

APPLICATION OF FLEXURAL REINFORCEMENT WITH CFRP ON FINGER-JOINTED LAMINATED TIMBER BEAMS

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Abstract

The increasing demand for sustainable construction materials has driven the use of engineered wood products, particularly finger-jointed glued laminated timber (glulam). This study evaluates the mechanical performance of finger-jointed glulam beams made from Merbau hardwood waste, reinforced with carbon fiber reinforced polymer (CFRP). A four-point bending test was conducted according to ASTM D198-02 to determine the flexural strength, stiffness, and failure behavior of different CFRP reinforcement configurations. The results indicate that CFRP reinforcement significantly enhances the load-bearing capacity, maximum bending moment, and mid-span deflection of finger-jointed glulam beams. The face-butt joint with short CFRP U-reinforcement increased load capacity by 38%, whereas the face-finger joint with long CFRP U-reinforcement exhibited a 102% improvement. The study also reveals that CFRP reinforcement enhances the modulus of rupture (MOR), particularly in the long U-configuration, where an increase of 101.05% was observed. However, the modulus of elasticity (MOE) did not always show consistent improvement, suggesting that reinforcement efficiency is influenced by joint orientation and bonding characteristics. Failure analysis indicates that CFRP significantly alters the fracture mode, reducing brittle failure at the finger joints and improving overall structural resilience. The analysis of hardwood glulam finger-joint provides insights into its mechanical behavior and structural feasibility. These findings confirm the effectiveness of CFRP as a strengthening material for finger-jointed glulam beams, making them a viable alternative to traditional construction materials. Further studies are needed to optimize reinforcement configurations and evaluate long-term performance.

Keywords: finger-jointed glulam, Merbau wood waste, CFRP reinforcement, modulus of rupture.

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1. Introduction

Given the increasing focus on environmental sustainability and concerns about global warming, wood is considered an environmentally friendly construction material with low CO₂ emissions. Wood is natural, renewable, and offers many advantages over other materials from the ecological standpoint [1]. The application of wood for construction purposes is the most important because it is the only material among all that is sustainable [2]. Wooden building has been somehow a rediscovery of a potentially complex building material combining economic sustainability and superior mechanical performance [3].

As our research proceeds, evidence renders that the replacement of laminated timber in concrete components brings a great reduction to the carbon footprint. This happens especially when using hybrid construction systems that consist of steel elements for seismic resistance [4]. Glue-laminated timber also exhibits improved sustainability in comparison with prestressed concrete, in terms of a reduction in emissions and improvement in CO₂ absorption [5].

Wood use should be conducted in a manner that ensures environmental sustainability. The wise and creative use of wood has been shown to increase the economic value of the remaining wood, aligning with the Indonesian government's program on natural environment conservation. Glulam mix processing of sengon and coconut wood enhances the mechanical performance of sengon wood for structural applications, increasing its flexural strength and modulus of elasticity by 8.4% and 26%, respectively. However, the lamination process reduces ductility by 14%, resulting in more brittle glulam beams [6].

Industrial waste wood, particularly from Merbau, can be reused to produce engineered wood products such as finger joint laminated timber beams. These products serve as a cost-effective alternative to solid wood for the construction of building structures. Consequently, the transformation of waste wood into valuable engineered wood products can be a lucrative endeavor for industrial entities.

It has been identified that optimum utilization of the resource and environmental and economical construction can be attained by using wood waste. One of the key technologies in reusing wood waste is finger jointing. Application of finger jointing in the manufacturing process of glued laminated beams brings a number of considerable advantages, among which the most essential are increased mechanical resistance and structural stability of materials that naturally possess low strength. According to [7], "finger-jointed hardwoods have presented a high tensile strength of 36.4 MPa for white ash wood species". Besides, material use optimization techniques were proven by [8] to enhance the capacity through minimizing wood waste by optimizing finger joint design parameters.

Overall, finger-joint laminated timber is a structural building material that offers significant reduction of carbon emissions, thereby contributing to various associated environmental benefits such as carbon sequestration and reduction of embodied energy in the construction process, as noted by [9, 10]. Thus, laminated timber stands out as a more environmentally friendly and sustainable option compared to traditional construction materials like steel and concrete.

The performance of the laminated timber beams can further be improved by external reinforcement using new advanced materials such as CFRP. In civil engineering, the use of composite fiber-reinforced polymer (CFRP) has seen a remarkable growth in recent decades, especially for the structural strengthening application. The unique combination of high strength, light weight and corrosion resistance offered by CFRP has led to its increased popularity for strengthening and rehabilitating existing structures [11, 12]. It is versatile in application, either in sheets, bars, or strips form, enhancing the load-bearing capacity, rigidity, and durability of structural members such as beams, columns, and floor slabs [13, 14].

