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IDENTIFICATION OF FLEXURAL PERFORMANCE OF FINGER-JOINTED LAMINATED TIMBER BEAMS REINFORCED WITH CARBON FIBER REINFORCED POLYMER

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This paper presents the study of the mechanical performance of finger jointed laminated timber beams, unreinforced and reinforced with Carbon Fiber Reinforced Polymer, made from waste Merbau wood as an alternative to conventional structural materials. The present study focuses on the ultimate load capacity, modulus of elasticity, modulus of rupture, and load-deflection behavior of laminated beams with face butt and face finger joint orientations against solid beams. Tests were conducted by the four-point bending method according to ASTM D198-02. The results indicated that solid beams had the highest load bearing capacity compared to finger-jointed laminated beams. CFRP reinforcement increased the load capacity by 7.15% for face butt orientation and 38.58% for face finger orientation. CFRP reinforced face finger joints showed a significant increase in modulus of elasticity (MOE) and modulus of rupture (MOR) compared to face butt joints, indicating the effectiveness of CFRP reinforcement in certain orientations. Load-deflection analysis shows that CFRP-reinforced beams exhibit better ductility than unreinforced beams, with peak deflection increasing by 27.2% for face-butt and 26.0% for face-finger. Results confirm that CFRP reinforcement can enhance finger-jointed laminated beams; however, despite these improvements, the reinforced laminated beams still do not reach the strength level of solid beams, with the maximum load capacity and bending moment being approximately 31% of the solid beam values. This study offers insights into the development of robust, efficient, and sustainable wood-based building materials. Furthermore, the findings indicate that finger-jointed laminated wood, produced from waste cuttings from the wood processing industry, possesses the potential to be developed into structural building materials, thereby enhancing the value of wood waste

Keywords: laminated timber, finger joint, carbon fiber reinforced polymer (CFRP), modulus of elasticity (MOE), modulus of rupture (MOR)

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1. Introduction

Glulam, or glued laminated timber, has increasingly gained recognition as a structural material in the modern construction industry. It is composed of multiple layers of wood adhered with structural adhesives, offering superior strength and stiffness compared to solid sawn timber [1]. Recent studies demonstrate that glulam derived from species such as Portuguese eucalyptus wood shows higher mechanical properties than conventional softwood glulam, providing a cost-effective alternative amidst rising prices of solid timber [2]. The integration of fiber-reinforced polymers (FRP), particularly carbon fiber reinforced polymer (CFRP), has been proven to further enhance flexural and shear performance of glulam beams, making this material an attractive option for sustainable and high-performance structures [3].

Nevertheless, a fundamental challenge of glulam lies in the presence of joints. Finger joints, while improving material utilization and enabling long-span members, are often weaker than solid wood sections due to stress concentration at the joint regions [4]. Mechanical properties of glued laminated timber are influenced by adhesive type, joint geometry, and lamella layup. Although rigid adhesives and optimized layups improve stiffness [4], weaknesses in joint performance remain a limiting factor. To address these shortcomings, research has explored the use of synthetic fibers and composites, such as CFRP and glass fiber reinforced polymer (GFRP), to strengthen glulam beams and improve reliability in structural applications [5].

At the same time, the utilization of wood waste in engineered timber products has gained significant attention in the context of sustainability and resource efficiency. Studies show that recycling wood residues into construction materials not only reduces waste but also supports circular economy practices and lowers environmental impacts [6]. The use of production-cut wood waste in laminated beams contributes to achieving Sustainable Development Goals by creating added value from materials otherwise considered waste [6–8]. In this regard, finger-jointed laminated beams manufactured from wood waste, when reinforced with CFRP, may provide a viable alternative to conventional timber, combining mechanical performance improvements with environmental benefits.

Furthermore, CFRP has been widely recognized for its outstanding tensile strength, high elastic modulus, and excellent resistance to environmental degradation. Research confirms that externally bonded or implanted CFRP can significantly enhance the structural performance of timber beams. For instance, [9] demonstrated that prestressed glulam beams reinforced with CFRP bars achieved increases in flexural capacity of up to 64.8% for reinforced beams, 93.3% for prestressed beams, and 131% for prestressed & reinforced beams, while the maximum improvement of the bending stiffness reached 42.0% compared to unreinforced beams. The effectiveness of CFRP has been reported across different wood species, orientations, and reinforcement configurations, indicating its potential as one of the most advanced solutions to overcome weaknesses in laminated timber beams [10–12]. However, detailed investigations remain necessary to evaluate how reinforcement interacts with different finger joint orientations, particularly in beams fabricated from hardwood waste.

In light of these considerations, the scientific topic of strengthening finger-jointed laminated timber beams with CFRP remains highly relevant. It addresses two major challenges in the construction industry: the need for stronger and more reliable engineered timber members, and the imperative to utilize wood waste for sustainable and eco-friendly building materials. Therefore, research on the flexural performance of finger-jointed laminated timber beams reinforced with CFRP is timely and essential for advancing both structural engineering practice and sustainable construction development.

2. Literature review and problem statement

Wood is a superior structural material that has been extensively utilized on account of its exceptional mechanical properties and abundance in nature. The wood processing industry produces significant quantities of waste in the form of sawdust and side cuts, which have not been optimally utilized. Through the application of sophisticated engineering and processing technologies, this wood waste can now be transformed into high-performance structural materials that exhibit strength levels that even exceed those of metals and commercial laminated wood products. This innovation creates prospects for the development of eco-friendly composites that not only minimize industrial waste but also promote the tenets of resource efficiency and sustainability in the construction sector [13]. Several studies suggest that transforming this waste into finger-jointed laminated timber beams represents an effective strategy to reduce production losses while creating value-added products [14, 15]. This approach not only improves raw material efficiency but also supports sustainable construction practices aligned with circular economy principles [6, 8]. In paper [6] conducted a bibliometric review of wood waste utilization for bioenergy production, which highlighted the potential of construction wood waste but did not address structural applications of processed waste wood. In paper [8] examined wood waste ash utilization in construction technology, providing valuable insights into waste valorization, but their emphasis on ash-based composites differs significantly from the mechanical assembly approach used in finger-jointed laminated beams.

Finger joints are among the most widely adopted joining methods in engineered timber, enabling the fabrication of long-span members from shorter offcuts. Research has shown that optimizing finger length and joint profile significantly improves tensile and flexural performance [14, 16]. For example, laminated beams fabricated with vertically oriented finger joints demonstrate higher flexural strength than those with horizontal orientation [17]. Adhesive type and wood ring orientation also play critical roles in joint performance, influencing adhesion quality and stress distribution [15]. Despite these advances, finger-jointed beams remain weaker than solid timber because stress concentrations around the joints create localized weaknesses [4].

