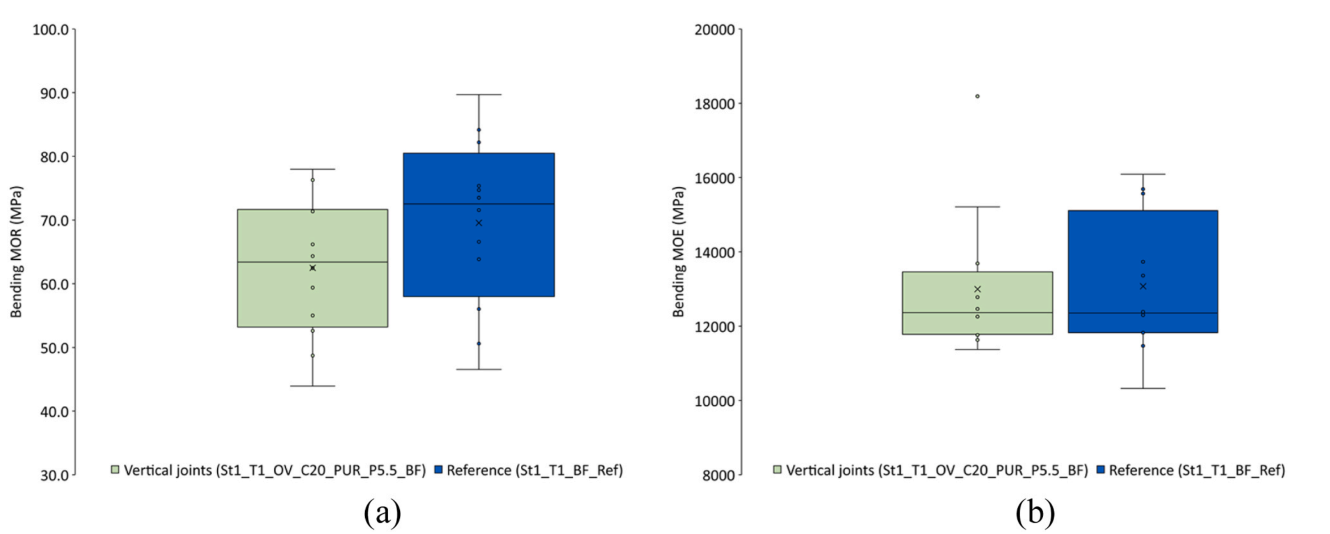


Fig. 9. Stage 1, bending test results for Type 1 LVL finger jointed samples tested on flat with vertical joints, (a) MOR and (b) MOE.

Table 6
Stage 1, test results for Type 1 LVL samples tested on flat bending with vertical finger joints.

Label	Experimental results			Performance ratios relative to reference		
	Average f_b (MPa)	Characteristic f_b (MPa)	Average E_b (MPa)	Average f_b	Characteristic f_b	Average E_b
St1_T1_OV_C20_PUR_P5.5_BF	62.5	42.6	12,997	0.90	0.94	0.99
St1_T1_ BF_Ref	69.6	45.1	13,075	–	–	–

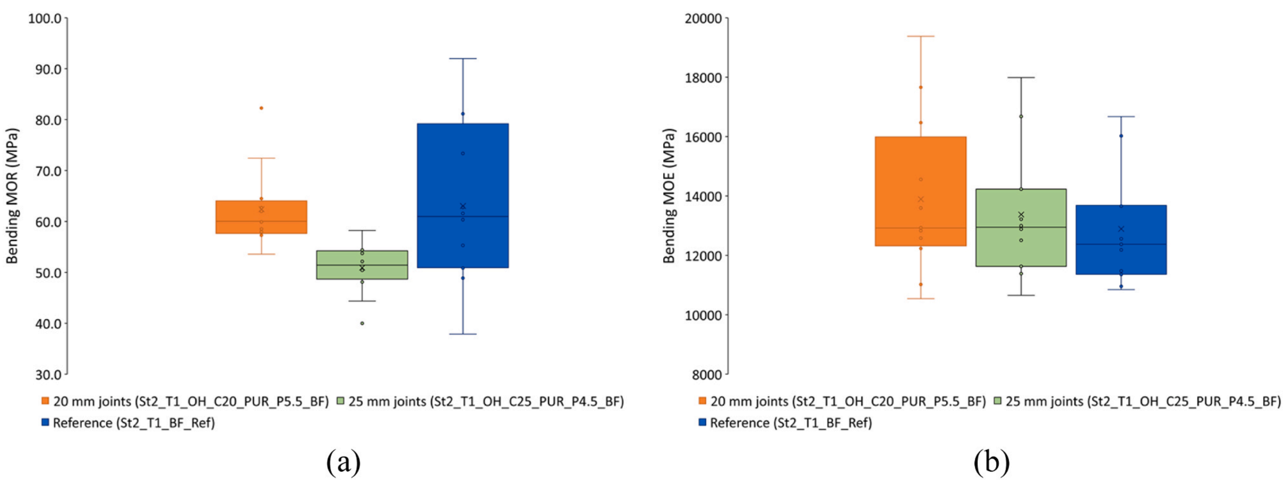


Fig. 10. Stage 2, bending test results for finger jointed samples tested on flat with either 20 mm or 25 mm joints, (a) MOR and (b) MOE.

