Effects of Layer Number and Finger Direction on Bending Behavior of Glulam Beams

Ümmü Karagöz İşleyen,[a,*] and İrfan Peker [b]

Effects of the number of layers and the number and typology of finger joints were studied relative to the bending behavior of glulam beam made of Scots pine (*Pinus sylvestris*) laminates. The investigated parameters of glulam beams with constant overall dimensions (width × depth × length) of 90 mm × 90 mm × 1710 mm were lamination thickness (18 mm or 30 mm), the distance of the finger joints (200, 400, and 600 mm), and finger direction (horizontal and vertical). A total of 14 experimental samples were produced (12 different finger joint beams and two reference beams without finger joints) and tested under four-point bending tests. Taguchi orthogonal experimental design was used to evaluate and optimize test results using the S/N ratio. The effects of main and interactions between producing parameters on strength of glulam beam were determined by variance analysis. According to the results of the analysis, it was determined that the number of layers and the direction of the finger had a significant effect on the flexural strength of the beams, but the finger distance was not significant. Moreover, the highest strength values were obtained in 5-layer finger-jointed beams with vertical finger direction.

Keywords: Finger joints; Glulam beam; Finger direction; Ultimate load capacity

Contact information: a: Kastamonu University, Faculty of Forestry, Department of Wood Products Industrial Engineering, Kastamonu, Turkey, 37100; b: Ondokuz Mayıs University, Vezirköprü Vocational School, Department of Materials and Material Processing Technology, Samsun, Turkey;
** Corresponding author: ukaragoz@kastamonu.edu.tr*

INTRODUCTION

The engineering of wood products provides effective techniques for reducing and eliminating the negative properties of solid wood and for obtaining high performance products, as an alternative to solid wood material. Finger jointing technology is a common and economical application used in the wood industry for the production of both structural and non-structural products. Currently, finger-jointed wood products are widely used in the construction industry. Moreover, finger-jointed studs are considered the equivalent to solid wood studs without finger joints, and they can be used interchangeably in Canadian residential construction (Gong *et al.* 2014). The short wood parts, which are free from defects, are combined end-to-end with a finger joint, allowing for limitless dimensional lengths.

There have been many studies on the structural behavior of finger joints (Milner and Yeoh 1991; Smardzewski 1996; Serrano *et al*. 2001; Karastergiou *et al.* 2006). Some of these studies focused on the lamella thickness, bond-line strength, damage model, and formation in finger-jointed glulam beams. The lamella thickness, wood properties, and species were found to affect glue joint resistance in glulam beams (Bourreau *et al.* 2013). At the same time, the number of layers has a significant effect on the strength of the beams. With the reduction of layer thickness, the less stresses usually occur in the finger joint under loading, and thus, the beam is provided with more strength (Tran *et al.* 2015). In a previous study, the influence of several variables on finger-joint bending strength and failure mode, such as end pressure, dynamic elastic modulus of the wood, density, length, and width of the fingertip, were analyzed, and better results were obtained in finger joints with the longest finger length and the smallest tip width (Lara-Bocanegra *et al.* 2017). In another study, the effects of finger orientations (horizontal and vertical) and finger lengths (15 mm and 25 mm) on the mechanical properties of finger-jointed beams were evaluated, and the beam-jointed vertical finger orientations and the longer finger length showed a better behavior than the beam-jointed horizontal finger orientations and the shorter finger length (Ahmad *et al*. 2017). The finger joint geometry has a significant effect on the strength of finger-jointed wood elements. The bending strength of the finger-jointed wood elements increases as greater bonding area is formed by increasing the length of the finger joint (Özçiftçi and Yapıcı 2008). Moreover, the finger joints with short finger length can be used to fabricate finger-jointed structural lumber in the wood industry (Rao *et al.* 2012). The first damage occurred in the bottom surface and finger joint in the tension zone of the finger-jointed beam due to excessive stress accumulation. Reinforcement methods were applied to increase the strength of the finger-jointed wood beams. The finger-jointed wooden beams reinforced with different strengthening materials (such as CFRP, FRP, steel rods, and steel plates) have increased load bearing capacities and initial stiffness in comparison with an unreinforced finger-jointed beam (Khelifa *et al.* 2015, 2016). Srivaro *et al*. (2019) investigated the effects of the finger length (6, 8, and 10 mm) and wood density on the bending and compression properties of finger-jointed oil palm wood products. In another study, the effects of finger and scarf joints on the bending, tensile, and compression properties of bamboo-based composites were investigated by Deng *et al.* (2014).

Recently, numerical finite element methods have been widely used to describe the progressive failure mode of the finger-jointed beams and glued laminated wood. These methods predict the properly nonlinear behavior of wood with failure and mechanical connections and adhesive behavior under tension and shear. The cohesive zone model in numerical simulations has been used to determine the progressive damage of the glue lines within the finger joint up to failure. The behavior of the timber is assumed to describe an orthotropic elasto-plastic material model, and the behavior of glue lines in the interlayer were modeled with the Cohesive Zone Model (CZM) of finite element code and proper damage law (Tran *et al.* 2015; Dourado *et al.* 2018). An interface element formulation developed by Schmidt and Kaliske (2009) consists of an anisotropic traction separation law for wood. For the cohesive model, the traction separation law is mostly described by three cohesive parameters including maximum cohesive strength, initial stiffness, and maximum displacements (Lee *et al.* 2010; Khelifa *et al.* 2015).

This study aimed to determine the effect of three parameters on the strength, stiffness, and energy dissipation of glulam beams. The investigated parameters of glulam beams at constant overall dimensions (width × depth × length) of 90 mm × 90 mm × 1710 mm^3 were: i) lamination thickness (18 mm or 30 mm) and hence 3 or 5 laminations per build-up, ii) the distance of finger joints (200, 400, and 600 mm) and hence the number of joints in the beam, and iii) the finger joint direction (vertical or horizontal).

According to these variables, a total of 12 finger-jointed wood beams and 2 finger unjointed control beams were produced. The bending behavior of the beams under four-point bending loading was tested and load-deflection graphs were obtained. Maximum load, stiffness, energy dissipation capacities, finger joint efficiency, and failure mode of the beams were examined and compared with the unjointed control beam.

EXPERIMENTAL

Materials

In this study, to determine the bending behavior of finger-jointed wood beams and compare with the reference beams without finger joints, wood beam design was performed by taking into consideration several variables, such as number of layers, finger joint direction, and distance of the finger joints. The design details of the finger-jointed wood beams are presented in Table 1.