In order to overcome these limitations, researchers are increasingly focusing on efforts to reinforce laminated timber beams with advanced composite materials. Carbon fiber reinforced polymer (CFRP) has garnered considerable attention due to its noteworthy tensile strength, stiffness, and resistance to environmental degradation. Research has demonstrated that the implementation of CFRP sheets within the tension zone of wood beams can result in an enhancement of flexural stiffness by up to 64% and flexural strength by up to 50% [9, 18]. Other research has demonstrated that CFRP rods and strips can enhance ductility and shift the failure pattern toward a more desirable form [19]. Additionally, an experimental program on laminated oak beams reinforced with CFRP implants demonstrated an increase in flexibility ranging from 4% to 94%, contingent on the reinforcement configuration [19]. These findings substantiate the efficacy of CFRP in enhancing structural capacity while preserving its lightweight properties [19].

However, there are still unanswered questions regarding the reinforcement of finger-jointed laminated timber beams assembled in blocks. The extant research has predominantly centered on solid laminated beams or beams devoid of finger joints [5, 18, 20]. In paper [5], experimental studied of glued-laminated timber beams with Vectran-FRP reinforcement were conducted, providing valuable insights into fiber reinforcement effects, but their exclusive use of continuous laminated beams without joints limits applicability to finger-jointed waste wood assemblies. Paper [18] demonstrated significant improvements with GFRP and CFRP sheets on laminated wood beams, though their focus on horizontally glued specimens does not address the complex stress distributions found in finger-jointed configurations. Paper [20] examined ductility and stiffness of laminated veneer lumber beams strengthened with fibrous composites, showing promising results, but LVL manufacturing processes and mechanical properties differ substantially from finger-jointed laminated timber produced from waste wood.

A paucity of studies has examined the interaction of CFRP with various finger joint orientations, particularly in relation to modulus of elasticity (MOE), modulus of rupture (MOR), and load-deflection behavior [11, 21, 22]. Paper [11] investigated the use of carbon and basalt fibers to improve physical and mechanical properties of plywood, demonstrating fiber reinforcement potential, although plywood structure and manufacturing methods differ significantly from finger-jointed laminated timber assemblies. [21] provided experimental and numerical analysis of compression and bending strength of old wood reinforced with CFRP strips, offering insights into CFRP applications on aged timber, but their focus on solid wood elements does not address the complex joint interactions present in finger-jointed assemblies. Paper [22] examined physical and mechanical properties of laminated wood made from heat-treated Scotch pine reinforced with carbon fiber, providing valuable data on reinforced laminated timber, though their heat treatment and softwood focus limits direct applicability to untreated hardwood waste applications. This discrepancy can be attributed, at least in part, to the experimental complexity involved in testing beams with varying joint configurations. Additionally, the use of wood waste from wood processing plants introduces mechanical heterogeneity, which makes reliable assessment more challenging [14].

Overcoming these challenges necessitates a meticulous experimental study design that integrates the utilization of sustainable materials and state-of-the-art reinforcement methodologies. One potential approach involves the evaluation of beams derived from factory wood waste with finger joints in various orientations. These beams would then be reinforced using CFRP sheets and adhesives that are known to possess strong cohesive properties [20, 23]. A comparison of their flexural performance with that of solid wood beams is necessary to elucidate the effectiveness of CFRP reinforcement in reducing joint weaknesses.

In summary, previous studies have established the benefits of both finger joints and CFRP reinforcement separately. However, the combined effect of block-assembled finger joints and CFRP reinforcement on beams produced from wood waste, particularly wood processing mill offcuts that have been selected and cleaned of defects, has not been widely explored. This critical gap in the extant literature is the subject of the present study. The present moment is opportune for addressing this issue, as it not only serves to broaden our understanding of engineered wood design, but also to promote the sustainable utilization of industrial wood waste and to furnish pragmatic solutions for the development of high-performance structural materials.

3. The aim and objectives of the study

The aim of this study is to assess the feasibility of finger-jointed laminated merbau timber from unreinforced and CFRP-reinforced production cuts as structural material by evaluating its mechanical performance with a solid timber beam as a comparator. In order to achieve this objective, the following.

To achieve this aim, the following objectives were accomplished:

– analyze the ultimate load capacity, ultimate moment and mid-span deflection of finger-jointed timber beams without and with CFRP reinforcement compared to solid beams;

– analyze the modulus of elasticity and modulus of fracture of finger-joint laminated timber beams without and with CFRP reinforcement compared to solid beams;

– analyze the load and deflection behavior and failure patterns of finger-joint laminated timber beams without and with CFRP reinforcement.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of this study is the flexural performance of Merbau finger-jointed laminated wood beams made from production offcuts. The focus was being on beams that have been reinforced with external CFRP and those that have not been reinforced with CFRP. The beam was being compared with solid Merbau wood beams to establish a reference point. The experimental tests were conducted on a 210-centimetre span using three laminated beams.

The primary hypothesis advanced in this study is that the incorporation of CFRP reinforcement will enhance the flexural capacity, stiffness (MOE), and ductility of finger joint beams. Furthermore, this study investigates the distinction between face butt and face-finger joint orientations, operating under the supposition that the face finger orientation will yield superior performance enhancement in comparison to face butt. Although performance enhancement is anticipated, it is projected that CFRP reinforced laminated beams will not attain the same level of strength as solid wood beams.

The underlying assumptions of this study are that wood material is considered linear-elastic up to the proportional limit, with adhesive bonds free from defects. The moisture content of the wood is set to range between 10–12%, and is uniform throughout the sample. The testing process is conducted employing the quasi-static loading method, utilizing a four-point bending scheme with displacement control to ensure the attainment of precise results. In this study, simplifications were made by ignoring the effects of material defects, internal wood variability, and environmental influences such as humidity and temperature that could affect long-term results. Consequently, the results obtained are expected to represent ideal conditions for wood materials and CFRP reinforcement in structural applications.

4. 2. Merbau wood

The Merbau timber utilized in this study is a hardwood originating from Papua, Indonesia. It is a residual material from a furniture factory in Surabaya, Indonesia. Merbau wood is characterized by its resistance to deformation when dried, attributable to its low shrinkage value in tangential and radial directions. The timber's moisture content is uniform, ranging from 10–12%. The Merbau wood had been put through a series of tests in conformity with the specifications described in ASTM D 143-2000 before the current research to assure its quality and defect-free condition. Accordingly, three clear, small-scale test specimens, 25 × 25 mm in size with a span of 360 mm, were tested for their flexural strength by using the third point bending method on an Instron machine with a capacity of 5 tons at the Brawijaya University Structures Laboratory. The mechanical properties of Merbau wood are outlined in Table 1.