2.2.7. Internal bond tests

Internal bond tests were carried following Clause 8.3 of the Australian standard AS 5068 [17]. The samples were placed in an autoclave, weighed down and immersed in water. A vacuum was drawn at 65 kPa for 1.5 h followed by a pressure of 500 kPa for 1.5 h. The vacuum-pressure cycle was repeated a second time. The samples were then tested within a few hours in four-point and on flat bending as described in Section 2.2.5. The wood failure percentage of each joint was then visually assessed. A joint meets the adhesive bond durability requirements in the AS 5068 [17] if the average and minimum wood failure percentages of all joints are greater than 40% and 20%, respectively, for softwood, and 60% and 30%, respectively, for hardwood.

2.2.8. Additional analyses

The experimental results were further analysed as follow:

- The failure of each finger joint was recorded following Appendix C of AS 5068 [17]. The types of failure are based on the ASTM D4688 [18] and consist of six different failure modes (numbered from 1 to 6), as reported in Table 4. The higher the failure mode number is, the more mechanically efficient is the finger joint.
- For each set of tests, the characteristic strength design value was calculated following the methodology in the European standard EN 14358 [11] based on the number of tests performed and assuming lognormal distributions.
- One-way analysis of variance (ANOVA) was used to determine if there were statistically significant differences between the mean results of varying parameters.
- The efficiency of the joints was determined as (1) the ratio of the average MOR (or MOE) and (2) of the average characteristic MOR of the jointed samples to the reference samples.

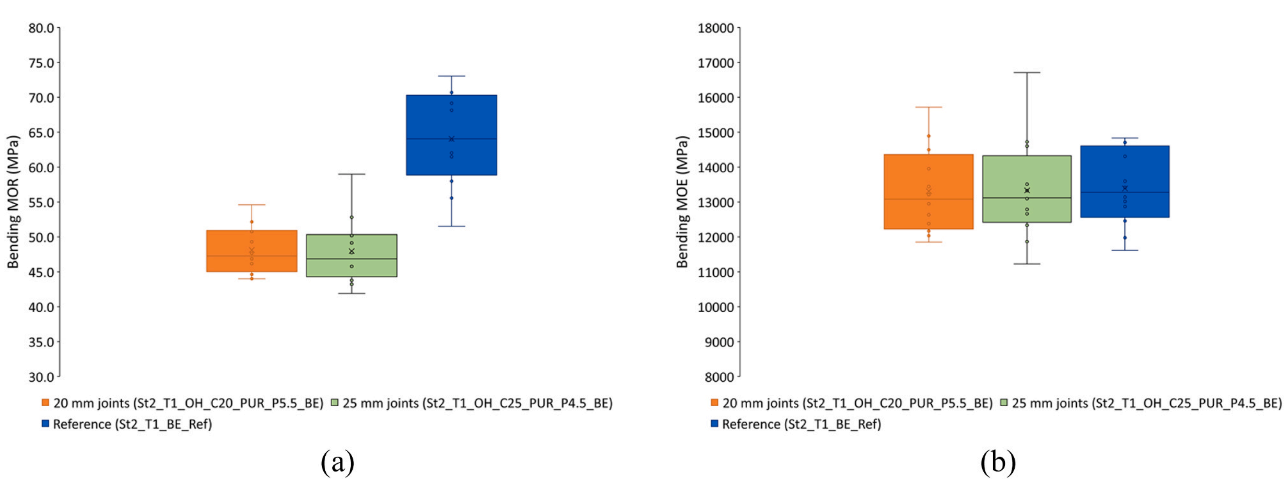


Fig. 11. Stage 2, bending test results for finger jointed samples tested on edge with either 20 mm or 25 mm joints, (a) MOR and (b) MOE.

Table 7
Stage 2, test results for all finger jointed samples tested on flat bending.

Label	Experimental results			Performance ratios relative to reference		
	Average f_b (MPa)	Characteristic f_b (MPa)	Average E_b (MPa)	Average f_b	Characteristic f_b	Average E_b
St2_T1_OH_C20_PUR_P3.7_BF	62.2	47.4	14,276	0.99	1.30	1.11
St2_T1_OH_C20_PUR_P5.5_BF	62.4	49.0	13,893	0.99	1.34	1.08
St2_T1_OH_C20_PUR_P7.2_BF	59.5	46.6	14,007	0.94	1.28	1.09
St2_T1_OH_C20_RF_P5.5_BF	54.3	39.2	13,024	0.86	1.07	1.01
St2_T1_OH_C25_PUR_P4.5_BF	50.9	41.2	13,375	0.81	1.13	1.04
St2_T1_ BF_Ref	63.0	36.5	12,891	–	–	–

Table 8
Stage 2, test results for all finger jointed samples tested on edge bending.

Label	Experimental results			Performance ratios relative to reference		
	Average f_b (MPa)	Characteristic f_b (MPa)	Average E_b (MPa)	Average f_b	Characteristic f_b	Average E_b
St2_T1_OH_C20_PUR_P3.7_BE	55.8	46.4	13,039	0.87	0.91	0.97
St2_T1_OH_C20_PUR_P5.5_BE	48.1	41.6	13,311	0.75	0.81	0.99
St2_T1_OH_C20_PUR_P7.2_BE	54.0	44.5	13,220	0.84	0.87	0.99
St2_T1_OH_C20_RF_P5.5_BE	55.3	42.4	13,416	0.86	0.83	1.00
St2_T1_OH_C25_PUR_P4.5_BE	48.0	39.3	13,332	0.75	0.77	1.00
St2_T1_ BE_Ref	64.0	51.2	13,387	–	–	–

