IDENTIFICATION OF THE MECHANICAL PERFORMANCE OF FINGER-JOINTED LAMINATED MERBAU TIMBER BEAMS REINFORCED WITH CARBON FIBER REINFORCED POLYMER (CFRP)

In this research, the mechanical properties and the reinforcement mechanism of finger-jointed laminated Merbau beams processed from wood-industry wastes are investigated and unreinforced specimens and externally U-shaped carbon fiber reinforced polymer (CFRP) strengthened beams are compared. The problem to be solved is the brittle failure and reduced flexural capacity of finger-jointed glulam; hence, it determines the combined impact of joint orientation (face-finger and face-butt), the number of lamination (three and five layers), and CFRP reinforcement on block-assembled beams with randomly distributed finger joints through four-point bending tests. The outcome of the study reveals that the use of CFRP has a huge impact on the flexural performance of the material, with the ultimate load being increased by 27.4–48.8% and the maximum bending moment being raised by 45.3% when compared to non-reinforced beams. The mid-point deflection at the maximum load has also increased by 6.5–51.4%, which shows a higher capacity for deformation and better ductility of the material.

The noted enhancements are credited to the successful shifting of the stress from the timber tension zone to the CFRP, lessening of stress concentration at the finger-joint discontinuities, and the crack initiation and propagation taking longer time in random locations which together change the structural response from sudden brittle fracture to more stable damage progression leading up to failure. Among the tested configurations, face-butt beams have obtained the highest modulus of elasticity of 20.46 GPa (an 8.8% increase), while the five-lamina face-butt configuration strengthened by CFRP has reached the greatest modulus of rupture of 55.85 MPa (a 33.4% increase). The three-lamina face-finger beams showed the highest increase of MOR after reinforcement, being at 48.30 MPa (a 46.4% increase). Changing lamination from three to five layers raised flexural strength by 18.9%, suggesting a homogenization effect that improves stress distribution in laminated beams composed of blocks. All in all, the collaboration of finger-joint configuration, number of lamination, random block assembly, and CFRP strengthening has opened a door to convert Merbau wood waste into higher-performance engineered timber elements for low-carbon structural applications

Keywords: merbau, glulam, beams, CFRP, reinforcement, bending, mechanical performance, MOE, MOR

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1. Introduction

The world shift to low-carbon and sustainable construction has led to the requirement of their structural materials to have the environmental advantages along with the reliable mechanical performance. Timber has been the most recognized renewable building material which has the capacity to sequester carbon and hence to contribute less to the greenhouse gases emitted through its lower energy during the whole life cycle compared to traditional materials like concrete and steel [1]. Recent studies that assessed the life-cycle of timber showed that buildings made of timber could have a considerable reduction in the global warming potential when the carbon stored during the usage of wood products is accounted for [2].

Even though solid wood has these benefits, its structural use still has a limited scope because of its variability, anisotropic mechanical properties, natural defects, and size limitations of the tree, which make it unreliable for large and heavily loaded structures [3]. Glued-laminated timber (glulam) is one of the engineered wood products that have been developed to mitigate these disadvantages by enhancing the overall efficiency of the material, the stability of the dimensions, and the creation of structural members with quite uniform mechanical properties [4]. Finger-jointed laminated timber also adds to this technique by making it possible to

put together short wood elements and industrial offcuts into longer structural parts, thus contributing to resource efficiency and recycling of materials [5].

Finger joints are considered as a significant vulnerability in laminated timber beams from the point of view of structural mechanics, since the varying materials at the joints cause stress concentration during bending loads [6]. Research has shown that the finger-joint interface is the major factor behind the creation of cracks and early deaths in glulam beams, notwithstanding the use of high-grade adhesives [7]. The finger-jointed beams' mechanical performance is greatly determined by the joint orientation, finger shape, adhesive properties, and lamination configuration, which altogether govern the stress distribution and failure modes [8].

In order to tackle the issues connected with the low quality of finger joints, fiber-reinforced polymer (FRP) materials have been very much used as external reinforcements for timber elements. Among them, carbon fiber-reinforced polymer (CFRP) is the most useful since it offers a very large tensile strength and elastic modulus which allow the material to carry tensile stresses that are well above the wood's capacity [9]. Also, some previous experiments have shown that wood composite reinforcements with CFRP can get the most benefit of wood's strength and have less damage accumulation in the beams of finger jointed timber [10]. More research has indicated that CFRP reinforcements lead to crack control and change failure modes through stress being diverted from the critical joint areas [11].