Table 1

MOE and MOR of defect-free small-scale Merbau timber

Number	Width (mm)	Height (mm)	Deflection (mm)	Maximum load (KN)	MOE (GPa)	MOR (MPa)
1	25	25	9.5	4.44	13.95	153.34
2	25	25	8.69	3.99	13.73	138.13
3	25	25	11.33	4.12	10.84	142.21
Mean	25	25	9.84	4.18	12.84	144.56

The results in Table 1 show that the average modulus of elasticity (MOE) of Merbau wood specimens reached 12.84 GPa, while the average modulus of rupture (MOR) was 144.56 MPa. These values confirm that Merbau wood possesses high stiffness and strength compared to many tropical hardwoods, justifying its use as the base material for laminated beams.

4. 3. Carbon fiber reinforced polymer and epoxy resin

Carbon fiber was the FRP material used in the testing program represented by Fig. 1. The epoxy resin and the carbon fiber sheets used in this study were provided by FOSROC Constructive (Table 2). The two-part epoxy resin used in the present research includes Nitowrap 30 epoxy primer and Nitowrap 410 epoxy adhesive, which was provided by FOSROC. Nitowrap 30 epoxy primer has 2:1 base/hardener ratio. According to the supplier recommendation, 0.3 kg/m^2 coverage rate is allowed for Nitowrap 30 epoxy primer. Nitowrap 410 epoxy adhesive: Mixed base and hardener in the ratio 2:1. Coverage is 0.8 kg/m^2. The carbon fiber was bonded to laminated wood by the epoxy resin, which was to play the pivotal role of transferring strength across both materials, and also served to protect the fibers against abrasion and environmental degradation. The adhesive bond strength was identified from the comparative studies between FRP-wood bond interface and wood-wood bond specimens made using epoxy adhesive.

a *b*

Fig. 1. Reinforcement materials: *a* – carbon fiber reinforced polymer sheets; *b* – epoxy and encapsulation resin

Table 2

Mechanical properties of the CFRP and epoxy resin

Mechanical properties	Remarks	Value
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
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

As shown in Table 2, the CFRP exhibited very high tensile strength (> 4,900 MPa) and tensile modulus (> 230 GPa), confirming its suitability for structural reinforcement. Meanwhile, the epoxy adhesives demonstrated shear adhesion strength above 7 MPa and compressive strength exceeding 90 MPa, ensuring reliable bonding between the CFRP sheets and laminated timber.

4. 4. Application of carbon fiber reinforced polymer and epoxy resin on test specimens

The application of carbon fiber reinforced polymer (CFRP) reinforcement on laminated timber beams is shown in Fig. 2. The process begins by applying an epoxy primer to the underside of the laminated beams. The primer used is Nitowrap 30, mixed in a 2:1 ratio of base mix and hardener, with a coverage of 0.3 kg/m^2. After the primer is applied, it is allowed to dry for approximately 24 hours. Next, an epoxy adhesive, Nitowrap 410, is applied in the same 2:1 ratio, with a coverage of 0.8 kg/m^2. Following this, carbon fiber sheets, cut to dimensions of 800 mm long and 60 mm wide, are placed on the treated surface and pressed manually with gloved hands. To further secure the bond, the carbon fiber fabric is covered with an encapsulating resin adhesive. The entire assembly is then conditioned at room temperature for seven days to allow proper curing before testing. This reinforcement is expected to enhance the flexural strength and stiffness of the laminated beams by transferring tensile forces from the timber to the CFRP during loading.

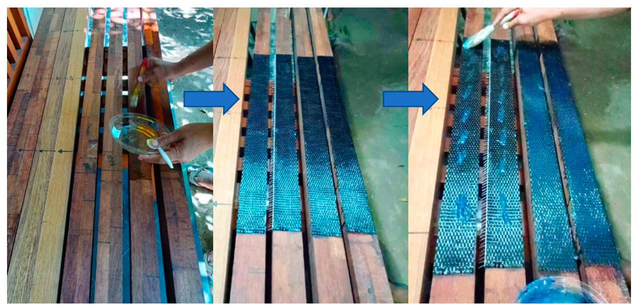

Fig. 2. Application of carbon fiber reinforced polymer (CFRP) reinforcement on laminated timber beams

As illustrated in Fig. 2, the application of CFRP on laminated timber beams aims to enhance the flexural strength and stiffness of the beams through a load transfer mechanism from the timber to the CFRP during loading. After the drying and curing process, this reinforcement is expected to increase load capacity, reduce deflection, and delay crack initiation at finger joints. This strengthening technique offers an effective solution to improve the overall structural performance of laminated timber beams.

4. 5. Adhesive

The adhesive used to laminate the wood layers for beam fabrication for this study was Polychemie PVA Wood Glue (PVAc B4), which can be applied to hardwood.

4. 6. Beam manufacturing and testing program

The material has been transformed into laminated timber beams through the process of block finger jointing. The removal of natural defects ensured that the base material was of a satisfactory quality. The material utilized for the test specimens was Merbau wood, which was obtained from production cuts. It was then conditioned at 20°C and 65% relative humidity in a conditioning room and later kiln-dried to an equilibrium moisture content of about 10 to 12%. Lengths of the timber varied between 20 to 40 centimeters.

The first process undertaken in fabricating the wood was molding to ensure the wood was flat on all sides. This was followed by the assembly of the wood using a finger joint connection, with the length of the wood being adjusted to 210 cm for the testing stage. Subsequently, the wood was then subjected to the process of making laminated boards using an adhesive composed of two components, with a ratio of 1:1.5 by weight, applied in a quantity of 250–300 g/m^2. Subsequent to the formation of the laminated board from the stick finger joint, it is then blocked into test objects according to the dimensions of 6 × 9 cm and 210 cm long with an arrangement of 3 lamina. The test specimens consisted of five configurations: solid beams, face finger joints without reinforcement, face finger joints with reinforcement, face butt joints without reinforcement, and face butt joints with reinforcement. These are shown in Fig. 3–7. The total number of test objects is 10, comprising 4 beams without CFRP reinforcement, 4 beams with CFRP reinforcement, and 2 solid beams.

The geometry of the finger joints, illustrated in Fig. 8, was determined according to technical recommendations and manufacturer availability. The random placement of the finger joints along the beam span is presented in Fig. 9, while their key characteristics are summarized in Table 3.