Table 1. Experimental Design of Finger-jointed and Unjointed Wood Beam

Spec. No	Number of Layer	Distance of Finger Joints (mm)	Finger Joint Direction
CB1	3	-	-
CB2	5	-	-
FJ1	3	200	Vertical joint
FJ2		400	
FJ3		600	
FJ4	5	200	
FJ5		400	
FJ6		600	
FJ7	3	200	Horizontal Joint
FJ8		400	
FJ9		600	
FJ10	5	200	
FJ11		400	
FJ12		600	

The finger-jointed glulam beams were manufactured in a factory in Kastamonu, Turkey. Scots pine (*Pinus sylvestris*) lumber was chosen due to its widespread use in the construction sector in Turkey. First, the lumber was conditioned at 20 ± 2 °C and 65 ± 5% relative humidity to reach 12% moisture content, prior to cutting it into the required dimensions for the fabrication of finger-jointed beams. In this study, wood samples without strength-reducing defects, such as knots, were selected and prepared in cross-sections of 90 mm (width) × 30 mm (thickness) for 3-layer lamination and 90 mm (width) × 18 mm (thickness) for 5-layer lamination. Afterwards, these wood specimens were cut into small sizes for 200, 400, and 600 mm of the distance of the finger. Each of the small-sized wood parts was machined with a desired finger profile (Fig. 1) and horizontal and vertical directions (Fig. 2) using a finger joint machine (Ultra TT205/600/1000 RE; Weining Grecon GmbH & Co. KG., Alfeld, Germany). Finger joint profile parameters were as follows: finger length (L): 10 mm; finger pitch (P): 3.8 mm; tip width (B): 1 mm; tip gap (S): 0.1 mm; and finger angle (α): 5°. Polyvinyl acetate (PVAc, Kleiberit 303; Kleiberit, Weingarten, Germany) adhesive was used in the finger joint and between the layers of the glulam beams. The finger portion was pressed using polyvinyl acetate adhesive for 10 s under 0.7 N/mm^2 pressure in the finger machine. The viscosity value is 13,000+2,000 mPas at 20 °C, and its pH value is ~3. After joint assembly, the adhesive was applied as 200 g/m^2 on one face of the finger-jointed single layer beams with a glue roller and 3- and 5-layer glulam beams were produced by placing other layers on this layer in a lamination press machine (UL6200; Umur Machine Industry, Istanbul, Turkey). The mechanical parameters of wood used glulam beams are given in Table 2.

To take account of the joint symmetry between the layers and to not overlap the joints, the lamination operation was performed with a distance of 100 mm, 200 mm, and 300 mm between the finger joints in the adjacent layer. The final dimensions of the finger-jointed beams and the control beams were 1710 mm of length × 90 mm width × 90 mm thickness.

Table 2. Mechanical Properties of Wood

	Density (g/cm$^{3)}$	Modulus of Elasticity (MPa)	Tensile Strength [MPa]	Compression Strength (MPa)
Pinus sylvestris	0.460	11700	83	58.06