Although CFRP reinforcement of laminated timber beams has been studied in the past, little is known about the mechanical performance of finger-joint laminated beams made from Merbau hardwood waste with CFRP reinforcement. Further research is needed to analyze the effect of CFRP on critical aspects such as load-carrying capacity, flexural strength, stiffness, and load-deflection behavior of wood waste laminated beams, and also investigate how CFRP changes these aspects.

The aim of this study was to determine the mechanical performance of finger-jointed glulam beams, unreinforced and reinforced with CFRP, in terms of load-bearing capacity, flexural strength, stiffness and collapse pattern of finger-jointed glulam beams, in order to determine the optimum configuration of CFRP in this type of finger-joint orientation in glulam beams.

2. Material and methods

2.1. Merbau wood

The Merbau timber used is hardwood from the remaining cuttings of a factory in the Surabaya area. Physically, Merbau timber is not easily deformed when dried due to its small shrinkage value in tangential and radial directions. The Merbau wood from the production cuttings has a uniform moisture content between 10–12%. Tests according to ASTM D 143-2000 conducted

previously, the flexural strength of Merbau timber ranged from 135.46 MPa to 150.37 MPa with an average of 141.76 MPa (12% moisture content). The MOE value of Merbau timber ranged from 10635.25 MPa to 13676.46 MPa with an average of 12593.44 MPa, placing Merbau timber in strength class I according to Indonesian timber classification standards.

2. 2. FRP

The fiber-reinforced polymer (FRP) material utilized in the experimental program was a unidirectional carbon fiber sheet supplied by Fosroc Constructive Solutions (United Kingdom), as illustrated in **Fig. 1**. The CFRP sheet was selected due to its high tensile strength, elastic modulus, and compatibility with epoxy-based bonding systems commonly used in structural strengthening applications.

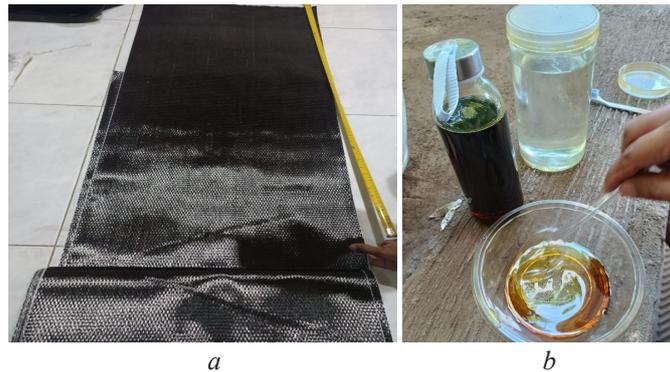


Fig. 1. Reinforcement materials used: *a* – carbon fiber reinforced polymers; *b* – epoxy resin

2. 3. Epoxy resin

The epoxy resin system used in this study consisted of two components: Nitowrap 30 epoxy primer and Nitowrap 410 epoxy adhesive, both supplied by Fosroc Constructive Solutions (United Kingdom). Nitowrap 30 epoxy primer is composed of a base and hardener mixed in a ratio of 2:1, with a recommended coverage of approximately 0.3 kg/m². Nitowrap 410 epoxy adhesive consists of a base and hardener mixed in a ratio of 2:1, with a coverage of approximately 0.8 kg/m², as specified by the manufacturer. This epoxy system plays a critical role in ensuring effective stress transfer between the CFRP reinforcement and the laminated timber, as well as protecting the fiber layer from abrasion and environmental effects. The mechanical properties of CFRP and epoxy resin are delineated in **Table 1**.

Table 1

Mechanical properties of CFRP and epoxy resin

Mechanical properties	Remarks	Value
1	2	3
CFRP	Fiber tensile strength (MPa)	> 4.900
	Fiber tensile modulus (GPa)	> 230
	Fiber density (g/cm ³)	1.8
	Fiber area weight (g/m ²) (±10%)	230
	Fiber sheet thickness (mm)	0.131
Epoxy resin (Nitowrap Primer)	Specific gravity	~1.1
	Viscosity (cps)	~2000
	Pot life at 20°C (minutes)	70
	Shear adhesion strength (MPa) (ASTM D1002-10)	> 7
	Compressive strength (MPa) (ASTM D695-15)	> 90
	Flexural strength (MPa) (ASTM D790-17)	> 70
	Tensile strength (MPa) (ASTM D638-14)	> 38

Continuation of Table 1

1	2	3
Epoxy resin (Nitowrap Encapsulation Resin)	Specific gravity	1.1
	Viscosity (cps)	2000
	Pot life at 20°C (minutes)	60
	Shear adhesion strength (MPa) (ASTM D1002-10)	> 7
	Compressive strength (MPa) (ASTM D695-15)	> 100
	Flexural strength (MPa) (ASTM D790-17)	> 60
	Tensile strength (MPa) (ASTM D638-14)	> 50