On the one hand, the majority of current research concerns the behavior of finger-jointed timber and CFRP reinforcement as separate design variables instead of engaging mechanisms. The most considerable part of the scientific contributions has been published regarding softwoods, regular joint spacing, or uniform lamination layouts with hardly any reference made to hardwoods and complicated joint configurations [8]. Specifically, the interaction among finger-joint orientation, number of laminations, and CFRP reinforcement on the mechanical behavior and failure modes of laminated beams made from tropical hardwood waste has not yet been thoroughly investigated [6].

Merbau (Intsia spp.) is a thick tropical hardwood that is very stiff, strong, and durable, so it is considered to be a very good choice for use in humid environments as an engineered wood timber. Tropical hardwood-based laminated products have been previously reported to provide mechanical performance that is better than softwood-based systems, but only if proper joint design and material processing are used [12]. Notwithstanding, the structural action of finger-jointed laminated Merbau beams with CFRP external reinforcement has still not been wholly studied.

Therefore, studies that are devoted to understanding the mechanical behaviour, failure mechanisms, and ductility development of finger-jointed laminated timber beams, including the influence of joint configuration, lamination number, and external reinforcement strategies, are of high scientific relevance.

2. Literature review dan problem statement

Structural systems have extensively used finger-jointed laminated timber beams because they can make full use of short-length timber elements and also turn industrial wood offcuts into load-bearing parts. Nevertheless, the bending and tensile strength of finger-jointed laminates have been consistently reported to be lower than that of solid wood or continuous laminations by various studies, which is mostly due to the concentration of stress at the finger-joint interfaces [6]. Research trials on laminated beams made of Eucalyptus nitens also indication that even with the use of high-grade adhesives, finger joints determine crack opening and final failure in the case of laminated beams [6].

Further studies maintained that joint geometry, joint orientation, and adhesive properties were the key factors determining the degree of stress transfer across finger joints. Simulation and optimization studies further enabled to identify the position of the joints in the layout as the major factor causing stress concentration and crack propagation, thus revealing the necessity for the joint redesign that gives better flexural performance and less material waste [7]. Comparing the different finger-joint orientations in experiments with bending loads, it was found that the vertically oriented joints are superior in strength over the horizontally oriented ones since the wood grain alignment allows the stress to be more favorable [8].

The paper at hand reviews the reinforcement of beams made of horizontally layered wood by GFRP and CFRP composites applied on the surface. This paper was published by [13]. It was revealed that the application of the FRP reinforcement led to a substantial increase in the flexural capacity where the tensile strength was transferred from the wood substrate to the composite layers. Nevertheless, the study was limited to continuous laminated elements free of finger joints, thus underestimating the finger joints' stress concentration and material discontinuity. In addition, the specimens were manufactured with a standard laminate layout and a controlled reinforcement configuration that did not reflect the random joint distribution and block assembly conditions found in the use of industrial wood waste. As a result, the interaction between the characteristics of finger joints and the mechanisms of CFRP reinforcement, especially in laminated beams made from tropical hardwood waste, has not been addressed in their research.

Subsequent research verified that joint orientation is still a major factor determining the flexural performance of tropical hardwood finger-jointed beams. Testing of the mechanical properties of finger-jointed beams made of different Malaysian hardwoods showed a strong impact of joint configuration on both joint efficiency and bending capacity thus making the role of joint orientation even more significant in hardwood applications [14]. However, the majority of previous studies consider regular spacing of finger joints across the length of a beam which is not a correct reflection of industrial manufacturing conditions since joint spacing is usually irregular due to different offcut lengths [14].

To lessen the natural drawback of finger joints, the use of fiber-reinforced polymer (FRP) materials as external reinforcement systems for timber beams has been proposed. Among the different types of fiber-reinforced polymers, the most prominent one carbon fiber-reinforced polymer (CFRP) has been able to increase the ability of wood to flex by a considerable amount since it is able to take the tensile stresses that surpass the tensile capacity of wood. In the case of strengthening the finger-jointed spruce beams with CFRP, the increase of flexural strength was over 30%, accompanied by a better control of crack propagation and a later failure of the material [9].

The subsequent studies verified that the use of CFRP reinforcement changed the failure mode of timber beams

with finger joints from brittle tensile rupture to more stable damage mechanisms characterized by gradual cracking and interface delamination [10]. Recent research proved that the application of externally bonded CFRP strips not only increased the load-carrying capacity but also improved the post-peak behavior through stress diversion from the most vulnerable areas, leading to higher ductility and structural reliability [11].