3. Results

3.1. Stage 1

Fig. 8(a) and (b) plots the bending MOR and MOE distributions, respectively, for the Type 2 LVL samples tested in Stage 1, i.e., comparing the difference between horizontal and vertical joints. The results are also tabulated in Table 5 along with the characteristic design values and the MOR and MOE ratios of the finger jointed samples to the reference samples. On average, the vertical and horizontal joints reached a similar efficiency in terms of bending MOR, ranging between 0.83 and 0.88. However, the vertical joints showed a coefficient of variation of 12.5% against 6.5% for the horizontal joints, likely because in the testing orientation, the load is principally resisted by the bottom finger for the vertical joints versus all fingers sharing the load for the horizontal joints. The one-way ANOVA showed that there were no statistically significant differences between bending MOR group means of the Type 2 LVL vertical and horizontal joints ($F(1,26) = 2.413$, $p = 0.13$). However, a statistically significant difference was found between all Type 2 LVL bending MOR group means ($F(2,39) = 15.98$, $p = 8.5 \times 10^{-6}$), showing that the joints had an effect on the bending strength of the LVL. Regarding the characteristic bending MOR, the horizontal joints were more efficient than vertical joints, with an efficiency ratio of 0.91 versus 0.73. No effect of the joints was found on the bending MOE, with the one-way ANOVA demonstrating no statistically significant differences between group means ($F(2,39) = 0.766$, $p = 0.47$).

Similar to Fig. 8 and Table 5, Fig. 9 and Table 6 provide the results of the Type 1 LVL samples manufactured with vertical joints and tested on flat bending in Stage 1. The efficiency in terms of bending MOR was higher than for the Type 2 LVL samples and equal to 0.90 and 0.94 for the average and characteristic values, respectively. The one-way ANOVA showed no statistically significant differences between bending MOR group means ($F(1,22) = 2.007$, $p = 0.17$), outlining the efficiency of the joint. Similar, to the Type 2 LVL samples, the joint did not affect the bending MOE, with the one-way ANOVA showing no statistically significant differences between group means ($F(1,22) = 0.010$, $p = 0.92$).

Regarding failure modes outlined in Table 4, 71% of the vertical and 85% horizontal Type 2 LVL jointed samples tested on edge failed in Modes 2 and 3, respectively. 50% and 33% of the Type 1 LVL samples tested on flat failed in Modes 5 and 3, respectively.

The joints in Stage 1 were proven to be as or more efficient that previous studies on finger jointed LVL [1,3] and outlined that efficient

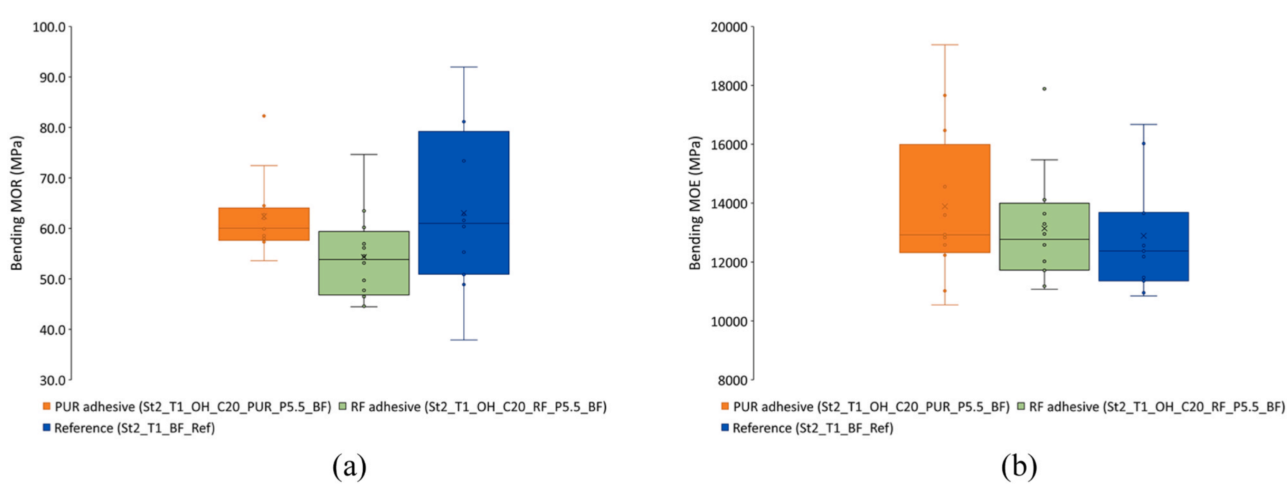


Fig. 12. Stage 2, bending test results for finger jointed samples tested on flat with either PUR or RF adhesive, (a) MOR and (b) MOE.