Table 3

Characteristics of finger joints

Configuration	Values
Length (l), mm	12
Range (p), mm	3
Tip (t), mm	5

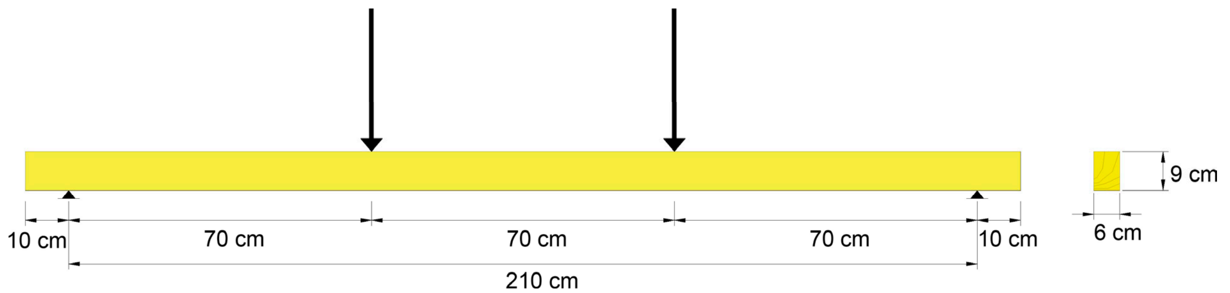

Fig. 3. Solid beam specimen

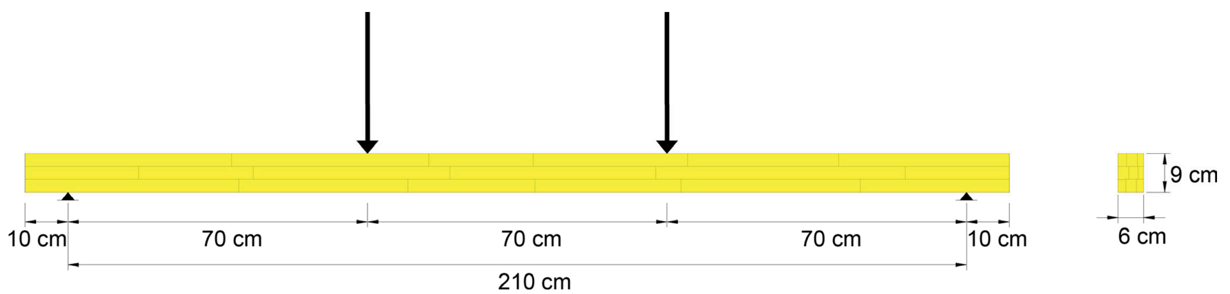

Fig. 4. Face finger joint specimen without reinforcement

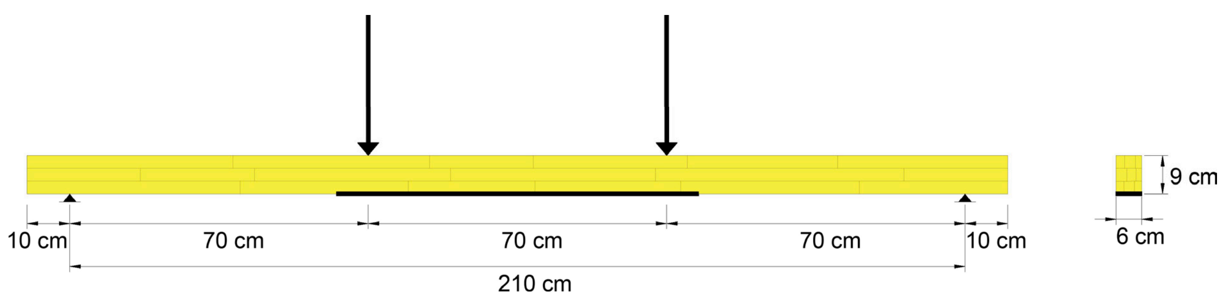

Fig. 5. Face finger joint specimen with reinforcement

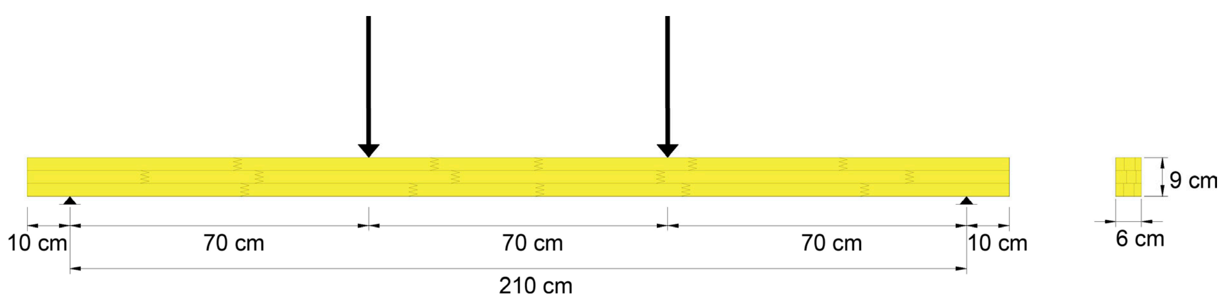

Fig. 6. Face butt joint specimen without reinforcement

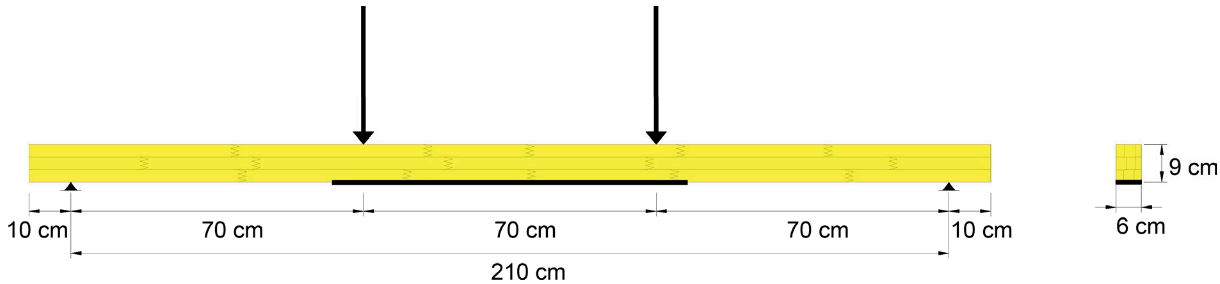

Fig. 7. Face butt joint specimen with reinforcement

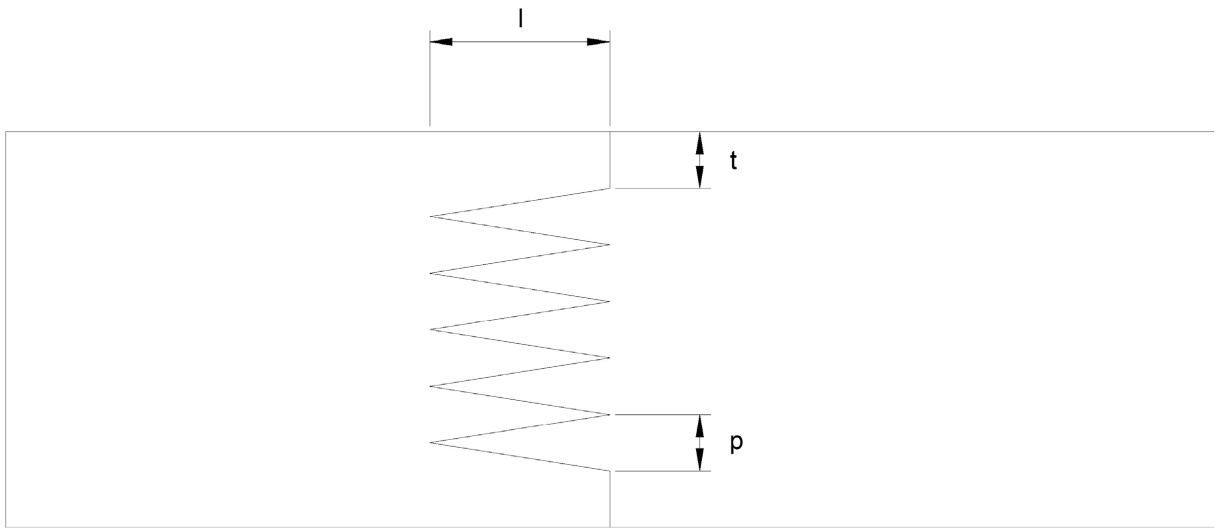

Fig. 8. Geometry of finger joints

Fig. 9. Random placement of finger joints

Static flexural tests by four-point bending loading method were used to observe the mechanical performance and the flexural behavior of laminated beams, and tests were done according to the method described under ASTM. D198-02 (ASTM, 2000). A loading rate was 3 mm/min. The instrument setup is shown in Fig. 10. The support of the beam was made with a 100×55 mm^2, 6 mm thick steel plate and a ϕ 25 mm, cylindrical steel. To avoid the local failure 100×55 mm^2, 16 mm thick plywood pads were added above the steel plate and beneath the load point. The load was distributed by a load spreader made of 1 m long WF-15 steel. The selection of the WF steel load spreader was made on the basis that it would ensure sufficient rigidity to guarantee even load distribution at the two loading points. Three LVDTs were strategically positioned at one quarter of the span on the right and left, and at the center of the span. To prevent local buckling during flexural testing, stiffeners were applied at two points.

The modulus of elasticity and modulus of rupture are calculated using the following equations

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

where b – cross-sectional width (mm), h – cross-sectional height (mm), P – centralized load magnitude (N), L – load distance to the pedestal (mm), Δ – deformation (mm)

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