The mechanical properties of local Terminalia superba wood were investigated by means of a beveled joint configuration in a laminated wood assembly system conducted by [15]. The current investigation was directed toward the mechanical response of laminated wood beams due to joint configuration with no external reinforcement applied. However, the current investigation neither dealt with finger joints nor was it about FRP/CFRP reinforcement systems. In addition, it was restricted to wood-wood joint systems and did not include multilayer laminate configurations. Besides, it was not concerned with post-peak ductility response which is a determining factor for engineered wood structural beam applications. Thus, the current investigation intends to investigate the effect of interaction between finger joint characteristics and CFRP reinforcement mechanisms on laminated beams from tropical hardwood waste.

While there has been a great deal of advancement in learning the behavior of finger-jointed timber and the strengthening with CFRP, still the joint configuration and reinforcement have been considered as independent design parameters in most of the research. In addition, most of the experimental studies are concentrated on softwood species, standard lamination patterns, and regular joint spacing. Fewer studies have been conducted on hardwood species and realistic block-assembled laminated beams made from industrial wood waste [8, 16].

Merbau (*Intsia* spp.) is a dense tropical hardwood characterized by high stiffness, strength, and durability, making it suitable for structural applications in humid environments. Previous research on laminated products manufactured from tropical hardwoods has shown that, when appropriate joint design and material processing are applied, such systems can achieve superior mechanical performance compared to softwood-based products [12]. However, the flexural behavior and failure mechanisms of finger-jointed laminated Merbau beams reinforced with CFRP have not yet been sufficiently investigated.

Thus, the combined effect of finger-joint orientation, number of laminations, random joint distribution and external CFRP reinforcement on the mechanical behavior and failure mechanisms of block-assembled laminated timber beams made from tropical hardwood waste is still to be clearly described in future research, forming a research gap.

3. The aim and objectives of the study

The aim of this study is to evaluate the mechanical performance and structural behavior of finger-jointed laminated timber beams assembled in a block configuration. This will allow the results to be used as a practical reference for selecting joint configurations, lamination numbers, and reinforcement methods to improve the structural reliability and material efficiency of laminated timber beams manufactured from tropical hardwood waste.

To achieve this aim, the following objectives were accomplished:

– to analyzes the ultimate load capacity, maximum moment, and mid-span deflection of finger-joint laminated wood beams. The beams are examined in two configurations: without reinforcement and with CFRP reinforcement;

– to analyzes the influence of joint orientation and number of laminations on the modulus of rupture (MOR) and modulus of elasticity (MOE) of unreinforced and CFRP-reinforced laminated timber beams;

– to analyzes the load-deflection relationship and failure mechanisms of CFRP-reinforced finger-jointed laminated timber beams with various configurations, including crack initiation patterns, post-peak behavior, and ductility characteristics.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is the flexural performance of Merbau finger-jointed laminated wood beams derived from high-quality wood processing industry offcuts. The focus is on the combined effects of joint orientation, number of laminations, and external CFRP reinforcement, in terms of load capacity, flexural strength, stiffness, and failure patterns under four-point bending conditions. The investigation will concentrate on beams that have been reinforced with external CFRP (carbon fiber-reinforced polymer) and those that have not been reinforced, arranged with face finger and face butt joints comprising 3 and 5 laminates, respectively. The reinforced beams will be compared with beams without CFRP reinforcement. Testing will be conducted on a span measuring 270 centimeters.

It is hypothesized that external CFRP reinforcement enhances the flexural capacity and ductility of finger-jointed laminated timber beams by mitigating stress concentration at finger-joint regions. In addition, beams with face-butt joint orientation are expected to exhibit higher flexural strength and more stable failure behavior than those with face-finger orientation due to more favorable stress transfer mechanisms. Furthermore, increasing the number of laminations from three to five is assumed to improve stress distribution across the beam cross-section, resulting in enhanced flexural performance. These hypotheses are examined through a comparative evaluation of reinforced and unreinforced laminated beams manufactured from Merbau wood offcuts under flexural loading.

The main assumption suggested in this research is that applying U-shaped CFRP reinforcement, changing finger joint orientation, and using five laminas will result in an increase in the load capacity, flexural capacity, and stiffness (in terms of MOE) of timber beams with finger-jointed connections.

The base of this research is under the belief that wood material behaves like a linear-elastic up to the proportional limit and that the adhesive bonds are perfect (defects-free). The wood moisture content is going to be between 10–12% and it will be the same throughout the sample. The testing will be done using the quasi-static loading technique and a four-point bending setup with displacement control, which ensures that the results will be very accurate. Among the factors that the study simplified were: material defects, internal wood variability, as well as environmental factors like humidity and temperature that may affect the long-term outcomes. Hence, the results obtained are predicted to be valid

only for finger-jointed laminated wood with CFRP reinforcement applied in structural applications.