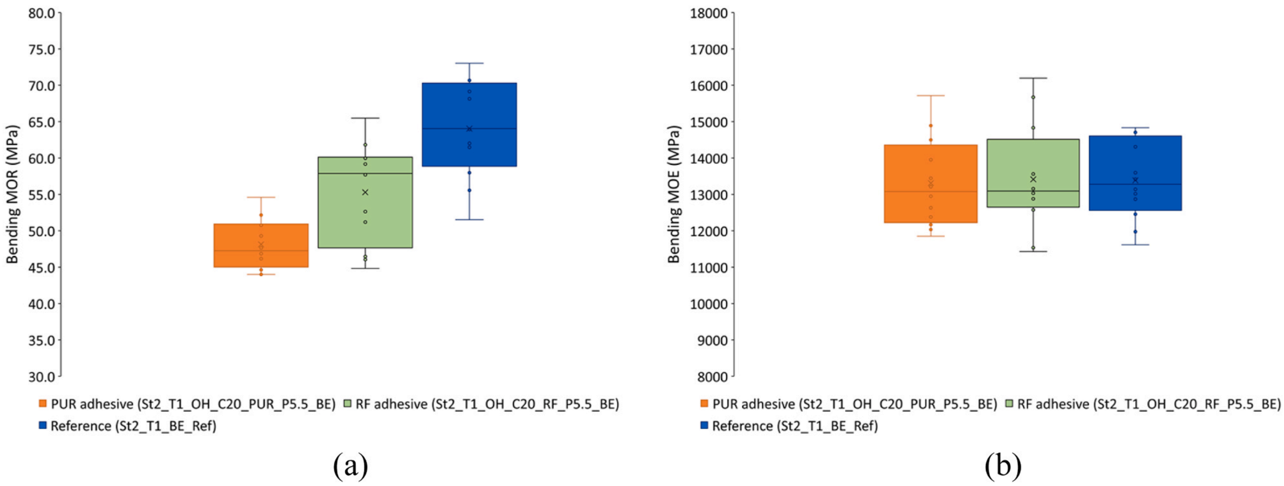


Fig. 13. Stage 2, bending test results for finger jointed samples tested on edge with either PUR or RF adhesive, (a) MOR and (b) MOE.

Table 9
Stage 2, internal bond test results on finger jointed samples.

Label	Experimental results		Requirements in AS 5068[17]			
			Softwood		Hardwood	
	Average (%)	Minimum (%)	Average (%)	Minimum (%)	Average (%)	Minimum (%)
St2_T1_OH_C20_PUR_P5.5_IB	55.8	20	60	30	40	20
St2_T1_OH_C20_RF_P5.5_IB	78.3	45				

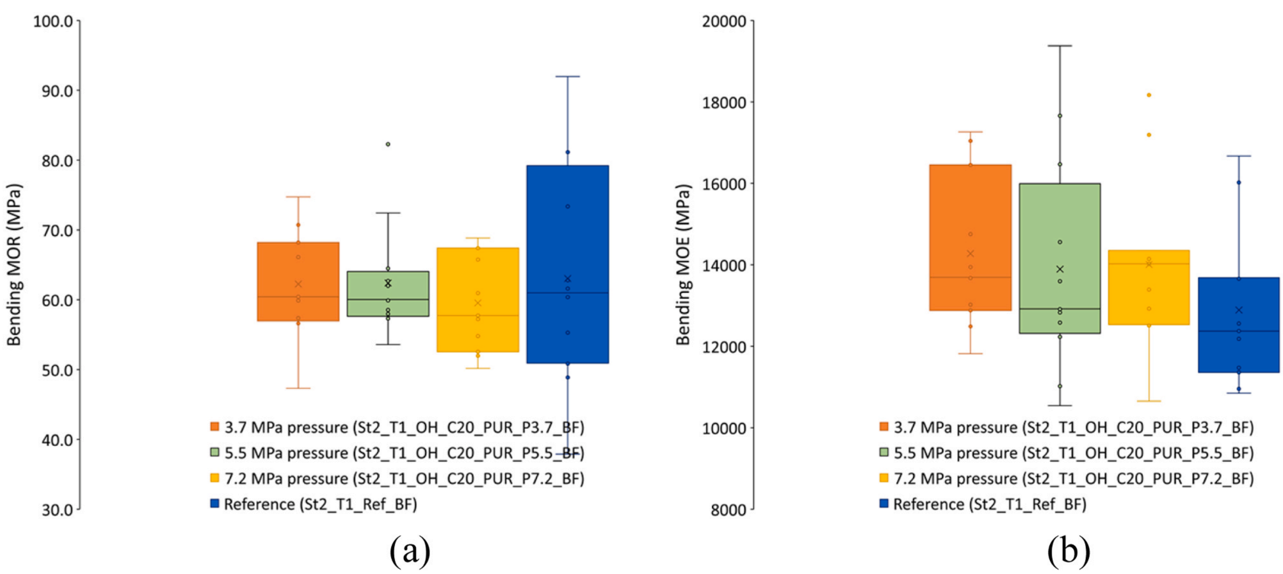


Fig. 14. Stage 2, bending test results for finger jointed samples tested on flat with varying gluing pressure, (a) MOR and (b) MOE.

finger joints can be manufactured, with an efficiency in terms of characteristic bending MOR higher than 0.90.

3.2. Stage 2

3.2.1. Effect of finger joint length

The effect of the finger length on the bending performance of the joints is plotted in Fig. 10 and Fig. 11 for the samples tested in Stage 2 on flat and edge bending, respectively. The analysed results are also provided in Table 7 and Table 8.

For flat bending, the 20 mm joints performed on average 1.22 times better than the 25 mm joints and as well as the reference joints, with an efficiency ratio 0.99. Indeed, the one-way ANOVA showed a statistically significant difference between the MOR group means of the 20 mm and 25 mm joints ($F(1,22) = 18.49$, $p = 2.9 \times 10^{-4}$), while no statistical differences were found between the 20 mm and reference MOR group means ($F(1,22) = 0.0156$, $p = 0.902$). Additionally, as the strength variability in the finger jointed samples was less than in the reference ones, the characteristic design strength of both the 20 mm and 25 mm joints is higher, by up to 34%, than the reference characteristic design value. Additional studies are needed to explain and confirm this observation.