2. 4. Preparation of test specimens

Test specimens were prepared from Merbau wood leftover production cuts, which were processed into finger-jointed laminated timber beams. Natural defects were removed to ensure good quality base material. The wood was conditioned at 200°C and 65% relative humidity to achieve an equilibrium moisture content of approximately 10–12%. The length of the wood varied between 20–40 cm. The production process began by cutting the wood to make it flat on all sides, then finger-jointing the wood into 210 cm long sticks. Laminated boards were fabricated using a two-component B4 structural wood adhesive supplied by a local manufacturer (Indonesia), applied at a dosage of 250–300 g/m² with a resin content of approximately 15%. The adhesive was selected based on its availability and suitability for laminated timber production in local industrial practice. After forming the laminated board from the stick finger joint, it is then blocked into test specimens according to the dimensions of 6 cm × 9 cm and 210 cm long with an arrangement of 3 laminations, random finger joint spacing, face butt and face finger type finger joint orientation, and one of the CFRP configurations can be seen in Fig. 2, 3. The number of specimens was 20, consisting of 16 CFRP reinforced beams and 4 unreinforced beams.

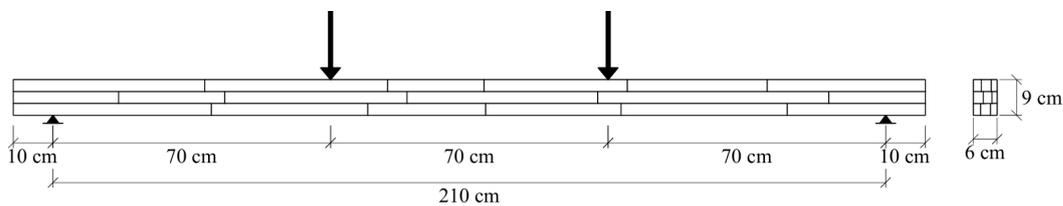


Fig. 2. Face finger laminated timber beams

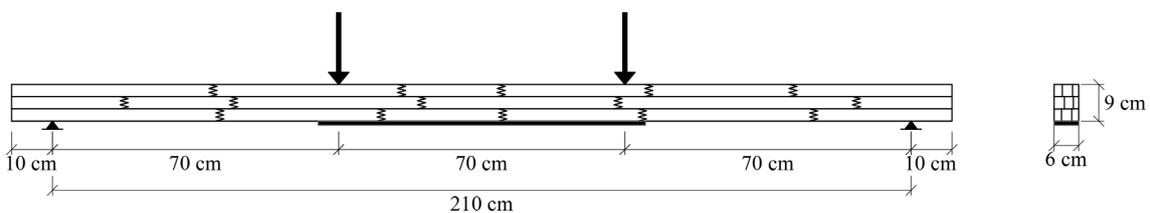


Fig. 3. Face butt laminated timber beams

2. 5. Application of CFRP to test specimens

An epoxy adhesive was used to bond the carbon fiber sheets to the glulam. First, an epoxy primer (Nitowrap 30 with a base mix and hardener in a 2:1 ratio with a coverage of 0.3 kg/m²) was applied to the underside of the laminated beam and allowed to dry for approximately 24 hours. The epoxy adhesive (Nitowrap 410 with a base mix and hardener in a 2:1 ratio with a coverage of 0.8 kg/m²) was then applied. CF fabric was cut to the required size and applied manually over the treated area with gloved hands. A layer of encapsulation resin adhesive was applied to the top carbon fabric. The application of the CFRP reinforcement is shown in Fig. 4. Conditioning of the assembly took one week at room temperature, after which flexural testing could be carried out.



Fig. 4. Application of reinforcement to test specimens:
a – resin application; *b* – CFRP application

The geometry of the finger joints in **Fig. 5** was determined following technical recommendations and manufacturer availability with characteristics as shown in **Table 2**.

The configuration and length of CFRP reinforcement used can be seen in **Table 3**.