4. 2. Merbau wood

The wood utilized in this project is Merbau from Papua, Indonesia, a high-quality hardwood sourced from woodworking factory offcuts in the Surabaya area. The wood's texture is characterized by a coarse, even consistency, with predominantly straight grain. The merbau wood shows very little damage during the drying process because it has low tangential and radial shrinkages. The merbau wood that is being considered as scrap has been dried consistently to 10–12% moisture content, and it is therefore classified as scrap for the woodworking industry. The wood that is being considered as scrap has a length of 30 to 50 centimeters and is free of any defects. This is because it has been sorted during the processing stage before entering the industrial process. The mechanical properties of merbau wood were tested on three defect-free small-scale specimens measuring 25×25 mm with a span of 360 mm. The three-point bending test was used to determine the flexural strength of the specimens which showed that the average modulus of elasticity (MOE) of the specimens was 12.84 GPa, while the average modulus of rupture (MOR) was 144.56 MPa, according to [17]. These values indicate that merbau wood has a high stiffness and strength compared to many tropical hardwoods, thus, it is suitable for use as a base material for structural laminated beams.

4. 3. Carbon fiber reinforced polymer and epoxy resin

Carbon fiber, an FRP (fiber-reinforced polymer) material, is utilized in the testing program illustrated in Fig. 1. The materials utilized in this study, specifically epoxy resin and carbon fiber sheets, were supplied by FOSROC Constructive (Table 1). The present study utilized a two-component epoxy resin composed of Nitowrap 30 epoxy primer and Nitowrap 410 epoxy adhesive from FOSROC. Nitowrap 30 epoxy primer has a base material and hardener ratio of 2:1, with a coverage rate recommended by the supplier of 0.3 kg/m^2 for this primer. At the same time, the Nitowrap 410 epoxy adhesive is mixed with a base and hardener in the ratio of 2:1 and covered with 0.8 kg/m^2, as stated by [17]. In this process, the carbon fiber is glued to the laminated wood with the help of epoxy resin. The main purpose of this resin is to transfer strength between the two materials and at the same time to shield the fibers from harm due to friction and environmental degradation.

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

Table 1, displays the findings of very high tensile strength (> 4,900 MPa) and tensile modulus (> 230 GPa) of the CFRP, which confirmed its applicability in structural reinforcement. On the other hand, it was the case that the epoxy adhesives showed the shear adhesion strength above 7 MPa along with the compressive strength of more than 90 MPa, which is the reason why they are considered as a source of reliable bonding between the CFRP sheets and laminated timber.

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

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

The carbon fiber-reinforced polymer (CFRP) reinforcement in laminated wood beams is depicted in Fig. 2. This procedure initiates with the coating of the laminated beam's underpart with an epoxy primer. The primer employed in this research is Nitowrap 30, which was prepared in a mixing ratio of 2:1 of base to hardener, producing a coverage of 0.3 kilograms per square meter. After the primer is applied, it is truly necessary for it to be dried for about 24 hours before the next step. Then, epoxy adhesive, Nitowrap 410, is applied in the same 2:1 ratio, at a coverage of 0.8 kg/m^2. After that, carbon fiber sheets that had been accurately cut to the dimensions of 135 centimeters in length and 23 centimeters in width were carefully placed to wrap around a part of the wooden sample in a partial U-shape configuration. This setup was then put on the treated surface and lightly pressed down with gloved hands. To further reinforce the bond's reliability, the carbon fiber fabric is treated with an adhesive encapsulation resin. The whole assembly is then exposed to a conditioning process at room temperature for at least one week. This is to allow proper drying before testing, as per the manufacturer's advice. The strengthening is expected to allow the finger joint laminated beam to not only absorb more loads but also become less deformed by the loads during the transfer from the wood to the CFRP.