For edge bending, the 20 mm and 25 mm joints performed similarly, with an average efficiency of 75%. There were no statistically significant

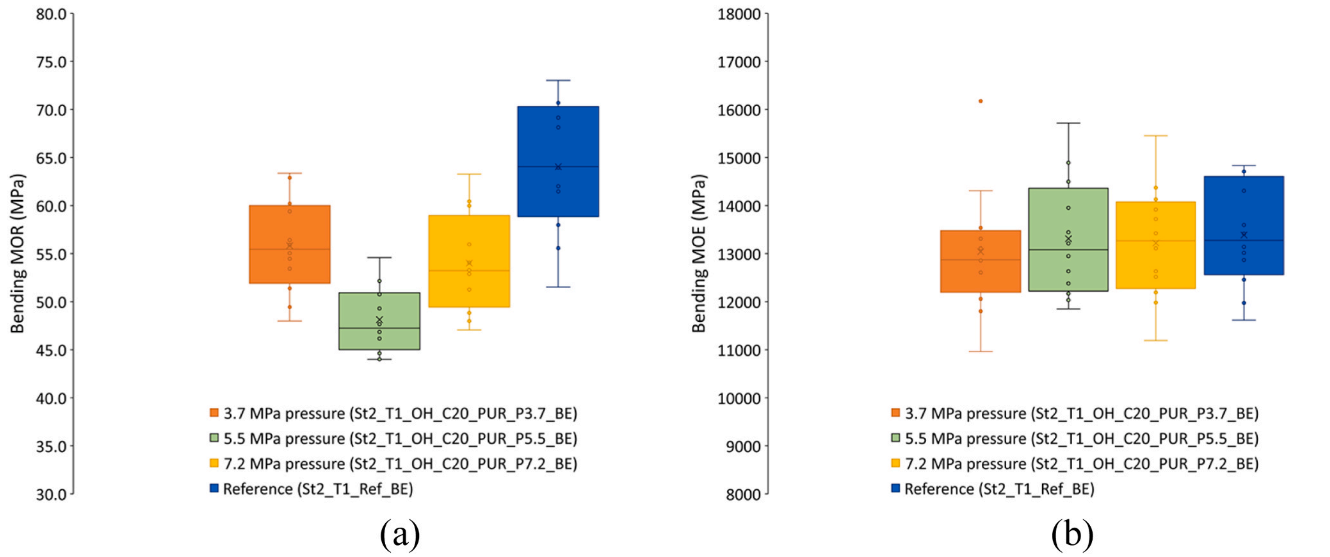


Fig. 15. Stage 2, bending test results for finger jointed samples tested on edge with varying gluing pressure, (a) MOR and (b) MOE.

differences between MOR group means of the 20 mm and 25 mm joints as determined by one-way ANOVA ($F(1,22) = 0.0084$, $p = 0.927$) but there was a statistical difference between all group means ($F(2,33) = 38.95$, $p = 2.06 \times 10^{-9}$). The latter statistical analysis indicates that the finger joints influence the edge bending performance of the LVL to some extent. The characteristic design MOR value of the 20 mm joints was higher than that of the 25 mm joints amounting to 0.81 times the characteristic design value of the reference samples.

Regarding the MOE, for both flat and edge bending, the one-way ANOVA showed no statistically significant differences between all group means ($F(2,31) = 0.541$, $p = 0.587$ for flat bending and $F(2,33) = 0.011$, $p = 0.988$ for edge bending).

In reference to Table 4, more than 95% of the samples failed in Mode 3 or better. These observed failure modes, combined with the efficiency ratios presented in Table 7 and Table 8, which are similar to the ones in Table 5 and Table 6, indicate that the laboratory-based manufacturing process used in Stage 2 adequately replicated the commercial practices from Stage 1, and presents valid results.

As the 25 mm joint did not provide a mechanical advantage over the 20 mm joint, it is recommended to use the 20 mm joint to reduce wastage. However, more investigations can be performed, outside the scope of this paper, to improve the performance of the 25 mm joints, such as using a different finger geometry and tip gap depth.

3.2.2. *Effect of adhesive type*

Fig. 12 and Fig. 13 plots the influence of the adhesive on the flat and edge bending properties, respectively. The results are also presented in Table 7 and Table 8.

A one-way ANOVA showed a statistically significant difference between the MOR groups of joints bonded with PUR and RF, this for both flat bending ($F(1,22) = 5.600$, $p = 0.027$) and edge bending ($F(1,22) = 10.477$, $p = 0.004$). However, the difference in efficiency is small, with the PUR performing on average 15% better and 15% worse than the RF when tested on flat and edge bending, respectively. Using the RF adhesive resulted in efficiency ratios in terms of the characteristic design

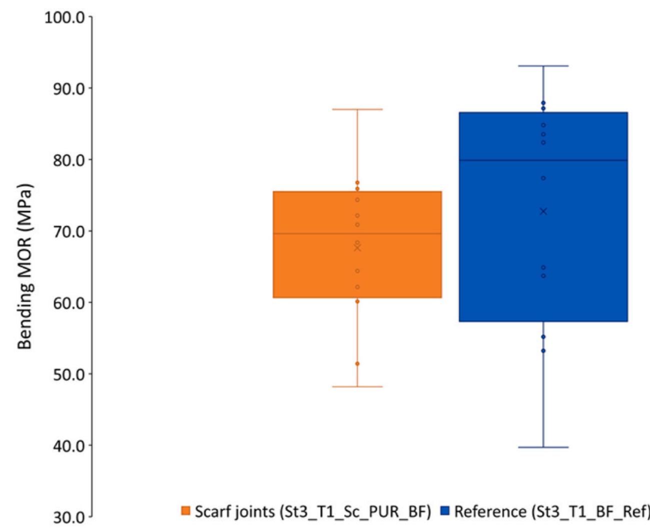


Fig. 16. Stage 3, MOR bending test results for scarfed samples tested on flat.