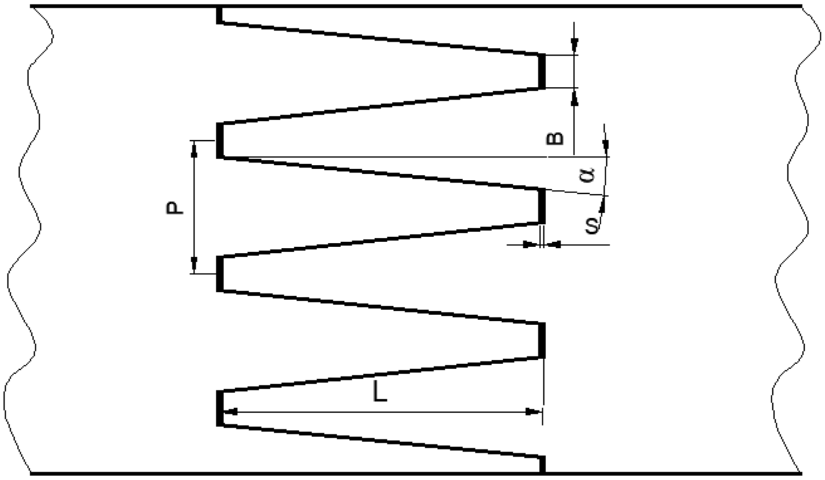


Fig. 1. The finger joint profile

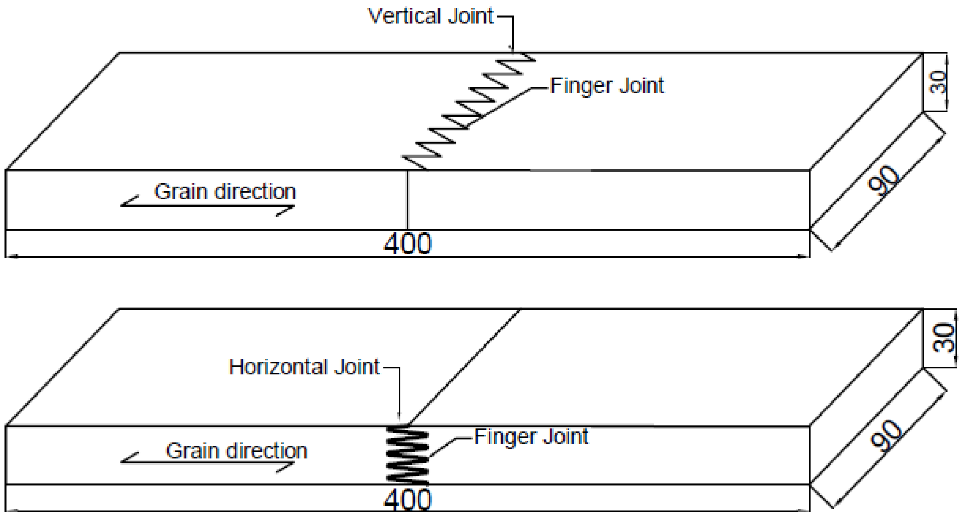


Fig. 2. The finger joint direction

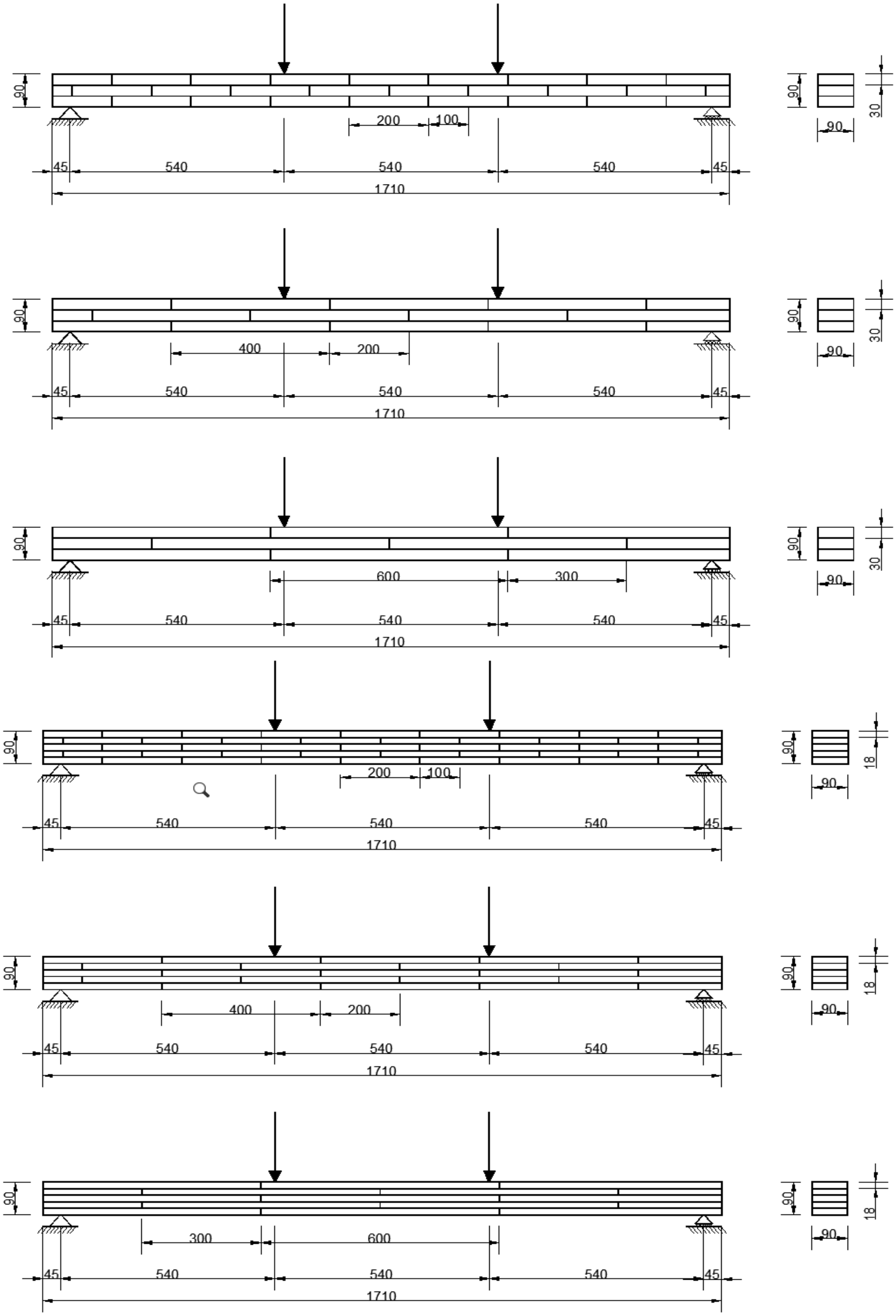


Fig. 3. Joint symmetry arrangement for horizontal and vertical finger joint direction in 3- and 5-layers of lamination; units are in mm

A total of 14 finger-jointed specimens were produced for different types of test conditions. All of the 12 finger-jointed beams produced according to the distance between the finger joint, finger joint direction, and the number of layers are given in Fig. 3. The two reference beams (*i.e.*, 3-layer and 5-layer) were manufactured without finger joints to compare the strength of the finger-jointed beams as shown Fig. 4.

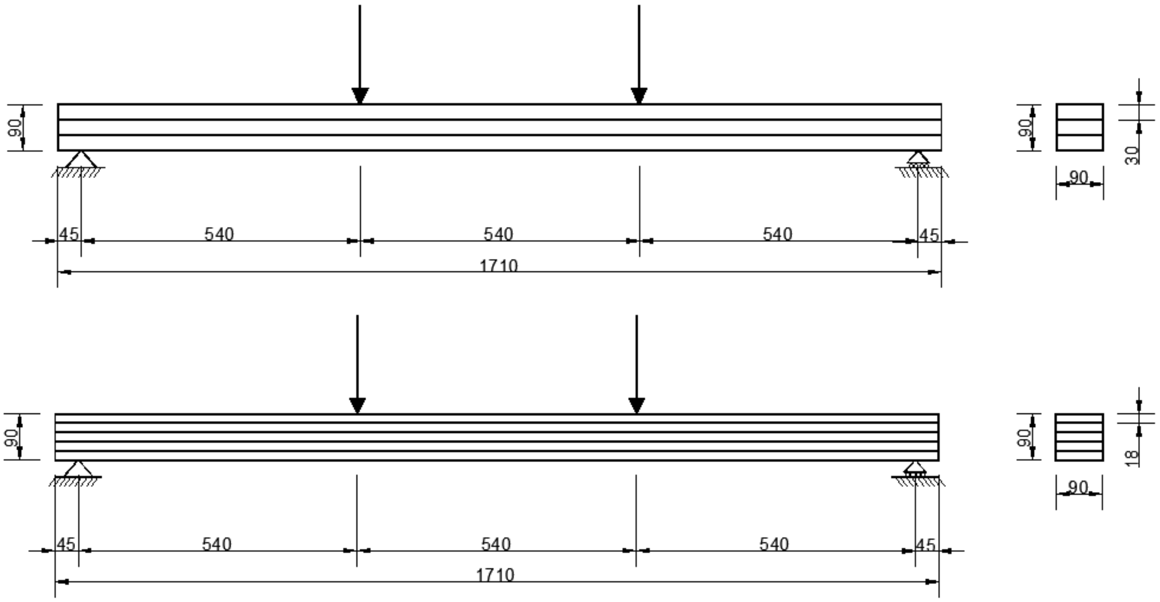


Fig. 4. The control glulam beam without finger joint; units are in mm

Methods

Experimental set-up and procedure

The bending test of both the finger-jointed and unjointed control samples were conducted using a universal testing machine with 100 kN capacity according to the EN 408 (2010) requirements. The distances between load point and supports were six times the specimen height (6 h = 540 mm). Four-point bending tests of the specimens were prepared with the distance between supports being 1620 mm, as shown Fig. 5.

The load-deflection curves of experimental specimens were obtained under four-point bending test. The effects of the variables (*i.e.*, the number of layers, finger joint direction, and distance of between the finger joints) were examined on bending strength, stiffness, energy dissipation capacity, failure mode, and the finger joint efficiency. In accordance to the EN 408 (2010) using the load-deflection graphs of the experimental elements, the global modulus of elasticity (MoE) and modulus of rupture (MoR) were obtained using Eqs. 1 and 2 below,

$$MoE = \frac{3al^2-4a^3}{2bh^3\left(2\frac{w_2-w_1}{F_2-F_1}\right)} \tag{1}$$

where a is the distance between a loading position and the nearest support (mm), l is the distance between support points, b is the width of the beam (mm), h is the height of the beam (mm), $F_2 - F_1$ is an increment of load on the straight line portion of the load-deflection curve, and $w_2 - w_1$ is the increment of deformation corresponding to $F_2 - F_1$ (mm). Equation 2 is as follows,

$$MoR = \frac{3aF_{max}}{bh^2} \tag{2}$$

where $F_{\max}$ is the maximum load, a is the distance between loading position and the nearest support (mm), b is the width of the beam (mm), and h is the height of the beam (mm).