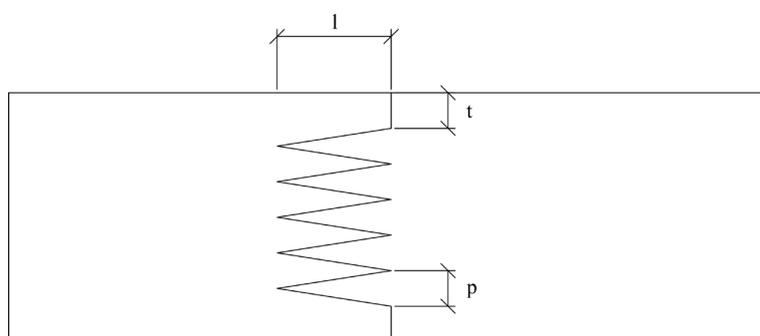


Fig. 5. Geometry of finger joints

Table 2

Characteristics of finger joints

Characteristics	Value
Length (<i>l</i>) (mm)	12
Range (<i>p</i>) (mm)	3
Tip (<i>t</i>) (mm)	5

Table 3

CFRP Configuration

Specimens	Percentage of CFRP from the span of the beam.
1	2
FB.1	unreinforcement
FB.2	unreinforcement
FBPD.1	30%
FBPD.2	30%
FBPL.1	50%
FBPL.2	50%
FBUS.1	U 30%
FBUS.2	U 30%
FBUL.1	U 50%
FBUL.2	U 50%
FF.1	unreinforcement

Continuation of Table 3

1	2
FF.2	unreinforcement
FFPD.1	30%
FFPD.2	30%
FFPL.1	50%
FFPL.2	50%
FFUS.1	U 30%
FFUS.2	U 30%
FFUL.1	U 50%
FFUL.2	U 50%

2. 6. Bending testing

The mechanical performance and flexural behavior of laminated beams were observed through static flexural tests using the four-point bending loading method as per ASTM D198-02, with a loading rate of 3 mm/min. The instrument setup is illustrated in **Fig. 6**. Static four-point bending tests were conducted in the Structures Laboratory of Universitas Brawijaya using a hydraulic jack testing system manufactured by Enerpac (United States). The applied load was measured using a load cell with a capacity of 100 kN supplied by a local manufacturer (Indonesia) and monitored through a load indicator model CI-200A manufactured by CAS Corporation (Indonesia). Beam deflections were recorded using linear variable displacement transducers (LVDTs) manufactured by AOGESON (Germany), model KTR-100MM (serial number: SY20190307). The displacement signals were acquired and stored using a ZK-DL3 data logger supplied by a local manufacturer (Indonesia). The load was distributed by a WF-15 steel load spreader fabricated locally (Indonesia) to ensure uniform load application at the two loading points during the four-point bending test. The beam support consisted of a $100 \times 55 \text{ mm}^2$ steel plate with a thickness of 6 mm and a cylindrical steel f 25 mm. To prevent local failure, $100 \times 55 \text{ mm}^2$ plywood pads with a thickness of 16 mm were placed above the steel plate and below the load point. The load was distributed by a 1 m long WF-15 steel load spreader to ensure even load distribution at the two loading points. Three LVDTs were strategically positioned at one-quarter span on the right, left, and center of the span. To prevent local buckling during flexural testing, stiffeners were applied at two points.



Fig. 6. Experimental setup:

1 – load cell; 2 – test piece; 3 – lateral stiffener; 4 – LVDT; 5 – data logger; 6 – hydraulic jack

The modulus of elasticity (MOE) of the laminated timber beams was calculated based on the linear elastic portion of the load-deflection response obtained from the four-point bending test, using the following equation

$$MOE = \frac{23PL^3}{108\Delta bh^3}, \quad (1)$$

where b – the cross-sectional width (mm), h – the cross-sectional height (mm), P – the magnitude of the centralized load (N), L – the load distance to the pedestal (mm), Δ – the mid-span elastic deflection (mm). The parameter Δ represents the vertical displacement measured at the mid-span of the beam using the LVDT installed at the center of the span. Only the elastic portion of the load-deflection curve was considered in the calculation of the MOE to ensure linear material behavior. The modulus of rupture is calculated using the following equations

$$MOR = \frac{PL}{bh^2}, \quad (2)$$

where b , h , P , and L are defined as previously described.

3. Result and discussion

3.1. Ultimate load capacity, maximum moment and mid-span deflection at maximum load

The ultimate load (P_{max}), maximum bending moment (M_{max}), and mid-span deflection (Δ) test results for each specimen are presented in **Table 4**. All load values are expressed in kilonewtons (kN), bending moments in kilonewton-meters (kN · m), and deflections in millimeters (mm).