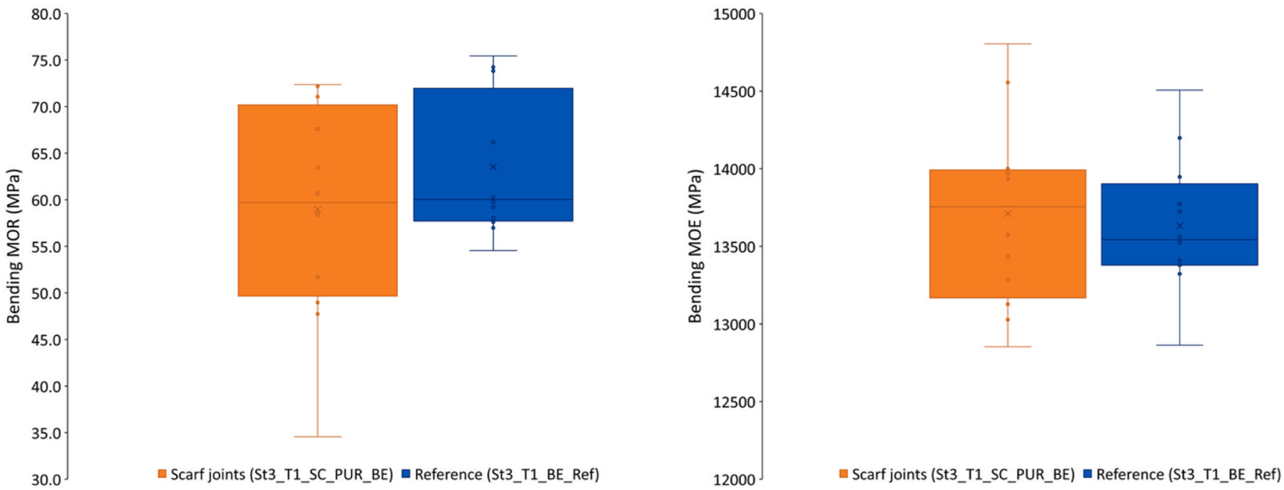
value of 1.07 and 0.83 for flat and edge bending, respectively.

Regarding the MOE, the one-way ANOVA showed no statistically significant differences between group means of both edge bending ($F(2,32) = 0.637$, $p = 0.535$) and flat bending ($F(2,33) = 0.002$, $p = 0.978$). Additionally, all samples manufactured with RF adhesive failed in Mode 3 or better (Table 4).

The internal bond assessments for the two investigated adhesives are provided in Table 9. For the mix hardwood-softwood LVL used in Stage 2 (See Section 2.1.1), the RF adhesive met the requirements for both softwood and hardwood in the AS 5068 [17], while the PUR adhesive satisfied these requirements for hardwood only. PUR adhesives are known to not perform as well as RF in internal bond assessments, but

Table 10
Stage 2, test results for all finger jointed samples tested in tension.

Label	Experimental results		Performance ratios relative to reference	
	Average f_b (MPa)	Characteristic f_b (MPa)	Average f_b	Characteristic f_b
St2_T1_OH_C20_PUR_P5.5_T	42.8	35.3	0.91	1.15
St2_T1_T_Ref	46.8	30.7	–	–



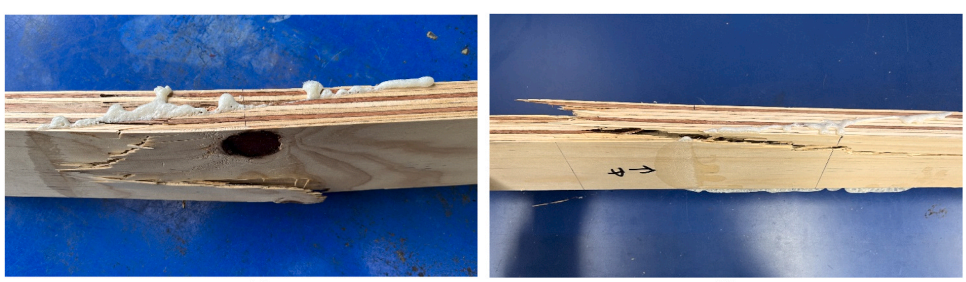
(a) (b)

Fig. 17. Stage 3, bending test results for scarfed samples tested on edge, (a) MOR and (b) MOE.

Table 11
Stage 3, test results for all scarf jointed samples tested in bending.

Label	Experimental results			Performance ratios relative to reference		
	Average f_b (MPa)	Characteristic f_b (MPa)	Average E_b (MPa)	Average f_b	Characteristic f_b	Average E_b
St3_T1_Sc_PUR_BF	67.6	47.2	–$^{(1)}$	0.93	1.14	–$^{(1)}$
St3_T1_ BF_Ref	72.7	41.6	–$^{(1)}$	–	–	–
St3_T1_Sc_PUR_BE	59.0	37.2	13,710	0.93	0.74	1.01
St3_T1_ BE_Ref	63.5	50.1	13,632	–	–	–

$^{(1)}$: MOE not recorded by error



(a) (b)

Fig. 18. Stage 3, typical failure mode of scarf jointed specimens for (a) flat and (b) edge bending.

would typically recover their bending strength if the samples were dried back at 20 °C and 65% relative humidity after the vacuum-pressure cycles explained in Section 2.2.7 [19].

Therefore, while RF provided better internal bond results, PUR and RF resulted in comparable mechanical performances and both adhesives can be used to produce efficient finger jointed LVL.

3.2.3. Effect of gluing pressure

Fig. 14 and Fig. 15 plots the influence of the gluing pressure on the properties of flat and edge bending, respectively. The results are also presented in Table 7 and Table 8.