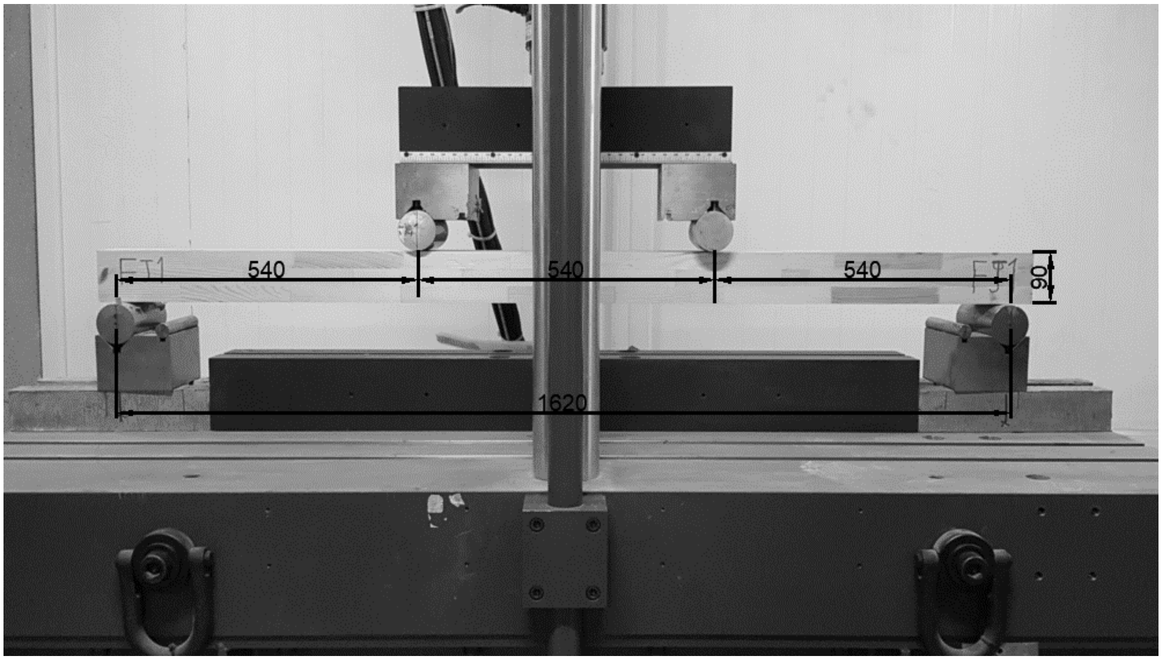


Fig. 5. The four-point bending test arrangement of the specimens

In the present study, joint efficiency of the finger joints was expressed in percentage based on the ratio of the MoR value of the finger joints to the unjointed wood and was calculated with Eqs. 3 and 4,

$$\text{Joint efficiency (\%) of 3-layer beam} = FJ_{\text{MoR}} - CB1_{\text{MoR}} / CB1_{\text{MoR}} \tag{3}$$

$$\text{Joint efficiency (\%) of 5-layer beam} = FJ_{\text{MoR}} - CB2_{\text{MoR}} / CB2_{\text{MoR}} \tag{4}$$

where FJ_{MoR} is the strength of the finger-jointed beams (MPa), $CB1_{\text{MoR}}$ and $CB2_{\text{MoR}}$ are the strength of the 3-layer and 5-layer control beams without joints, respectively (MPa).

A Taguchi orthogonal experimental design was used to evaluate and optimize the test results. The experimental design for number of layer with two levels (3- and 5-layer), the distance of finger joints with three levels (200, 400, and 600 mm), and finger joint direction with two levels (vertical and horizontal) were organized by the Taguchi's L12 ($3^1 \times 2^2$) orthogonal array. The larger load value resulted in better quality characteristics for the signal-to-noise (S/N) ratio to achieve ultimate load bearing capacities of the samples that were used in the Taguchi method using Minitab 19 software (Minitab Inc., State College, PA, USA). The S/N ratios with the larger load value resulted in better quality characteristics were calculated according to the following Eq. 5,

$$\text{SN ratio} = -10log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{\frac{1}{2}}\right) \tag{5}$$

where y is the measurement value of the parameters and n is the number of the measurement.

The effects of the main single effect and interactions between three parameters on the strength of glulam beams were determined by variance analysis. The variance analysis was carried out with a full factorial experimental design (2 × 3 × 2) with one replicate, at a 95% confidence level using Minitab 19 software (Minitab Inc., State College, PA, USA). The factorial regression model fitted for maximum load was obtained and are represented by Eq. 6,

$$\begin{aligned}\text{Load} &= 2.25 + 2.656\ \text{Layer} + 0.0250\ \text{Distance} - 4.85\ \text{Direction} + 0.0011 \\ &\quad \text{Layer*Distance} + 0.389\ \text{Layer*Direction} + 0.0291\ \text{Distance*Direction}\end{aligned} \tag{6}$$

RESULTS AND DISCUSSION

Ultimate Load Bearing Capacities and Stiffness

The load-deflection curves of 3-layer and 5-layer beam with and without finger-jointed beams are given in Fig. 6. The load-deflection curve showed that the finger-jointed beams exhibited linear behaviors, while the reference groups indicated nonlinear behaviors. All test specimens displayed vertical unloading behavior following maximum load. In addition, the finger joints significantly affected the strength of the beams.

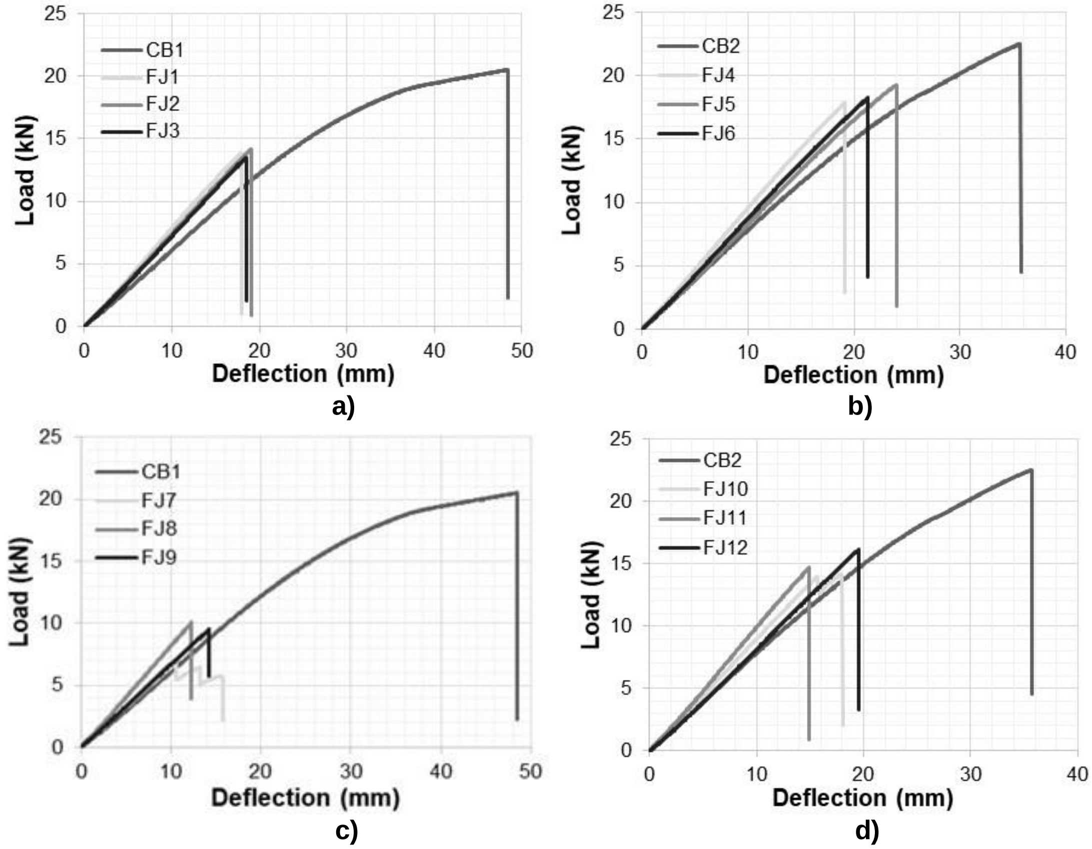


Fig. 6. Load–deflection curves for all test specimens: a) 3-layer beam and b) 5-layer beam with vertical finger joint direction; c) 3-layer beam and d) 5-layer beam with horizontal finger joint direction