Fig. 2. Usage of carbon fiber reinforced polymer (CFRP) strengthening on laminated timber beams

Utilization of CFRP in laminated woods which are shown in Fig. 2, is meant to increase the strength and stiffness of beams by transferring the load from the wood to the CFRP during the process of loading. After the drying and curing, this reinforcement is expected to give a higher load capacity, less deflection, and slower crack development at the finger-joints. This reinforcement technique has been demonstrated to be an effective solution for enhancing the overall structural performance of laminated wood 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 programme

During the finger jointing process undertaken, the board was converted to laminated wood blocks. Removing natural defects ensured the base material's satisfactory quality. Merbau wood obtained from production offcuts was used for the test specimens. The wood was conditioned at a temperature of 20°C and a relative humidity of 65% in a conditioning chamber. Then, it was dried in a kiln to an equilibrium moisture content of approximately 10–12%. The wood pieces were between 30 and 50 centimeters long. The first step in the wood fabrication process was printing to ensure the wood was flat on all sides. Next, the wood was assembled using finger joints, and its length was adjusted to 270 cm for the testing stage. Next, the wood was subjected to a laminated board manufacturing process using a two-component adhesive with a 1:1.5 weight ratio, applied at 250–300 g/m^2. After forming the laminated board from the finger joints, it is cut into test specimens measuring 8×15 cm with a 3- or 5-lamina arrangement and face finger or face butt joint orientations, all 270 cm in length. The test specimens consisted of eight configurations, namely beams with three-lamina and five-lamina face finger orientation, beams with three-lamina and five-lamina face butt orientation, both without reinforcement and with CFRP reinforcement. These configurations are shown in Fig. 3–10. The total number of test specimens is 24, consisting of 6 three-lamina face finger beams without reinforcement and with CFRP reinforcement, 6 five-lamina face finger beams without reinforcement and with reinforcement, 6 three-lamina face butt beams without reinforcement and with reinforcement, and 6 five-lamina face butt beams without reinforcement and with reinforcement.

The finger joint geometry illustrated in Fig. 11 is determined based on technical recommendations and manufacturer availability. In the wood industry, the naming of finger joint orientation is adapted so that face finger orientation is identical to vertical orientation, and face butt is identical to horizontal orientation, as shown in Fig. 12, and Table 2 summarizes the main characteristics.
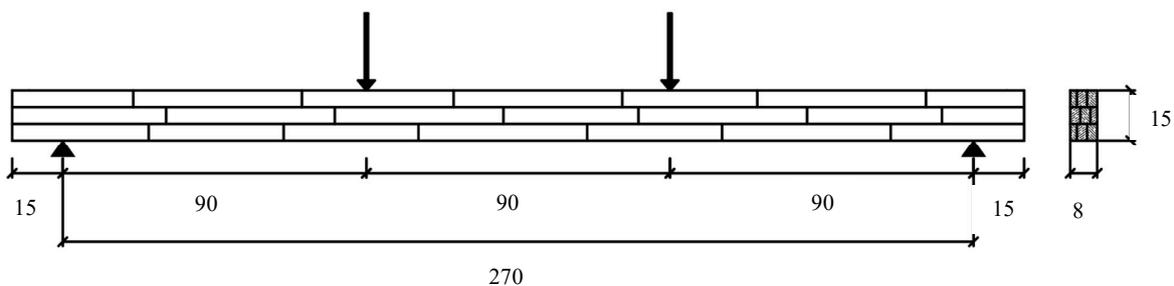

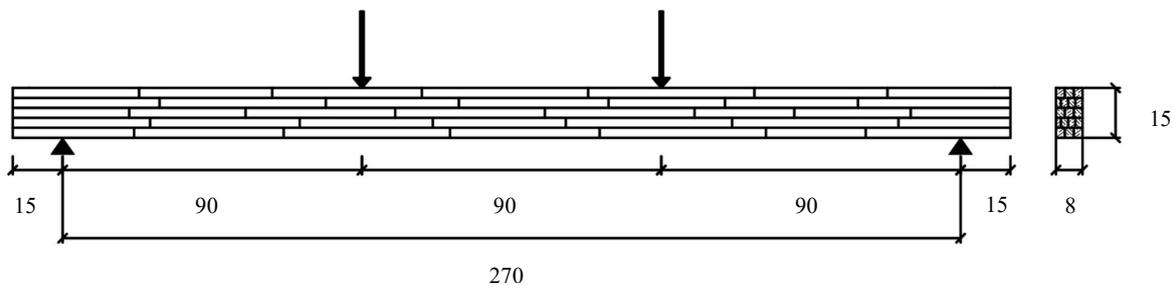Fig. 3. Three-lamina face finger specimen without carbon fiber reinforced polymer reinforcement