Table 4

Ultimate load, maximum bending moment, and mid-span deflection

Specimens	P_{max} , KN	M_{max} , KN · m	Δ , mm
FB.1	7.28	2.55	11.06
FB.2	7.50	2.63	9.26
FBPD.1	7.70	2.70	12.25
FBPD.2	8.14	2.85	13.59
FBPL.1	9.15	3.20	22.31
FBPL.2	9.51	3.33	23.43
FBUS.1	10.67	3.73	24.37
FBUS.2	9.76	3.42	25.13
FBUL.1	9.38	3.28	25.12
FBUL.2	9.73	3.41	21.46
FF.1	5.20	1.82	7.04
FF.2	6.23	2.18	8.87
FFPD.1	8.09	2.83	10
FFPD.2	7.66	2.68	10.06
FFPL.1	8.39	2.94	22.61
FFPL.2	8.39	2.94	19.5
FFUS.1	8.13	2.85	18.64
FFUS.2	8.32	2.91	22.8
FFUL.1	11.21	3.92	26.63
FFUL.2	11.83	4.14	29.41

For unreinforced face-butt (FB) beams, the average mid-span deflection (Δ) was 10.16 mm. The incorporation of short CFRP reinforcement (FBPD) increased the deflection by up to 27.17%, while long CFRP reinforcement (FBPL) resulted in a more pronounced increase of up to 125.10%. The U-shaped CFRP reinforcement (FBUS) showed the highest increase in deflection, reaching 143.60%, indicating enhanced deformation capacity prior to failure.

For the mid-span deflection (Δ), the beam without reinforcement at the face butt joint exhibited an average of 10.16 mm. With the incorporation of short CFRP reinforcement (FBPD), the

deflection exhibited an increase of up to 27.17%, while the installation of long CFRP reinforcement (FBPL) resulted in the most substantial augmentation, reaching up to 125.10%. The U-type reinforcement contributed the most at 143.60% to the FBUS beams. It is evident that CFRP-reinforced beams exhibited substantial deformations prior to failure.

In beams with face finger (FF) connections, devoid of reinforcement, the mean P_{max} is 5.72 kN. With the incorporation of short CFRP reinforcement (FFPD), the augmentation in P_{max} attains 37.80%, and long CFRP reinforcement (FFPL) affords an escalation of up to 46.88%. In accordance with the increase in reinforcement area, the highest increase, reaching 101.64%, was observed in FFUL-reinforced beams.

The mid-span deflection (Δ) of the reinforced face finger joint laminated beams exhibited a substantial enhancement in all the reinforced beams, with the maximum increase recorded at 252.23% in FFUL beams in comparison to unreinforced beams. The findings of this study demonstrate that the incorporation of CFRP reinforcement, particularly the long and U-length configurations, leads to a consistent enhancement in the load capacity, maximum moment, and deflection of the finger joint laminated beams. This outcome signifies that these beams emerge as a robust and adaptable substitute for unreinforced beams.

3. 2. Modulus of elasticity and modulus of fracture of finger-joint laminated timber beams

The modulus of elasticity (MOE) and modulus of rupture (MOR) of four-point bending test results are displayed in **Table 5**, demonstrating the discrepancy in material performance based on the type of wood connection and configuration of CFRP (carbon fiber reinforced polymer) reinforcement. In general, beams with short face finger connection (FFPD) exhibited the highest MOE of 33.02 GPa, followed by FF beams without CFRP reinforcement (FF) with 31.09 GPa. This finding indicates that the incorporation of CFRP enhances the MOE, although this enhancement is marginal, with only 6.21% of the total observed. The face finger connection exhibits superior elasticity maintenance capabilities in comparison to the face butt (FB) connection, irrespective of the presence or absence of reinforcement. Face finger joints with or without CFRP reinforcement are recommended due to their superior elasticity performance.

Table 5

Modulus of elasticity and modulus of fracture of finger-jointed laminated timber beams

Specimens	MOE, GPa	Average of MOE, GPa	MOR, MPa	Average of MOR, (MPa)
FB.1	28.43	31.28	30.40	30.61
FB.2	34.13		30.82	
FBPD.1	26.14	25.59	31.30	32.23
FBPD.2	25.03		33.16	
FBPL.1	17.59	17.42	38.03	38.65
FBPL.2	17.24		39.26	
FBUS.1	18.81	17.59	44.41	42.23
FBUS.2	16.37		40.04	
FBUL.1	15.86	17.50	38.74	39.38
FBUL.2	19.14		40.03	
FF.1	31.90	31.09	21.71	23.83
FF.2	30.29		25.94	
FFPD.1	33.92	33.02	33.12	32.28
FFPD.2	32.11		31.44	
FFPL.1	15.93	17.06	34.90	34.70
FFPL.2	18.20		34.50	
FFUS.1	18.85	17.14	33.96	34.08
FFUS.2	15.43		34.19	
FFUL.1	18.07	17.66	46.62	47.91
FFUL.2	17.26		49.20	

In beams with face butt joints (FB), the highest MOE value was achieved by FB without reinforcement at 31.28 GPa compared to FB with short CFRP reinforcement at 25.59 GPa. However, when CFRP U reinforcement was applied (FBUS and FBUL), the MOE values decreased significantly, indicating the inefficiency of the reinforcement method for face butt joints.