All 3-layer and 5-layer finger-jointed beams with horizontal and vertical finger joint direction exhibited lower strength than the control groups. In a glulam beam, the bonding areas are different in vertical and horizontal joint direction, since width of the layers is not equal to its height. The weak joint strength and bonding area were formed on the wide face of the pieces in the horizontal joint direction. Therefore, according to Fig.6c, the bending moment capacity of specimen FJ7, FJ8, and FJ9 with horizontal finger joint direction was lower than the reference specimen. The ultimate stiffness and energy dissipation capacity were calculated with load-deflection curve obtained of experimental samples under bending load. The experimental results of glulam beams and S/N ratio are presented in Table 3. A high S/N value refers to the experimental parameter that ensures the maximum load bearing capacity surface quality. The effects of the finger joint direction, the distance of finger joints, and the number of layers on the ultimate load carrying capacities of the test elements were observed. According to the S/N ratio in Table 3, the optimum parameters were obtained in FJ5 with 5-layer, a finger distance of 400 mm, and vertical direction to achieve maximum load. The effects of main, two-way and three-way interaction on ultimate load bearing capacities were investigated by variance analysis using the full factorial experimental design, shown in Table 4. According to the variance analysis results in Table 4, the most important effect on the ultimate load bearing capacity of the experimental samples is the number of layers and the finger direction. However, it was determined that the interaction effect of parameters and the main effect of finger distances had no significant effect on ultimate load capacity.

Table 3. Experimental Results and S/N Ratio of Glulam Beam

Spec. No	Ultimate Load Capacity (kN)	Means of Ultimate Load Capacity (kN	S/N Ratio	Deflection at Ultimate Load (mm)	Elastic Stiffness (kN/mm)	Energy Dissipation Capacity (kN-mm)
CB1	20.53	-	-	48.46	0.58	653.26
CB2	22.54	-	-	35.61	0.75	465.27
FJ1	13.90	13.87	22.86	17.96	0.77	126.79
FJ2	14.18		23.03	19.03	0.75	133.75
FJ3	13.52		22.61	18.59	0.73	124.00
FJ4	17.89	18.49	25.05	19.11	0.94	173.54
FJ5	19.29		25.70*	23.97	0.80	237.47
FJ6	18.29		25.24	21.32	0.86	196.32
FJ7	6.88	8.84	16.75	10.62	0.65	91.53
FJ8	10.09		20.07	12.30	0.82	61.56
FJ9	9.53		19.58	14.27	0.67	67.68
FJ10	14.14	15.01	23.00	18.01	0.79	143.84
FJ11	14.72		23.35	14.94	0.99	109.34
FJ12	16.18		24.17	19.57	0.83	155.03

*Larger is better

The effects of layer numbers, finger direction, and finger distance on the ultimate load, ultimate deflection, stiffness, and energy dissipation capacities of the glulam beams were analyzed both graphically and statistically. According to the test results summarized in Table 3, the maximum load capacity and deflection values of 3-layer (CB1) and 5-layer (CB2) control beams were 20.53 kN and 22.54 kN and 48.46 mm and 35.61 mm, respectively. Additionally, finger joint direction had a significant effect on the strength of finger-jointed beams. Because the joint surface area and the number of fingers in the vertical direction were greater, the mean ultimate load of the vertical direction was better (35%) than the horizontal direction. The maximum load capacity of the control beam (CB1) was 1.5 times larger than finger-jointed 3-layer with vertical joint (FJ1, FJ2, and FJ3). The maximum load capacity of 5-layer control beam (CB2) were approximately 1.25 times larger than the 5-layer beam with vertical joint as FJ4 and FJ6, and it exhibited similar behavior as FJ5 with the highest strength in the same group (FJ4, FJ5, and FJ6).

Table 4. Analysis of Variance (ANOVA) for Ultimate Load Capacity of Finger-Jointed Beam

Source	DOF	Adj SS	Adj MS	*F*	P-Value
Model	6	149.078	24.8464	32.36	0.001
Linear	3	144.544	48.1814	62.75	0.000
Layer	1	87.487	87.4869	113.94	0.000*
Distance	1	2.779	2.7787	3.62	0.116
Direction	1	54.278	54.2785	70.69	0.000*
2-Way Interactions	3	4.534	1.5114	1.97	0.237
Layer*Distance	1	0.004	0.0039	0.01	0.946
Layer*Direction	1	1.812	1.8116	2.36	0.185
Distance *Direction	1	2.719	2.7187	3.54	0.119
3-Way Interactions	5	3.839	0.7678		
Layer*Distance*Direction	11	152.917			
Error	6	149.078	24.8464	32.36	0.001
Total	3	144.544	48.1814	62.75	0.000

DOF: degrees of freedom, Adj SS: adjusted sum of squares, Adj MS: adjusted mean square, *: p < 0.05

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,876261	97,49%	94,48%	85,39%

The effect of layer numbers on the ultimate load capacities of the beam was considerably important. The ultimate load values of finger-jointed and unjointed beams increased with the increasing number of layers. The mean ultimate load values of the finger-jointed 5-layer beam was approximately 50% higher than the finger jointed 3-layer beam. Moreover, the mean maximum load of the 5-layer control beam was slightly higher (9%) than the 3-layer control beam. According to the interactions of finger combinations and the number of layers, the mean maximum load bearing capacity in the 3-layer finger-jointed beam was 45% lower than the CB1 control beam, and the 5-layer finger-jointed beams were 25% lower than the CB2 control beam.

The other important parameter was the distance between the two finger joints in the layer and the adjacent layer. The finger-jointed glulam beams were manufactured in different combinations with distances of 200 mm, 400 mm, and 600 mm finger joints and not overlapping joints in the adjacent layer. The major stress effect on the finger joints under loading depends on the finger geometry. Additionally, significant stress concentrations occur around the finger tips. Because of the increase in the number of joints with the decrease of finger distance, the finger joint region of the beam was exposed to higher stress. In other words, the reason for the reduction of the load bearing capacity of the beams results completely from increased probability of a weak joint in the tensile-loaded cross-section and thus in the highest stressed part. It can be seen that the ultimate load values of beams with finger joint (FJ) distances of 400 mm or 600 mm provided almost similar results, while the beams with 200 mm FJ distance were lowest. However, when looking at the build-up of the beams and the positions of the joints (Fig. 4), it becomes evident that for 3- and 5-layer beams exclusively the build-ups with 200 mm FJ distance were significantly different from the other build-ups with FJ-distances of 400 mm and 600 mm, respectively. For 3-layer beams, the beams FJ1 and FJ7 have four finger joints in the outer bottom tension lamination within the constant moment area, whereas for the 400 mm and 600 mm FJ distances (beams FJ2, FJ3, FJ8, and FJ9) throughout only two finger joints occur within/close to the constant moment area. Therefore, beams with a distance of 400 and 600 mm behave similarly. However, the first deformations in the middle moment field occurred in the finger joints located under the two loading cells in beams with finger joint (FJ) distances of 600 mm. This situation caused great deformation in the shear direction with increasing loading. As for beams with a distance of 400 mm, there are more finger joints in the middle moment area. These finger joints gradually spread the stresses to adjacent layers. So, the ultimate load of beam with finger jointed distance of 400 mm was higher than beams with 600 mm finger distance. The average load-bearing capacities of the experimental specimen with finger distances of 200 mm, 400 mm, and 600 mm were 13.20 kN, 14.57 kN, and 14.38 kN, respectively.