where b – cross-sectional width (mm), h – cross-sectional height (mm), P – centralized load magnitude (N), L – load distance to the pedestal (mm).

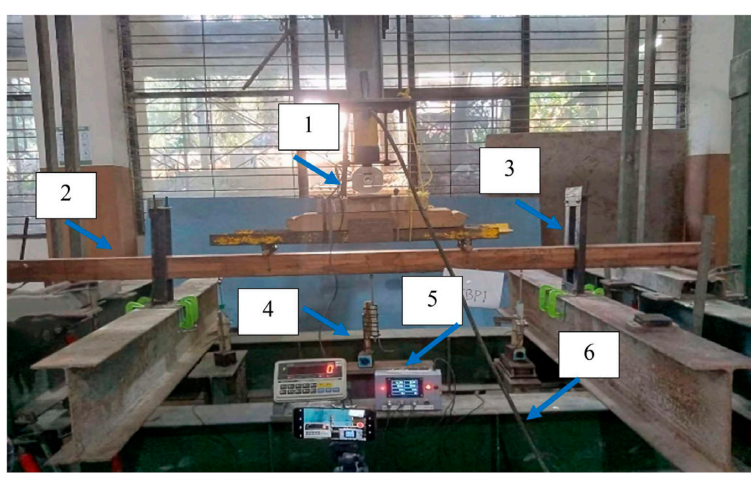

Fig. 10. Experimental setup: 1 — load cell; 2 — test piece; 3 — lateral stiffener; 4 — LVDT; 5 — data logger; 6 — hydraulic jack

5. The research results on flexural reinforcement of finger-jointed laminated timber beams

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

The results of the ultimate load capacity, maximum moment, and mid-span deflection for each specimen type are presented in Table 4.

As demonstrated in Table 4, solid beams (BS) demonstrate the highest load capacity in comparison to other beam types, with a maximum moment (M_{max}) ranging from 8.37 to 9.24 KN·m and a deflection at maximum load (Δ) ranging from 34.73 to 34.87 mm. This finding indicates the highest structural durability of solid beams. In comparison, the unreinforced Face Butt finger joint laminated beam (FB) exhibited a load capacity of 7.28–7.5 KN, a maximum moment (M_{max}) of 2.55–2.63 KN·m, and a deflection at maximum load (Δ) of 9.26–11.06 mm. It is clear that the FB exhibits much lower load carrying capacity as compared to the solid beam. The ultimate load-carrying capacity increased to 7.7–8.14 KN, M_{max} to 2.70–2.85 KN·m, and Δ to 12.25–13.59 mm at the introduction of CFRP strengthening, but still much lower than the values for solid beams. The load capacity of the face finger joint laminated beams without reinforcement was in the range of 5.2–6.23 KN, while M_{max} was in the range of 1.82–2.18 KN·m and Δ was in the range of 7.04–8.87 mm, which is less than that of FB. With the addition of CFRP reinforcement, the load capacity increased significantly to attain 7.66–8.09 KN, while M_{max} increased to 2.68–2.83 KN·m and Δ decreased to 10–10.06 mm for FFP. Although this improved performance was superior to that of FB, it still remained inferior compared to solid beams. CFRP reinforcement resulted in an average increase in load-carrying capacity of 7.15% for FB and 38.58% for FF.