For flat bending, the end pressure has no effect on the bending properties. The one-way ANOVA showed no statistically significant differences between the three investigated pressure groups for both MOR ($F(2,31) = 0.507$, $p = 0.607$) and MOE ($F(2,31) = 0.086$, $p = 0.918$). The average and characteristic efficiency ratios of MOR are greater than 0.94 and 1.28, respectively. Regarding the MOE, no statistically significant differences were observed among the three pressure group means ($F(2,31) = 0.086$, $p = 0.918$). However, the MOE of the reference samples was about 10% lower than the jointed ones, likely due to the natural variability of the material.

For edge bending, there was a statistically significant difference between the MOR of the three pressure groups as determined by one-way ANOVA ($F(2,33) = 9.355, p = 6.04 \times 10^{-4}$). However, this difference is due to the samples glued with an end pressure of 5.5 MPa which showed a lower efficiency (Fig. 13 (a) and Table 8) when compared to the other two pressures. Indeed, the one-way ANOVA showed no statistically significant differences between the MOR of the 3.7 MPa and 7.2 MPa pressure groups ($F(1,22) = 0.781$, $p = 0.386$). A statistical difference was also found between either the 3.7 MPa pressure and reference group means ($F(1,22) = 11.734, p = 2.41 \times 10^{-3}$) or the 7.2 MPa pressure and reference group means ($F(1,22) = 17.077, p = 4.37 \times 10^{-4}$). In terms of MOE, no statistically significant differences were observed among the three pressure group means ($F(2,33) = 0.148, p = 0.862$).

All samples manufactured with either a 3.7 MPa or 7.2 MPa gluing pressure failed in Mode 3 or better (Table 4), i.e., showing similar failure modes to those manufactured with the reference pressure of 5.5 MPa. These failure modes also indicated that a pressure lower than the one recommended in the Eurocode [13] for solid timber is appropriate.

In view of the above, the end pressure does not represent a critical manufacturing factor to produce efficient finger jointed LVL and does not need to be precisely controlled.

3.2.4. Effect of loading type

The results of the samples tested in tension are provided in Table 10 and can be compared to the flat and edge bending results in Table 7 and Table 8, respectively. The tension samples resulted in similar efficiency ratios to the flat bending samples, with the characteristic design value of the finger jointed samples surpassing the characteristic design value of the reference samples due to a lower variability in the strength of finger jointed samples. As outlined previously, edge bending resulted in lower efficiency ratios than the other two loading types.

3.3. Stage 3

Fig. 16 and Fig. 17 compare the bending MOR and MOE of the scarf jointed samples to the reference samples when tested on flat and edge bending, respectively. The results are further tabulated in Table 11. Note, that due to a manipulation error, the flat bending MOE was not recorded.

The scarf joints performed efficiently, with failure always developing in the timber and not in the joints (Fig. 18). For flat bending, the one-way ANOVA showed no statistically significant differences between the jointed and reference MOR group means ($F(1,22) = 0.765$, $p = 0.391$). The corresponding average and characteristic MOR efficiency ratios are equal to 0.93 and 1.14, respectively. Similarly for edge bending, the one-way ANOVA showed no statistically significant differences between the jointed and reference group means for both MOR ($F(1,22) = 1.333, p = 0.261$) and MOE ($F(1,22) = 0.130, p = 0722$). The corresponding average and characteristic efficiency ratios for the MOR are equal to 0.93 and 0.74, respectively.

3.4. Discussion: Finger versus scarf joints

Regarding the bending strength, the scarf (Table 11) and finger (Table 7) joints behave similarly and efficiently on flat bending, both showing no statistical difference to their respective reference samples. However on edge bending, the scarf joints in Table 11 performed better than the finger joints in Table 8, as (1) the scarf joints always failed in the timber and (2) contrary to the finger joints, no statistical difference was found between the scarf and reference samples. However, the difference in edge bending efficiency between the scarf and finger jointed samples is not significant, with the average efficiency for the MOR equal to 0.93 for the scarf joints and up to 0.87 for the finger joints. This gain in efficiency needs to be balanced by a manufacturer over the longer pressure time and additional wastage of the scarf joints compared to the finger joints.

Additionally, if serviceability is the governing design parameter, then both scarf and finger joints behave similarly. Indeed, in all investigated cases, no statistical differences were found between the MOE group means of the jointed and reference samples. In such cases, there would be manufacturing advantages using finger joints instead of scarf joints.

4. Conclusion

With the aim of reducing the capital cost of setting up a LVL plant, this paper investigated the possibility of producing usable LVL lengths from billets manufactured with batch-type presses. The mechanical efficiency of finger jointed LVL was explored. This efficiency was also compared to the efficiency of scarf joints, providing essential data for a manufacturer for decision making on the type of joints to be used. The following conclusions arose from the paper:

- It is possible to manufacture continuous and efficient LVL through finger jointing LVL sections together.
- Horizontal joints represent the most practical finger joint orientation to connect LVL sections together and were found to have no specific mechanical disadvantages when compared to vertical joints.
- No mechanical benefits were found in using 25 mm long joints instead of 20 mm.
- When tested in flat bending and tension, the characteristic design strength values of the finger jointed pieces were found to be higher than of the reference non-finger jointed LVL due to a reduction in strength variability. The lowest efficiency of the finger joints was found when tested on edge bending, resulting in characteristic design values for 20 mm long joints no less than 81% of the characteristic design value of the reference samples.
- The investigated adhesives, PUR and RF, resulted in similar performances with an advantage of the RF over PUR regarding adhesive bond durability (internal bond). The choice of the adhesive would depend on the manufacturer preferences.
- The end pressure was found not to influence the mechanical performance, for the range of pressures analysed, and does not need to be accurately controlled. A pressure lower than the one recommended in the Eurocode [13] for finger jointing solid timber seems appropriate for LVL. The statement would need to be verified on LVL manufactured from additional manufacturers.
- The scarf joints were found to have similar mechanical performances to the reference samples, both on flat and edge bending. Therefore, no efficiency gain was found using a scarf over a finger joint on flat bending. However, more than 5% additional efficiency for the MOR can be achieved on edge bending when scarf joining LVL instead of finger joining them. This strength efficiency gain needs to be balance over the manufacturing advantages of the finger joints (i.e., less wood wastage and faster manufacturing process) over the scarf joints. However, if serviceability is the governing design parameter, as both finger and scarf joints resulted in the same bending MOE as their respective reference samples, finger joints would represent a more viable option due to its manufacturing benefits.