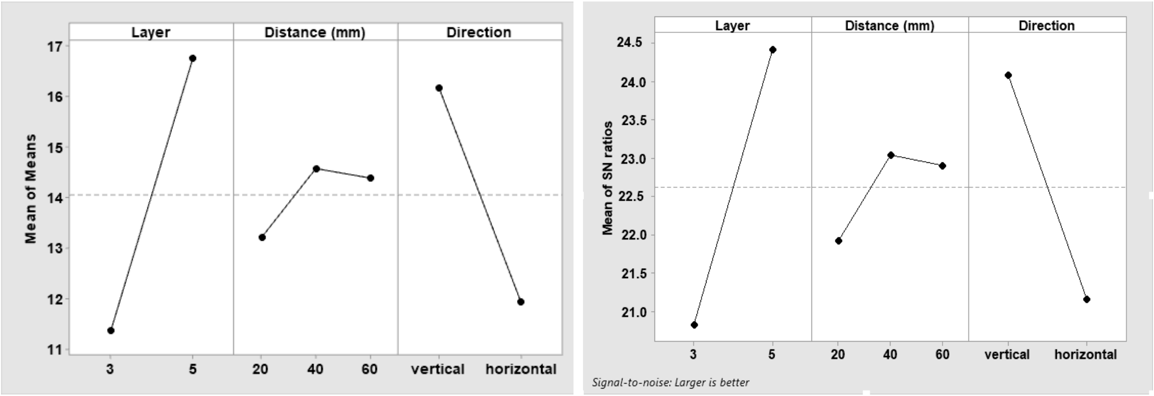
The elastic stiffness values were calculated by the ratio of the ultimate load to the displacement values at the ultimate load from load-deflection curve for finger jointed beam. While the initial stiffness values of all specimens were considerably high, the finger-jointed wood beams exhibited no ductility until maximum load was reached, as shown in Figs. 6a through 6d. However, for control beams (CB1 and CB2) without finger joints, each curve was comprised of linear and nonlinear parts. Elastic stiffness of the control beams were calculated for the linear part of the curve. Beyond this limit, ductility behavior of the control beam allowed for large displacements to be attained without losing too much strength in a material specimen/joint/member/structure loaded in displacement control (Jorissen and Fragiacomo 2011). Therefore, the elastic stiffness values of the control beams were lower than the finger-jointed beams. The effects of the number of layers and finger direction on the ultimate stiffness were less pronounced. The mean stiffness values of the 5-layer beam with finger joint were 19% higher than 3-layer finger-jointed beams. In addition, the mean stiffness values of the 3-layer and 5-layer beams with finger joints were 23% and 14%, respectively, higher than the 3-layer (CB1) and 5-layer (CB2) control beams.

Energy Dissipation Capacity

The energy dissipation capacities of the experimental specimens were obtained by calculating the areas under the load–deflection curve. The energy dissipation capacities of the test specimens were calculated until a maximum deflection point corresponding to ultimate load was reached. It was found that the number of layers of wood beam were significantly effective on the energy dissipation capacity. With the increase of the number of layers and finger joints within the beam, the energy dissipation capacity values of wood beams with and without finger joint increased, and the 5-layer beams were 67% larger than the 3-layer beams with finger joints. Similar results were found in previous studies by Uzel *et al.* (2018), which stated that the increase in the number of layers is the most effective variable on the values of the energy dissipation capacities, and that the 5-layer beams exhibited a higher average energy dissipation capacity than the 3-layer beams. Because of the number of fingers in vertical joint direction, the vertical-jointed wood beams provided 57% more energy dissipation from horizontal-jointed beams. Because finger joint fails brittle in the tension zone under load, the energy dissipation values of the 3-layer and 5-layer control beams without finger joints were 6.5 times and 3 times higher than the 3-layer and 5-layer beams with finger joints, respectively.

Analysis of main effects

The S/N ratio and means graphics of levels of parameters were used for the evaluation of the optimal producing parameters for ultimate load bearing capacities. The main effect plot for S/N ratio and means according to surface roughness are shown in Fig. 7. Each level of producing parameters affected the ultimate load bearing capacities. The number of layers and direction of finger parameters were effective factors for the producing process as denoted by a sharp slope in Fig. 7a and 7b.



a **b**

Fig. 7. The main effect plot for (a) means load and (b) mean S/N ratio for ultimate load capacity

The finger joint efficiency

To determine the effect of finger joint on the strength of experimental specimens, finger joints within the layers were placed at different distances such as 200 mm, 400 mm, and 600 mm. As the distance between the finger joints increased, the number of finger joints in the layer decreased. Therefore, the maximum number of finger joints was 200 mm distance. The joint efficiency of finger-jointed wood beams was found in bending, as given in Table 5. According to Table 5, the finger joint clearly increased the MoE value and decreased the MoR values of the glulam beams. The MoR values of the 3-layer and 5-layer control beams were approximately 2 times and 1.5 times higher than the mean MoR value of 3-layer and 5-layer beams with finger joints, respectively.

The mean finger joint efficiency of 3-layer groups was 44% lower than the control beam (CB1). Within this group (FJ1, FJ2, FJ3, FJ7, FJ8, and FJ9), the FJ2 beam jointed vertical direction with the number of 12 finger joints provided the nearest (30%) MoR value to the control group (CB1). The mean efficiencies of the 5-layer finger-jointed beam with the 200, 400, and 600 mm finger distance were 29, 24, and 23%, respectively. The mean efficiencies value of 5-layer groups was 25% lower than control beam (CB2). Within the vertical and horizontal finger-jointed 5-layer beam with the number of 42, 20, and 12 finger joints (FJ4, FJ5, FJ6, FJ10, FJ11, and FJ12), FJ5 with a number of 20 finger joints in vertical direction and FJ11 with a number of 42 finger joints in horizontal direction exhibited the nearest (14%) and furthest (37%) strength values for the control groups (CB2), respectively. The mean joint efficiencies of vertical and horizontal fingers were 25% and 45%, respectively. Although the finger joint disturbs the uniform distribution of stresses in the adhered (Smardzewski 1996), because of more adhesive quantity, adhesive surface area, and the number of fingers in the vertical finger joint direction, the effect of finger spacing on the strength in vertical direction was smaller according to horizontal direction.