As per comparative studies, solid timber beams are largely found to have a superior performance than finger-jointed laminated beams in terms of load carrying, moment capabilities, and deflection. Finger-jointed lamella, for instance, have demonstrated weaker ability in tensile tests compared to their solid timber counterparts, indicating that solid timber evidently demonstrates superior mechanical performance when starkly compared [16]. On one hand, by analytical and experimental means it was proved that while the finger-jointed and laminated beams could achieve satisfactory performance their flexural properties as well as strength were often slightly lesser compared to any solid timber beams, especially when finger joints are present in critical stress zones. The presence of finger joints introduces localized weaknesses, which can reduce the overall strength of the beam, even though advanced adhesives and optimized joint designs can mitigate some of these effects [16, 18]. Hence, one says finger-jointed laminated beams have advantages associated with material utilization as well their greater span lengths, but solid timber beams exceed finger-jointed laminated beams in absolute structural capacities and constructional deflection characteristics [5, 19].

Although highly efficient in terms of material use and capable of achieving high loads, finger jointed beams require reinforcement to attain the performance levels of solid timber beams. Research into the use of CFRP has shown that these can increase the load-bearing capacity of finger-jointed beams, but they still fall short of the natural strength and deflection characteristics of solid timber beams [14, 24, 25]. The application of laminated veneer lumber (LVL) beams, though preferred in many cases due to their ability to allow larger openings and greater resistance to load in specific applications, still does not surpass the maximum moment and deflection resistance of solid timber beams [5, 18]. The failure modes in solid beams and finger-joint laminated beams can be seen in Fig. 11.

Table 4

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

Spec. No.	P_{max} (KN)	M_{max} (KN·m)	Δ (mm)	Failure mode
BS.1	26.39	9.24	34.87	Tensile failure at the bottom
BS.2	23.92	8.37	34.73	Tensile failure at the bottom
FB.1	7.28	2.55	11.06	Finger joint damage with delamination
FB.2	7.5	2.63	9.26	Finger joint damage at the bottom
FBP.1	7.7	2.70	12.25	Delamination/crack propagation at finger-joints
FBP.2	8.14	2.85	13.59	Delamination/crack propagation at finger-joints
FF.1	5.2	1.82	7.04	Finger joint damage at the bottom
FF.2	6.23	2.18	8.87	Finger joint damage at the bottom
FFP.1	8.09	2.83	10	Finger joint damage with delamination at the bottom
FFP.2	7.66	2.68	10.06	Finger joint damage with delamination at the bottom

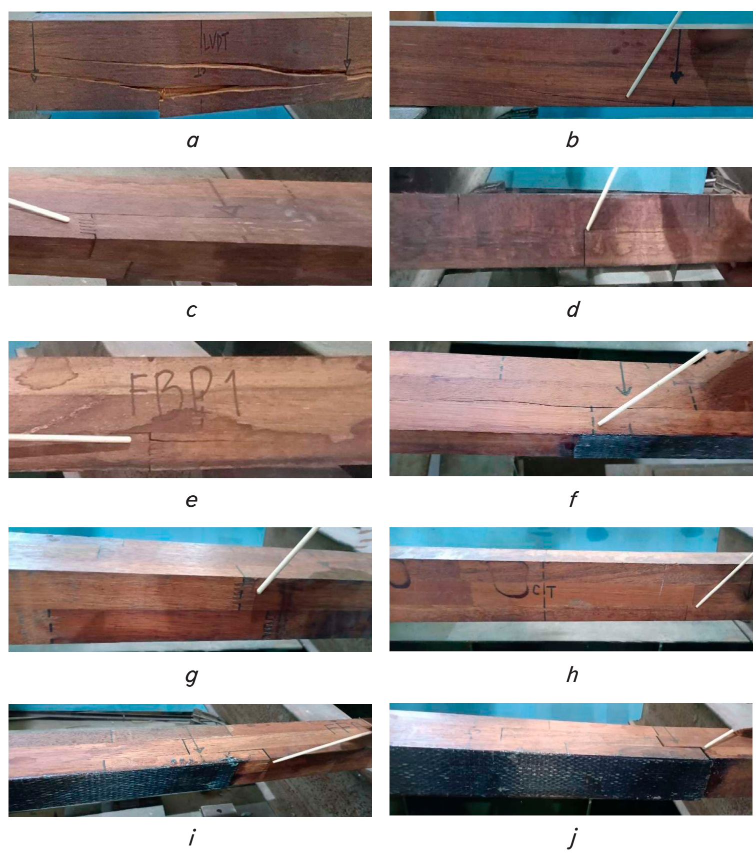

Fig. 11. Failure modes of beams: *a*, *b* — solid beams; *c*, *d* — face butt beams without reinforcement; *e*, *f* — face butt beams with reinforcement; *g*, *h* — face finger beams without reinforcement; *i*, *j* — face finger beams with reinforcement

As illustrated in Fig. 11, the predominant failure mode in finger-jointed beams was cracking and delamination around the joints, while solid beams generally failed in tensile rupture at the bottom fibers. The CFRP-reinforced beams showed delayed crack propagation and improved load transfer, particularly in the face finger configuration, although complete mitigation of joint weakness was not achieved.

5. 2. Modulus of elasticity and modulus of rupture of finger-joint laminated timber beams

As demonstrated in Fig. 12, the analysis of the graph indicates that face butt (FB) joints with reinforcement (FBP) exhibited a decline in modulus of elasticity (MOE), accompanied by a modest rise in modulus of rupture (MOR). This suggests that the reinforcement may have been less efficacious in enhancing stiffness, yet it demonstrated an enhanced capacity to endure the applied load up to the point of fracture. In contrast, face finger (FF) joints with reinforcement (FFP) exhibited a substantial enhancement in both MOE and MOR, suggesting that the face finger orientation is more responsive to the increased strength provided by the reinforcement. It is evident that solid beams exhibited significantly superior mechanical performance in comparison to all variations of finger joints, particularly with regard to the MOR, which reached three times the level of the FB joints. However, the MOE of the FFP beams approached the MOE of the solid beams, indicating the potential of reinforcement in the face finger orientation as a better stiffness enhancement solution than face butt.

Carbon fiber-reinforced polymers, serving to enhance both finger-jointed and sawn timber beams, have been under extensive research. Although the integration of CFRP has resulted in improvements within the mechanical properties of the wood beams, such as an increase in flexural strength and ductility, that of MOE is complex and varies according to influencing factors. In fact, the parameters which will affect the MOE of CFRP-reinforced timber beams include the interaction between CFRP and timber, cohesive stiffness of adhesive [23], reinforcement configuration, number of layers of CFRP, and their placing [19, 26]. All these call for a great deal of consideration with appropriate modelling for accurate predictions of the reinforcement.