Fig. 4. Five-lamina face finger specimen without carbon fiber reinforced polymer reinforcement
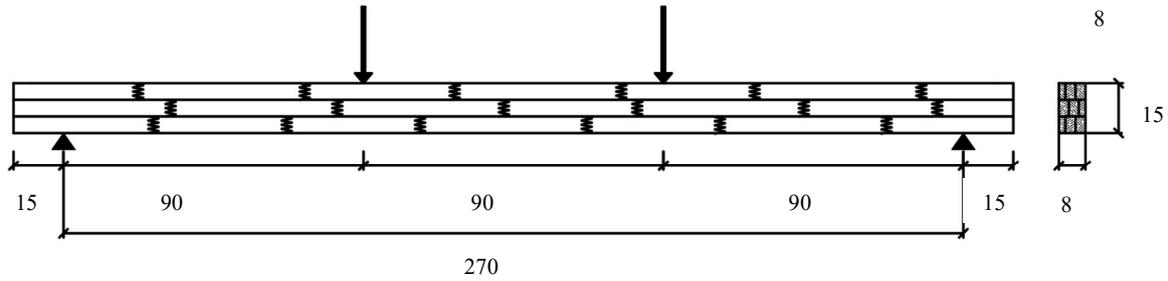
Fig. 5. Three-lamina face butt specimen without carbon fiber reinforced polymer reinforcement
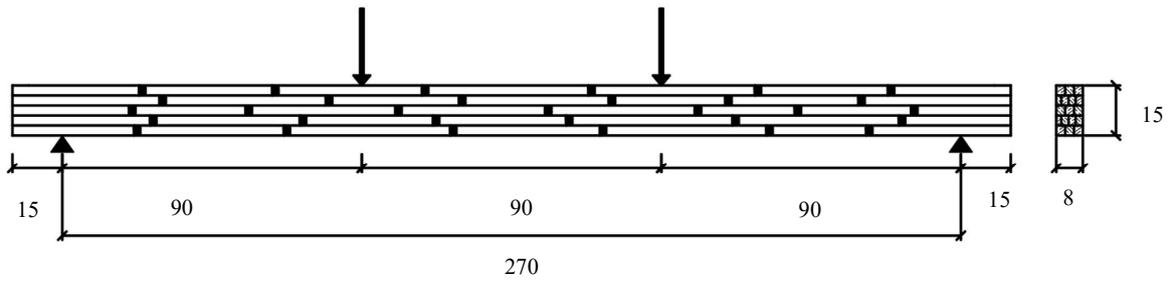

Fig. 6. Five-lamina face butt specimen without carbon fiber reinforced polymer reinforcement
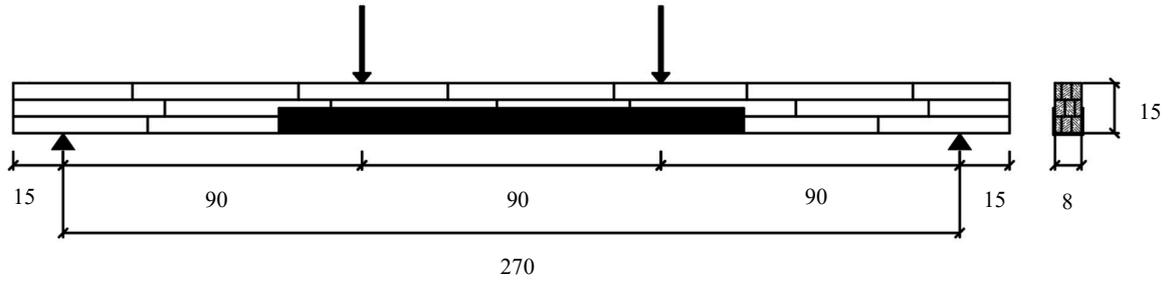

Fig. 7. Three-lamina face finger specimen with carbon fiber reinforced polymer reinforcement
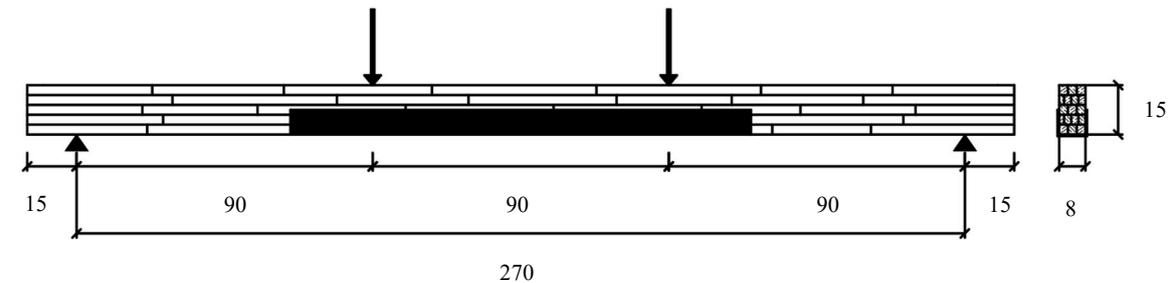