The finger joint efficiency of with the 5-layer beam, which had a greater number of finger joints than the 3-layer beam, was determined to be the lowest, due to increasing strength with an increasing number of layers. In other words, the number of layers was more effective than the number of fingers on the strength value of 5-layer beams. In addition, the mean MoR values (37.2 MPa) of the 5-layer beam horizontal and vertical joints were 50% higher than the 3-layer beams horizontal and vertical joints 25.2 MPa). The mean MoR values of vertical and horizontal joint were 36.0 MPa and 26.5 MPa. The finger-jointed beam with vertical joint direction provided approximately 36% greater strength than the horizontal joined beam. The number of fingers and the adhesion area were less in the horizontal joint placed along the thickness of the beams; thus, the strengths of the beams were lower. It was stated in previous studies that the local elastic properties of each finger affected the failure modes and strength, and the vertical finger-jointed beam displayed higher bending strength (Yeh and Lin 2012; Ahmad *et al.* 2017; Lara-Bocanegra *et al.* 2017).

As shown in Table 5, global MoE was higher throughout for the 5-layer beams (unjointed and jointed) compared to the 3-layer beams. Assuming rigid compounds of the same cross-section and moment action and disregarding stiffness differences of the laminations in a beam, then thicker laminations have lower centroid stresses as thin laminations. All strength-increasing effects reported in this study stemmed from the so-called lamination effect that is present at non-finger-jointed and finger-jointed beams. The experimental specimen jointed vertical direction also exhibited a better MoE compared to the samples beam jointed horizontally.

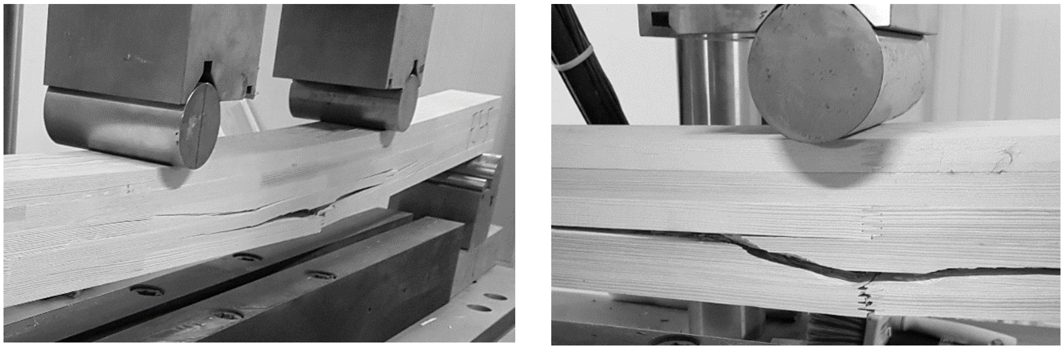
Table 5. Finger Joint Efficiency of Samples According to Reference Group

Spec. No	Number of Finger Joints in Beam	MoE (MPa)	MoR (MPa)	Joint Efficiency (%)
CB1	-	8130	45.62	-
CB2	-	10400	50.09	-
FJ1	25	10700	30.89	-32.30
FJ2	12	10300	31.51	-30.94
FJ3	7	10000	30.04	-34.15
FJ4	42	12900	39.75	-20.65
FJ5	20	11100	42.87	-14.42
FJ6	12	11800	40.65	-18.85
FJ7	25	8940	15.30	-66.47
FJ8	12	11300	22.42	-50.86
FJ9	7	9220	21.18	-53.57
FJ10	42	10840	31.42	-37.28
FJ11	20	13600	32.71	-34.69
FJ12	12	11400	35.95	-28.22

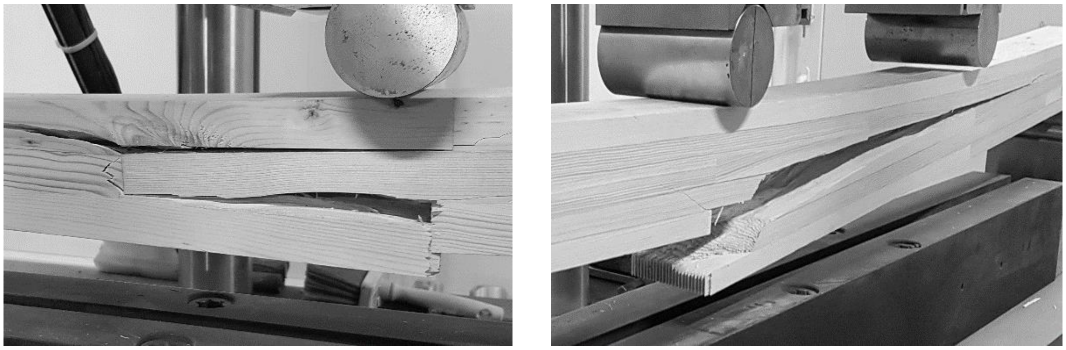
While the mean MoE values of beams jointed vertically were 11140 MPa, the mean MoE values of beams jointed horizontally were 10890 MPa. The beams jointed vertical also exhibited better MoE compared to that of beams samples jointed horizontal. The MoE values of control groups were lower than finger jointed beams. Although the control groups had a low elastic value, after the elastic boundary, the control samples exhibited ductile behavior and showed higher bending strength.

Failure modes of finger-jointed beam

It can be seen that the finger joint distance, number of layers, and finger joint directions affected the failure modes of the beams, when the cracks distributions of the finger-jointed experimental specimens were examined. The failure modes that occurred within the beam with and without finger joints under the bending test are shown in Fig. 8. It was determined that damage occurred in the tension zones of the beam, where the maximum bending moment accumulated under bending load (Fig. 8a). Moreover, with the increasing load, the first damage occurred at the finger joint areas in the tension zone, and it was directed towards the adjacent layers (Fig. 8b). It was observed that the finger joint distances have different effects on damage distribution of the beams. The distance between finger joint of adjacent layers were 100, 200, and 300 mm in the finger-jointed beams placed at 200, 400, and 600 mm distance on layer, respectively. As the stresses in the finger joint increased with the decrease of the finger distance, the crack gradually grew up the longitudinal direction, from the finger joint at the bottom surface of the beam to the other layers in the beam. The load-bearing capacity of the specimens (FJ1, FJ4, FJ7, and FJ10) with distance of 200 mm between the joints was lower due to the finger joint damage.



(a) Tension failure **(b)** Failure of finger-jointed



(c) Inter-layer delamination **(d)** Diagonal crack

Fig. 8. Typical illustration of the failure mode of the beams

In addition to finger joint failure in the beams, the finger-jointed beam exhibited brittle crack failure because of inter-layer delamination ensued in the adhesive line between the layers with the increasing bending load (Fig. 8c). The finger-jointed beam with a joint distance of 400 mm (FJ2, FJ5, FJ8, and FJ11) indicated this damage distribution type. In fact, the main failure in the experimental specimens was originated by adhesive damage between the inter-layer and finger joint. During the loading, due to excessive stresses within the beam, normal and shear stress accumulations in the finger joint occurred, and the strength of the adhesive was lost (Tran *et al.* 2015). The cracks initiated in finger roots and progress away, and subsequently lead to wood failure, as illustrated in Fig. 8d. The failure beginning mostly at the finger joint resulted in wood failure. Shear failure in the finger joint from the bottom layer to the adjacent layers occurred in the beams with a longer finger distance (FJ3, FJ6, FJ9, and FJ12).