As illustrated in Fig. 12, *a*, the modulus of elasticity of CFRP-reinforced face finger beams approached the values of solid beams, whereas face butt beams with reinforcement showed only marginal improvement. Meanwhile, Fig. 12, *b* indicates that the modulus of rupture of CFRP-reinforced face finger beams nearly doubled compared to unreinforced ones, highlighting the effectiveness of reinforcement in this orientation.

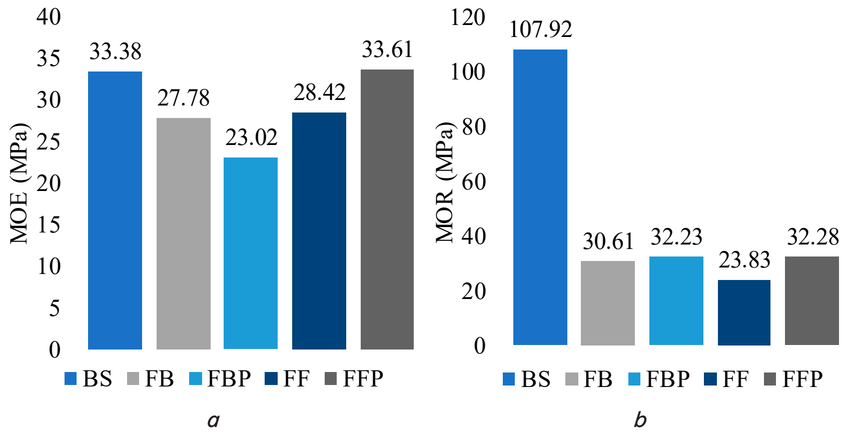

Fig. 12. Modulus of elasticity (MOE) and modulus of rupture (MOR) graph: *a* – modulus of elasticity (MOE) graph of finger-jointed laminated timber beams and solid beams; *b* – modulus of rupture (MOR) graph of finger-jointed laminated timber beams and solid beams

5. 3. Beam behavior based on load and deflection relationship

As illustrated in Fig. 13, laminated finger-jointed timber beams demonstrate distinct behaviors. Solid beams (BS) possess maximum load-bearing capacity, exhibiting linear behavior up to the maximum load, thereby demonstrating adequate ductility. Unreinforced end-face finger-jointed laminated beams (FB) demonstrate a reduced load-bearing capacity in comparison to BS, exhibiting an elevated deflection at equivalent loads. The incorporation of CFRP reinforcement in the FBP beam enhances its load-bearing capacity in comparison to FB. The FF connected beam has been observed to demonstrate superior performance in terms of load capacity and stiffness when compared to the FB. The incorporation of CFRP reinforcement in the FFP beam has been shown to enhance its load-bearing capacity and resistance to deflection to a degree that is nearly equivalent to that of a solid beam. This enhancement is accompanied by indications of increased ductility. This is reported as presented [25, 27], which details that the flexural capacity and initial stiffness of the beams increased by 33.84% and 16.7%, respectively, compared to the unreinforced specimens.

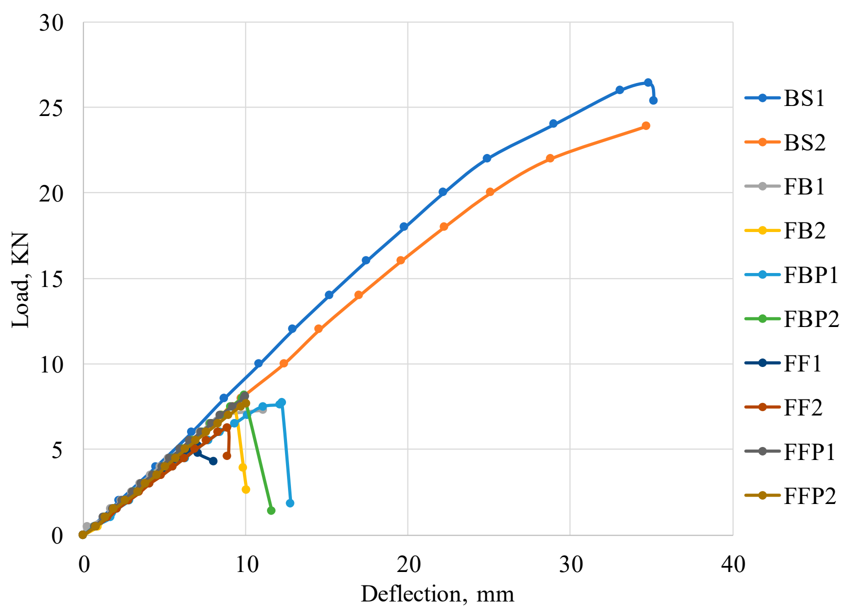

Fig. 13. Load and deflection relationship graph

As shown in Fig. 13, solid beams exhibited the highest stiffness and load capacity, while unreinforced finger-jointed beams showed lower performance with higher deflections. CFRP reinforcement improved the behavior of both face butt and face finger beams, with the latter showing curves closer to solid beams. This confirms that reinforcement effectiveness depends on joint orientation, with face finger joints benefiting more from CFRP strengthening [24–26].

6. Discussion of the results of flexural reinforcement of finger-jointed laminated timber beams

In this study, the mechanical performance of finger-jointed laminated beams reinforced with CFRP (carbon fiber reinforced polymer) was assessed. The performance metrics included maximum load capacity, modulus of elasticity (MOE), modulus of rupture (MOR), and load-deflection behavior. The experimental findings indicated that solid beams exhibited superior structural performance in comparison to finger joint laminated beams, irrespective of whether they were reinforced or not. This phenomenon can be attributed to the absence of stress concentration in solid wood, which, in contrast, weakens finger joint specimens [4]. The failure mode depicted in Fig. 11 further corroborates this observation, as finger joint beams predominantly fail at the joint area, while solid beams fail due to tensile failure at the bottom fiber.

Test results demonstrate that solid beams exhibit a higher maximum load capacity, with a maximum moment modulus (Mmax) ranging from 8.37 to 9.24 KN·m and a deflection at maximum load (*Δ*) ranging from 34.73 to 34.87 mm. These findings suggest that solid beams possess enhanced structural resistance. Conversely, laminated finger joints devoid of CFRP reinforcement (e.g., face butt and face finger joints) exhibit diminished load capacities, with Mmax ranging from 2.55 to 2.63 KN·m for face butt joints and from 1.82 to 2.18 KN·m for face finger joints as shown in Table 4. This phenomenon can be attributed to elevated stress concentrations in the finger joint region, which compromises the overall integrity and performance of the beam.