CRediT authorship contribution statement

Davies Thomas E.: Writing – review & editing, Methodology, Investigation, Conceptualization. **McGavin Robert L.:** Writing – review & editing, Methodology, Funding acquisition. **Gilbert Benoit Pierre:** Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Dowse Chris J.:** Validation, Resources, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgments

This study was funded by a joint Australian Centre for International Agricultural Research (ACIAR), Queensland Department of Agriculture and Fisheries (DAF) and Australian industry collaborative project titled "Coconut and other non-traditional forest resources for the manufacture of Engineered Wood Products" project number FST/2019/128. The authors would like to thank the staff at EcoCottages Pty Ltd. for their friendliness and the essential support they provided in manufacturing the samples in Stage 1. Jowat Universal Adhesives Australia Pty. Ltd. are acknowledged for the supply of adhesives and technical advice on their use. Finally, Mr Adam Faircloth, Dr Peraj Karbaschi and Mr Ryan Lovell of the Salisbury Research Facility are acknowledged in their critical assistance in preparing the specimens and performing or facilitating parts of the experimental testing. The support provided by DAF through the provision of the unique facilitates located at the Salisbury Research Facility is acknowledged as critical to facilitate processing and product studies of this nature.

References

[1] J.A. Youngquist, T.L. Laufenberg, B.S. Bryant, End jointing of laminated veneer lumber for structural use, For. Prod. J. 34 (1984) 25–32.

[2] H. Sasaki, Lumber: Laminated Veneer, in: K.H.J. Buschow, R.W. Cahn, M.C. Flemings, B. Ilschner, E.J. Kramer, S. Mahajan, P. Veyssière (Eds.) Encyclopedia of Materials: Science and Technology, 2001, pp. 4678–4680.

[3] E.J. Biblis, H.F. Carino, Factors influencing the flexural properties of finger-jointed southern pine LVL, For. Prod. J. 43 (1993) 41.

[4] C. Bustos, R. Hernández, R. Beauregard, M. Mohammad, Effects of end-pressure on the finger-joint quality of black spruce lumber: a microscopic analysis, Maderas Cienc. Y. Tecnol. 13 (2011) 319–328.

[5] J. Ayarkwa, Y. Hirashima, Y. Sasaki, M. Yamasaki, Influence of finger-joint geometry and end pressure on tensile properties of three finger-jointed Tropical African Hardwoods, South. Afr. For. J. 188 (2000) 37–49.

[6] G. Castro, F. Paganini, "Parameters affecting end finger joint performance in poplar wood", Proceedings of the International Conference of IUFRO S 5.02 Timber Engineering, Copenhqgen, Denmark, 1997.

[7] A. Morin-Bernard, P. Blanchet, C. Dagenais, A. Achim, Glued-laminated timber from northern hardwoods: Effect of finger-joint profile on lamellae tensile strength, Constr. Build. Mater. 271 (2021), 121591.

[8] D. Tsalagkas, Z. Börcsök, Z. Pásztory, The effect of finger length and adhesive type on the curing time of finger-jointed black pine (Pinus nigra L.) lumber, Wood Mater. Sci. Eng. 16 (2021) 312–320.

[9] Z. Ahmad, W.C. Lum, S.H. Lee, M.A. Razlan, W.H. Wan Mohamad, Mechanical properties of finger jointed beams fabricated from eight Malaysian hardwood species, Constr. Build. Mater. 145 (2017) 464–473.

[10] AS/NZS 2269.0 "Plywood - Structural, Part 0: Specifications", *Standards Australia*, 2012.

[11] EN 14358 "Timber structures — Calculation and verification of characteristic values", *European Committee for Standardization*, 2016.

[12] AS/NZS 1604.1 "Preservative-treated wood-based products, Part 1: Products and treatment", *Standards Australia*, 2021.

[13] EN 15497 "Structural finger jointed solid timber - Performance requirements and minimum production requirements", *European Committee for Standardization*, 2014.

[14] B.P. Gilbert, D. Fernando, C.H. Pham, Experimental techniques in structural Testing: Common Mistakes, how to avoid them and other advice, Structures 41 (2022) 1687–1699.

[15] AS/NZS 1080.1 "Timber - Methods of test, Method 1: Moisture content", *Standards Australia*, 2012.

[16] AS/NZS 4063.1 "Characterization of structural timber, Part 1: Test methods", *Standards Australia*, 2010.

[17] AS 5068 "Timber - Finger joints in structural products - Production requierements", Standards Australia, 2006.

[18] ASTM D4688, "Standard test method for evaluating structural adhesives for finger jointing lumber", American Society for Testing and Materials,, 2021.

[19] A. Faircloth, C. Kumar, R.L. McGavin, B.P. Gilbert, W. Leggate, Mechanical Performance and Bond Integrity of Finger Jointed High-Density Sub-Tropical Hardwoods for Residential Decking, Forests 14 (2023) 956.