CONCLUSIONS

In this study, the effects of finger joint distance and direction, number of layers on the maximum load-carrying capacities, stiffness, and energy dissipation capacities of finger-jointed 3- and 5-layer wood beams were examined under the bending test. The following are the summary of conclusions.

1. According to the ANOVA it was found that the number of layers and the finger direction had a significant effect on ultimate load capacity and strength. The interaction effect of the producing parameters and main effect of the finger distance had no significant effect on strength.
2. The maximum ultimate load capacity of the beams increased with the increasing number of layers.
3. Moreover, it was determined that the beam with vertical joint direction provided more strength than the beam with horizontal joint direction.
4. The finger-jointed beams were produced with finger distance of 200, 400, and 600 mm between fingers placed in layers, to take care not to overlap joints between the layers. The beam of the low finger distance (200 mm) showed lower strength than the high-finger distance beam. The best result was the test specimens with 400 mm finger joint distance.
5. It was determined that the mean ultimate stiffness value of the finger joint beam with 5-layer was higher than for a 3-layer beam.
6. The unjointed control beams showed nonlinear and ductility behavior and had more load and large displacement without loss of strength.
7. The results showed that the MoR values of the glulam beam decreased with the total number of finger joints in the layers due to the brittle behavior of finger joints under load.
8. The global MoE was higher throughout for the 5-layer beams (unjointed and jointed) compared to the 3-layer beams.
9. The failure mode in the finger-jointed and unjointed beam occurred such as tension failure, finger joint failure, inter-layer delamination, and diagonal crack. The damages

were spread towards middle layers from the tension zone, which accumulated maximum stress.

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REFERENCES CITED

Ahmad, Z., Luma, W. C., Lee, S. H., Razlan, M. A., and Mohamad, W. H. W. (2017). "Mechanical properties of finger jointed beams fabricated from eight Malaysian hardwood species," *Constr. Build. Mater.* 145, 464-473. DOI: 10.1016/j.conbuildmat.2017.04.016

Bourreau, D., Aimene, Y., Beauchene, J., and Thibaut, B. (2013). "Feasibility of glued laminated timber beams with tropical hardwoods," *Eur. J. Wood Prod.* 71, 653-662. DOI: 10.1007/s00107-013-0721-4

Deng, J., Li, H., Zhang, D., Chen, F., Wang, G., and Cheng, H. (2014). "The effect of joint form and parameter values on mechanical properties of bamboo-bundle laminated veneer lumber (BLVL)," *BioResources* 9(4), 6765-6777. DOI: 10.15376/biores.9.4.6765-6777

Dourado, N., Silva, F. G. A., and Moura, M. F. S. F. (2018). "Fracture behavior of wood-steel dowel joints under quasi-static loading," *Constr. Build. Mater.* 176, 14–23. DOI: 10.1016/j.conbuildmat.2018.04.230

EN 408 (2010). "Timber structures – Structural timber and glued-laminated timber – Determination of some physical and mechanical properties," European Committee for Standardization, Brussels, Belgium.

Gong, M., Delahunty, M. S., and Chui, Y. H. (2014). "Influence of number of finger joints per stud on mechanical performance of wood shearwalls," *Constr. Build. Mater.* 50, 335-339. DOI: 10.1016/j.conbuildmat.2013.09.041

Jorissen, A., and Fragiacomo, M. (2011). "General notes on ductility in timber structures," *Engineering Structures* 33(11), 2987-2997. DOI: 10.1016/j.engstruct.2011.07.024

Karastergiou, S., Barboutis, J., and Vassiliou, V. (2006). "Effect of the PVA gluing on bending strength properties of finger jointed turkey Oakwood (*Quercus cerris* L.)," *Holz. Roh. Werkst.* 64, 339-340. DOI: 10.1007/s00107-005-0075-7

Khelifa, M., Celzard, A., Oudjene, M., and Ruelle, J. (2016). "Experimental and numerical analysis of CFRP-strengthened finger-jointed timber beams," *Int. J. Adhes. Adhes.* 68, 283–297. DOI: 10.1016/j.ijadhadh.2016.04.007

Khelifa, M., Lahouara, M. A., and Celzard, A. (2015). "Flexural strengthening of finger-jointed spruce timber beams with CFRP," *J. Adhes. Sci. Technol.* 29(19), 2104-2116. DOI: 10.1080/01694243.2015.1057395

Lara-Bocanegra, A. J., Majano-Majano, A., Crespo, J., and Guaita, M. (2017). "Finger-jointed *Eucalyptus globulus* with 1C-PUR adhesive for high performance engineered laminated products," *Constr. Build. Mater.* 135, 529-537. DOI: 10.1016/j.conbuildmat.2017.01.004

Lee, M. J., Cho, T. M., Kim, W. S., Lee, B. C., and Lee, J. J. (2010). "Determination of cohesive parameters for a mixed-mode cohesive zone model," *Int. J. Adhes. Adhes.* 30(5), 322-328. DOI: 10.1016/j.ijadhadh.2009.10.005

Milner, H. R., and Yeoh, E. (1991). "Finite element analysis of glued timber finger joints," *J. Struct. Eng.* 117(3), 755-766. DOI: 10.1061/(ASCE)0733-9445(1991)117:3(755)

Özçiftçi, A., and Yapıcı, F. (2008). "Structural performance of the finger-jointed strength of some wood species with different joint configurations," *Constr. Build. Mater.* 22, 1543-1550. DOI: 10.1016/j.conbuildmat.2007.03.020

Rao, S., Gong, M., Chui, Y. H., and Mohammad, M. (2012). "Effect of geometric parameters of finger joint profile on ultimate tensile strength of single finger-jointed boards," *Wood Fiber Sci.* 4, 263-270.

Schmidt, J., and Kaliske, M. (2009). "Models for numerical failure analysis of wooden structures," *Engineering Structures* 31(2), 571-579. DOI: 10.1016/j.engstruct.2008.11.001

Serrano, E., Gustafsson, P. J., and Larsen, H. J. (2001). "Modelling of finger-joint failure in glued-laminated timber beams," *J. Struct. Eng.* 127(8), 914-921. DOI: 10.1061/(ASCE)0733-9445(2001)127:8(914)

Smardzewski, J. (1996). "Distribution of stresses in finger joints," *Wood Sci. Technol.* 30, 477-489. DOI: 10.1007/BF00244442

Srivaro, S., Cherdchim, B., and Pasztory, Z. (2019). "Bending and compressive properties of finger-jointed oil palm wood products," *BioResources* 14(3), 6341-6352. DOI: 10.15376/biores.14.3.6341-6352

Tran, V. D., Oudjene, M., and Meausoone, P. J. (2015). "Experimental and numerical analyses of the structural response of adhesively reconstituted beech timber beams," *Compos. Struct.* 119, 206-217. DOI: 10.1016/j.compstruct.2014.08.013

Uzel, M., Togay, A., Anil, Ö., and Sögütlü, C. (2018). "Experimental investigation of flexural behavior of glulam beams reinforced with different bonding surface materials," *Constr. Build. Mater.* 158, 149-163. DOI: 10.1016/j.conbuildmat.2017.10.033

Yeh, M., and Lin, Y. (2012). "Finger joint performance of structural laminated bamboo member," *J. Wood Sci.* 58(2), 120-127. DOI: 10.1007/s10086-011-1233-7

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