The incorporation of CFRP reinforcement has been demonstrated to enhance load capacity, with an observed average increase of 7.15% for face butt joints and 38.58% for face finger joints. The highest performance was demonstrated by CFRP-reinforced face finger beams, which exhibited a substantial enhancement in load capacity, nearly reaching that of solid beams. As illustrated in Fig. 13, the relationship between load and deflection in CFRP-reinforced beams demonstrates a substantial enhancement, particularly in face finger joints, which exhibit curves more analogous to those observed in solid beams. This finding substantiates the hypothesis that the incorporation of CFRP reinforcement confers a substantial enhancement in load capacity and resistance to deflection. A similar trend was reported by [24, 25], who observed higher flexural gains in CFRP-reinforced finger-jointed and glulam beams. The paper [26] further corroborated the hypothesis that externally bonded CFRP (carbon fiber-reinforced plastic) sheets enhance the load-deflection response by reducing deflection and delaying crack initiation. This finding is consistent with the results obtained in this study. The evident disparity in performance between unreinforced and reinforced beams underscores the pivotal role of adhesive type and bond efficiency. The paper [23] underscores the pivotal role of adhesive cohesive stiffness in dictating the elastic response of CFRP-reinforced beams, thereby elucidating the efficacy of the Nitowrap epoxy system in facilitating effective bonding. Moreover, extant research [9, 19] has demonstrated that CFRP rods and sheets can augment stiffness and flexural strength by up to 50–64%, thereby corroborating the extent of the increase observed in the reinforced specimens in this study.

The results of the MOE and MOR analyses depicted in Fig. 12 demonstrate that solid beams continue to demonstrate superiority in terms of elastic modulus and modulus of rupture. Face butt joints reinforced with CFRP demonstrate a modest increase in MOE, accompanied by a slight rise in MOR. This suggests that, while CFRP reinforcement augments stiffness to a certain extent, its impact is more pronounced in the beam's capacity to resist loads until it attains the point of failure. Conversely, the CFRP-reinforced face finger joint exhibited a substantial increase in both parameters, with MOE and MOR approaching the values of the solid beam. This performance is more clearly reflected in Fig. 12, *b*, which shows that the MOR of the reinforced face finger beam is almost double that of the unreinforced beam. These results suggest that the orientation of the face finger joint exhibits greater responsiveness to CFRP reinforcement compared to the face butt. More significant improvements in MOE and MOR at the face finger joints indicate that this orientation is more effective in transferring stress from wood to CFRP. This is in line with findings from previous studies which state that joint orientations that are more aligned with the tensile stress path can increase the efficiency of CFRP reinforcement.

As demonstrated in Fig. 13, the solid beam displays a linear load-deflection relationship up to the maximum load, suggesting enhanced resistance to deflection. The face butt beam, absent CFRP reinforcement, demonstrates increased deflection at reduced loads. This finding suggests that the performance of the beam in resisting loads is inferior to that of a solid beam. However, the incorporation of CFRP reinforcement in the face butt beam has been shown to yield substantial enhancements in performance, although its effectiveness remains inferior to that of a solid beam. Unreinforced finger joints demonstrate reduced load capacity and elevated deflection. However, subsequent to reinforcement with CFRP, these beams exhibit enhanced load capacity and resistance to deflection. The findings suggest that the incorporation of CFRP reinforcement in finger joints enhances the flexural properties and reduces the deflection capacity compared to butt joints.

The study has made very valuable contributions to the use of CFRP in the strengthening of finger-jointed laminated beams, nevertheless, it is necessary to highlight the limitations of the research. Firstly, the trial was limited to small-scale static load testing using the four-point bending approach. This technique does not adequately simulate the proper long-term performance of beams under cyclic loads or different environmental conditions. Secondly, the experimental set-up included the examination of only one adhesive system and one type of CFRP. Such limitation does not allow the conclusion that alternative reinforcement systems or different configurations might have better results. Thirdly, even though the wood was defect removed, still there would be the possibility of mechanical heterogeneity, which might affect the uniformity of the properties of the beams.

Future research efforts should primarily focus on evaluating how long the CFRP-reinforced beams would last under different environmental conditions, such as humidity, temperature variations, and fatigue loads. Besides, it would still be quite important for scientists to investigate alternative adhesives, hybrid reinforcement systems, and laminate configurations (CFRP combined with glass or basalt fibers, for example). In terms of methodology, a numerical modeling approach can be used side by side with the experimental research to predict the complicated interactions between CFRP, adhesives, and finger joints, as recent studies have indicated [21, 22]. Such measures would help to unlock the door for more elaborate design policies to become available for complete, high-performance engineered wood products that are also eco-friendly.

7. Conclusion

1. The ultimate load capacity, maximum moment, and mid-span deflection tests confirmed that solid beams exhibited the highest structural performance. CFRP reinforcement improved the load capacity of face butt beams by an average of 7.15% and face finger beams by 38.58%. The greater effectiveness in the face finger orientation is attributed to better alignment of CFRP with tensile stress paths, enabling more efficient stress redistribution.

2. The efficacy of CFRP reinforcement in enhancing the mechanical performance of laminated beams with finger joints has been demonstrated, although its effectiveness is significantly influenced by the orientation of the joints. The face finger joints demonstrated an optimal response to CFRP reinforcement, exhibiting an 18% increase in MOE (from 28.42 MPa to 33.61 MPa) and a significant 40% increase in MOR (from 23.83 MPa to 33.28 MPa). Conversely, the face butt joint exhibited less consistent results, manifesting a minimal increase in MOR (5%) but a decrease in MOE of 17%. However, it is noteworthy that the solid beam demonstrated superior performance, exhibiting an MOE value of 33.38 MPa and an MOR of 107.92 MPa. These findings indicate that the selection of the appropriate joint orientation is a critical factor in optimizing CFRP reinforcement in laminated beam structures.

3. The incorporation of CFRP reinforcement in finger joint laminated beams elicits a dual effect. On the one hand, CFRP has been shown to enhance load capacity by up to 38.58% at the face finger joint and improve ductility by increasing the deflection capacity by 26–27% before failure. However, despite the substantial enhancement in performance exhibited by the CFRP-reinforced face finger beams, their load capacity reached only 31% of solid wood beam capacity. The findings suggest that CFRP is a viable solution for enhancing the performance of laminated beams made from wood waste, particularly with regard to ductility and load capacity. However, it should be noted that CFRP cannot eliminate the fundamental weakness caused by the presence of finger joints.

Conflict of interest

We certify 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.

Financing

The study was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that artificial intelligence tools were utilized within acceptable ethical and scientific boundaries to support this research. All outputs generated by AI have been critically assessed and validated by the authors.

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