The increase in modulus of rupture (MOR) due to the addition of CFRP reinforcement in face butt finger joint laminated timber beams ranged from 5.30% to 37.94% with the highest increase in FBUS beams. In the face finger joint beams, the effect of CFRP reinforcement was also significant, the increase ranged from 35.47% to 101.05% with the long U configuration reinforced beams supporting the highest increase compared to the unreinforced beams.

3.3. Load and deflection relationships and failure modes of unreinforced and CFRP-reinforced laminated timber beams

As demonstrated in Fig. 7, the $P-\Delta$ relationship graph reveals substantial disparities between beams devoid of reinforcement (FB) and those with diverse CFRP reinforcement configurations. It is evident that FB beams exhibit the lowest load capacity, yet they demonstrate a considerable degree of deflection, a consequence of deficiencies in the finger joints. With CFRP in short, the improvement of the load-carrying capacity enhanced due to its length being so short that resulted in an unequal distribution of stress on CFRP and caused early failure. Long CFRP brought about a sharp improvement in ultimate load-carrying capacity with less deflection; thus, its effectiveness in increasing the flexural strength was highlighted. The short U configuration of FBUS gave the best stress distribution around the joint, therefore giving the highest maximum load capacity, while the long U-configuration of FBUL showed a lower capacity with least deflection. From the findings of this research, it seems that the FBUS configuration is optimal for a balanced compromise of strength and stiffness in the beam.

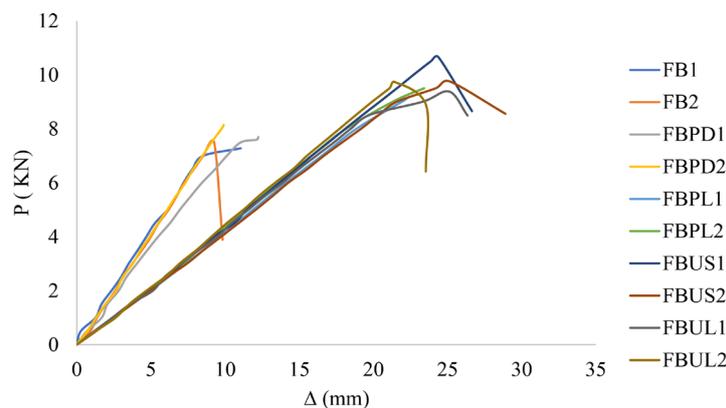


Fig. 7. $P-\Delta$ graph of face butt laminated timber beams

Fig. 8 presents the load-deflection relationship of face finger jointed laminated timber beams subjected to different reinforcement variations. It is shown that the mechanical responses to the bending loading are different. The lowest load-carrying capacity with high stiffness is presented by the unreinforced beam, FF. A significant increase in load-carrying capacity and stiffness was given by adding short CFRP reinforcement in FFPD. Long CFRP reinforcement (FFPL) gave the best performance with the highest load capacity and controlled deflection. Short U (FFUS) and long U (FFUL) CFRP shapes showed significant performance improvement but with lower stiffness than short CFRP reinforcement. CFRP length and shape had a major influence on performance, with long CFRP in a U configuration showing the highest efficiency in load distribution and increasing maximum capacity, despite low stiffness.

The failure mode identified as a combination of finger joint failure and buckling in timber material can be seen in Fig. 9. Finger joint failure is characterized by cracks or fractures at the joint area, indicating limitations in bond strength or joint geometry design in resisting buckling loads. Bending failure in glulam is characterized by significant bending deformation leading to fracture

in the area of maximum stress. Brittle crack failure due to delamination between the CFRP layer and the wood occurred at the bond line as a result of increased bending loads.

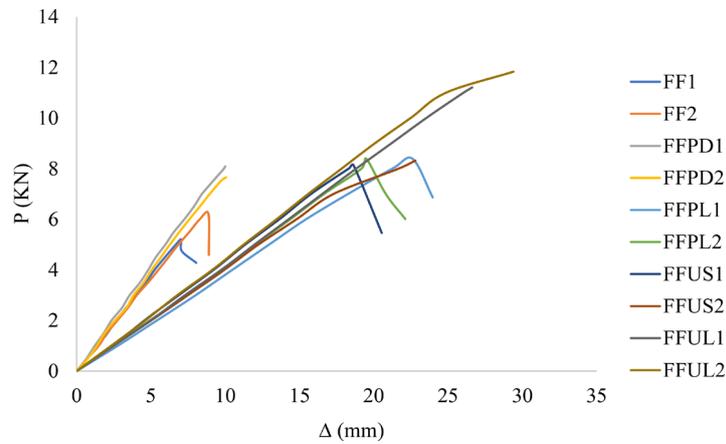


Fig. 8. $P-\Delta$ graph of face finger laminated timber beams



Fig. 9. Failure modes of finger-jointed laminated timber beams:
a – face butt orientation; *b* – face finger orientation

Adding CFRP to finger-jointed laminated timber beams significantly increased their load-bearing capacity, bending moment, and deflection. The face-butt joint with short CFRP U-reinforcement increased load capacity by 38%, while the face-finger joint with long CFRP U-reinforcement increased it by 102%. CFRP improves both strength and ductility, with the long U-shape configuration being most effective. However, further research is needed to optimize the structural design using different CFRP configurations.