Fig. 8. Five-lamina face finger specimen with carbon fiber reinforced polymer reinforcement
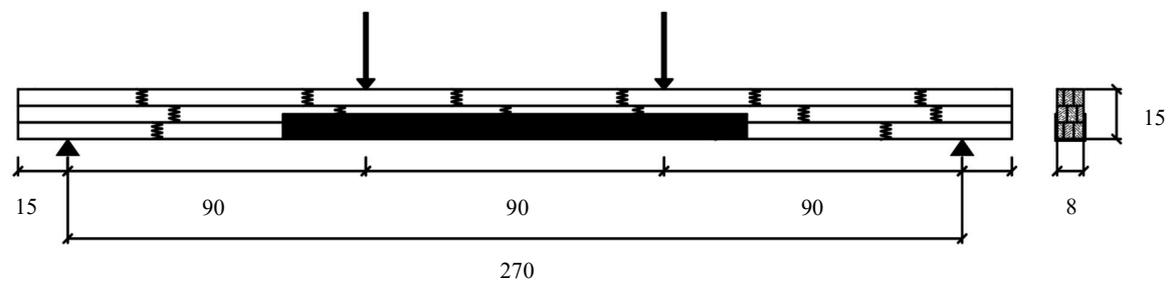

Fig. 9. Three-lamina face butt specimen with carbon fiber reinforced polymer reinforcement

Static flexural testing was conducted using the four-point flexural loading method to ascertain the mechanical performance and flexural behavior of laminated beams. The testing was conducted in accordance with the method described in ASTM D198-02 (ASTM, 2000) in order to ensure the reliability and repeatability of the results. The present study adopts an experimental approach, eschewing analytical or numerical modelling techniques such as finite element analysis. The analysis is based on load-deflection response, calculated flexural parameters, and observation of failure modes. Given the

manner in which the beams were assembled in blocks with irregular finger joints it could not be assumed that the stress distribution was uniform. Consequently, the failure mechanism was interpreted macroscopically, based on crack initiation, crack propagation, and post-peak behavior under short-term static loading conditions. The rate of loading was 3 millimeters per minute. The configuration of the instrument is illustrated in Fig. 13. The beam supports were composed of steel plates measuring 100×55 mm^2, with a thickness of 6 mm, and steel cylinders with a diameter of 25 mm. In order to avert

local failure, 100×55 mm^2 plywood pads, with a thickness of 16 mm, were affixed above the steel plates and below the load points. The load was distributed by a 1-meter-long WF-15 steel load spreader. The selection of the WF steel load spreader was made on the premise that it would ensure sufficient rigidity to guarantee even load distribution at the two loading points. Three LVDTs were strategically positioned at one-third of the span on the right and left sides, as well as in the center of the span. In order to avert local buckling during the flexural test, stiffeners are applied at two points.
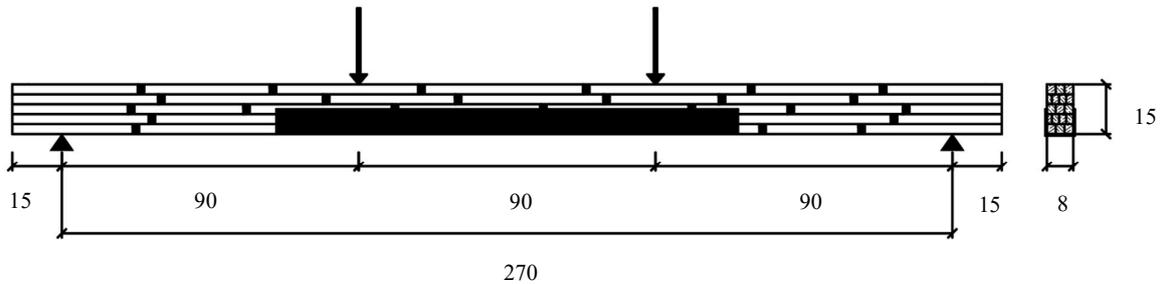

Fig. 10. Five-lamina face butt specimen with carbon fiber reinforced polymer reinforcement

Fig. 11. Finger joint geometry of laminated wood beams: *a* — finger joint geometry of three-laminate laminated wood beams; *b* — finger joint geometry of five-laminate laminated wood beams