In addition, a significant increase in modulus of rupture (MOR) was also observed, particularly in the long U-joint which showed an increase of up to 101.05%. The type of joint and the adhesion between wood and CFRP, however, tended to influence the values of MOE. In some of these configurations, like face-to-face joints with long CFRP, a decrease in MOE is realized, which might be due to non-optimal adhesion or uneven distribution of stresses [15, 16]. However, in all these strength increases, the expected increase in stiffness is not fully developed and mostly does not reach the expected analytical values [16, 17]. This might be because

of the complex interactions developed between CFRP and wood, which could not result in full increase in stiffness due to influences like those from bond-slip action and properties inherent to the materials in interaction [17–19]. This, therefore, indicates that while CFRP reinforcement significantly enhances strength in finger-jointed timber beams, the expected increased stiffness is not that clear, and again suggests further studies focused on the optimization of reinforcement techniques and their material interactions.

The failure modes observed included cracking at the finger joints and significant flexural deformation of the wood material. The unreinforced beams tended to exhibit brittle failure at the joints, whereas the CFRP-reinforced beams exhibited a more controlled flexural failure pattern. These results are consistent with previous studies that have highlighted the importance of CFRP length and orientation in improving the strength and ductility of laminated timber members [18, 19]. In laminated timber beams, finger joints are often a critical point as their mechanical properties tend to be weaker than whole wood fibers, especially in hardwoods. This analysis can also lead to an evaluation of the effectiveness of CFRP in strengthening the joints. However, it appears that damage still occurs in the critical zone, indicating that the reinforcement may not be optimal in resisting the bending stress in the joint area. Future research should consider placing the lamina in the tensile zone with an intact wood layer without joints to minimize the possibility of joint failure in order to achieve an optimal structural design.

4. Conclusions

The addition of CFRP material significantly increased the flexural capacity of the beams compared to the unreinforced beams. At the face butt (FB) joint, the highest increase in ultimate load capacity (P_{max}) was 38.22% with the short CFRP U configuration, while at the face finger (FF) joint, the highest increase of 101.64% was achieved with the long CFRP U configuration.

The CFRP reinforcement also increased the modulus of rupture (MOR) of the beams, especially at the face finger joints where the increase reached 101.05% compared to the unreinforced beams. However, the test results showed that the modulus of elasticity (MOE) did not always increase, especially for beams with CFRP-reinforced face butt joints.

CFRP reinforcement, particularly with a long and U-shaped configuration, significantly improves the structural performance of finger jointed glulam beams. This reinforcement renders the beams strong and flexible, making them suitable for various structural applications. Moreover, using high-density wood or hardwood can be an economical alternative in the fabrication of glulam beams.

Conflict of interest

The authors declare that they have no conflict of interest about this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors have used artificial intelligence technologies within acceptable limits to provide their own verified data.

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Authors' contributions

Lilis Nurhayati: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Corresponding author.

Sri Murni Dewi: Supervision, Validation, Writing – review & editing.

Wisnumurti: Data curation, Formal analysis, Writing – review & editing.

Devi Nuralinah: Visualization, Project administration, Writing – review & editing.

References

- [1] Aicher, S., Christian, Z., Stapf, G. (2015). Creep Testing of One-Component Polyurethane and Emulsion Polymer Iso-cyanate Adhesives for Structural Timber Bonding. *Forest Products Journal*, 65 (1-2), 60–71. <https://doi.org/10.13073/fpj-d-14-00040>
- [2] Hajihassani, R., Ghahri, S., Masoomeh Zamani, S., Nourbakhsh, A. (2022). Performance of Densified Wood Glulam as Building Bio-Material. *Journal of Renewable Materials*, 10 (2), 511–526. <https://doi.org/10.32604/jrm.2022.017781>
- [3] Kandler, G., Lukacevic, M., Zechmeister, C., Wolff, S., Füssl, J. (2018). Stochastic engineering framework for timber structural elements and its application to glued laminated timber beams. *Construction and Building Materials*, 190, 573–592. <https://doi.org/10.1016/j.conbuildmat.2018.09.129>
- [4] Morales-Beltran, M., Engür, P., Şişman, Ö. A., Aykar, G. N. (2023). Redesigning for Disassembly and Carbon Footprint Reduction: Shifting from Reinforced Concrete to Hybrid Timber – Steel Multi-Story Building. *Sustainability*, 15 (9), 7273. <https://doi.org/10.3390/su15097273>
- [5] Linkevičius, E., Žemaitis, P., Aleinikovas, M. (2023). Sustainability Impacts of Wood- and Concrete-Based Frame Buildings. *Sustainability*, 15 (2), 1560. <https://doi.org/10.3390/su15021560>
- [6] Chauf, K. A., Dewi, S. M. (2016). Structural Efficiency and Flexure Strength of Mix-Glulam Timber Beams are Composed of Sengon and Coconut Wood as Green Material Constructions. In: *Proceedings of the 2th International Multidisciplinary Conference 2016*.
- [7] Morin-Bernard, A., Blanchet, P., Dagenais, C., Achim, A. (2020). Use of northern hardwoods in glued-laminated timber: a study of bondline shear strength and resistance to moisture. *European Journal of Wood and Wood Products*, 78 (5), 891–903. <https://doi.org/10.1007/s00107-020-01572-3>
- [8] Le, S. T., Nguyen, T. N., Bui, D.-K., Ha, Q. P., Ngo, T. D. (2023). Modelling and Multi-Objective Optimisation of Finger Joints: Improving Flexural Performance and Minimising Wood Waste. *Buildings*, 13 (5), 1186. <https://doi.org/10.3390/buildings13051186>
- [9] Abed, J., Rayburg, S., Rodwell, J., Neave, M. (2022). A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability*, 14 (9), 5570. <https://doi.org/10.3390/su14095570>
- [10] Morris, F., Allen, S., Hawkins, W. (2021). On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. *Building and Environment*, 206, 108285. <https://doi.org/10.1016/j.buildenv.2021.108285>
- [11] Vijayan, D. S., Sivasuriyan, A., Devarajan, P., Stefańska, A., Wodzyński, Ł., Koda, E. (2023). Carbon Fibre-Reinforced Polymer (CFRP) Composites in Civil Engineering Application – A Comprehensive Review. *Buildings*, 13 (6), 1509. <https://doi.org/10.3390/buildings13061509>
- [12] Pawlak, A. M., Górny, T., Dopierała, Ł., Paczos, P. (2022). The Use of CFRP for Structural Reinforcement – Literature Review. *Metals*, 12 (9), 1470. <https://doi.org/10.3390/met12091470>
- [13] Wei, A., Al-Ameri, R., Koay, Y. C., Tan, M. Y. J. (2021). Triple-functional carbon fibre reinforced polymer for strengthening and protecting reinforced concrete structures. *Composites Communications*, 24, 100648. <https://doi.org/10.1016/j.coco.2021.100648>
- [14] Amaireh, L., Al-Rousan, R. Z., Ababneh, A. N., Alhassan, M. (2020). Integration of CFRP strips as an internal shear reinforcement in reinforced concrete beams. *Structures*, 23, 13–19. <https://doi.org/10.1016/j.istruc.2019.10.009>
- [15] Śliwa-Wieczorek, K., Ostrowski, K. A., Jaskowska-Lemańska, J., Karolak, A. (2021). The Influence of CFRP Sheets on the Load-Bearing Capacity of the Glued Laminated Timber Beams under Bending Test. *Materials*, 14 (14), 4019. <https://doi.org/10.3390/ma14144019>
- [16] Saad, K., Lengyel, A. (2022). Experimental, Analytical, and Numerical Assessments for the Controversial Elastic Stiffness Enhancement of CFRP-Strengthened Timber Beams. *Polymers*, 14 (19), 4222. <https://doi.org/10.3390/polym14194222>
- [17] Ianasi, A. C. (2015). On the role of CFRP reinforcement for wood beams stiffness. *IOP Conference Series: Materials Science and Engineering*, 95, 012015. <https://doi.org/10.1088/1757-899x/95/1/012015>
- [18] Khelifa, M., Celzard, A., Oudjene, M., Ruelle, J. (2016). Experimental and numerical analysis of CFRP-strengthened finger-jointed timber beams. *International Journal of Adhesion and Adhesives*, 68, 283–297. <https://doi.org/10.1016/j.ijadhadh.2016.04.007>

- [19] Khelifa, M., Lahouar, M. A., Celzard, A. (2015). Flexural strengthening of finger-jointed Spruce timber beams with CFRP. *Journal of Adhesion Science and Technology*, 29 (19), 2104–2116. <https://doi.org/10.1080/01694243.2015.1057395>

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