Fig. 12. Finger joint orientation on finger joint laminated wood beams: *a* — face finger orientation; *b* — face butt orientation
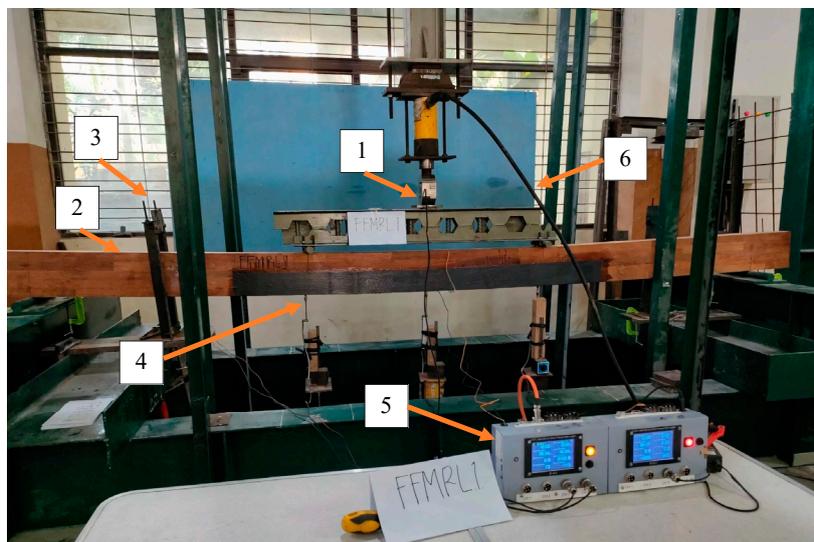

Fig. 13. Experimental setup: 1 — load cell; 2 — test piece; 3 — lateral stiffener; 4 — LVDT; 5 — data logger; 6 — hydraulic jack

Table 2

Characteristics of finger joints

Configuration	Values
Length (l), mm	12
Range (p), mm	3.8

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

$$MOE = \frac{23 \cdot P \cdot L^3}{108 \cdot \Delta \cdot b \cdot h^3}, \qquad (1)$$

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

$$MOR = \frac{P \cdot L}{b \cdot h^2}, \qquad (2)$$

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

5. The research results of mechanical performance 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 3.

An examination of the experimental data shown in Table 3, uncovers that the assessment of the structural strength of finger-joint laminated timber beams indicates that CFRP reinforcement has a positive impact on the beams' structural performance. Out of the total of 24 test samples, comprising different joint types and laminate counts, a steady trend of enhanced performance was seen in the beams with CFRP reinforcement.

CFRP reinforcement in terms of maximum load capacity (Pmax) beam reinforcement has shown a very significant increase with respect to the non-reinforcement beams. The three-lamina face finger configuration exhibited a spectacular increase from an average FFTL of 21.75 KN to an FFTRL of 32.36 KN, which is in fact a rise of 48.8% in the case of three-lamina supposedly. With five-lamina configuration, that number went up from FFML of 26.29 KN to FFMRL of 34.64 KN (generally, an increase of 31.8%). But the same trend was observed case of the face butt joint, so the three-lamina configuration rose from FBTL 23.78 KN to FBTRL 31.87 KN, thus being a 34% increase, and the five-lamina configuration was again brought up from FBML 27.99 KN to FBMRL 35.65 KN, which is a 27.4% increment. The conducted analysis clearly indicates that the use of CFRP reinforcement is a significant factor in increasing the ultimate load capacity of all beam configurations to a very high level.

A meticulous examination of the maximum moment (Mmax) showed that all the beams with CFRP reinforcements exhibited a uniform elevation of their performance. The moment capacity of the three-laminates finger joint configuration increased from FFTL of 10.02 KN·m to FFTRL of 14.56 KN·m, representing a rise of 45.3%. Furthermore, the moment value in the five-lamina setting went up from FFML of 11.83 KN·m to 15.59 KN·m of FBMRL, which is a 31.8% increase. In the case of face butt joints, the maximum moment increased from FBTL of 10.70 KN·m to

FBTRL of 14.34 KN·m (34% increase) in three laminates, and from FBML of 12.63 KN·m to FBMRL of 16.80 KN·m (33% increase) in five laminates. The findings of the present research validate the assumption that the incorporation of CFRP results in a constant increment in the bending strength of laminated timber beams irrespective of the joint type and the number of laminations used.

Table 3

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

Spec. No.	Pmax (KN)	Mmax (KN·m)	Δmax (mm)
FFTL.1	21.29	9.58	20.17
FFTL.2	19.25	9.35	30.60
FFTL.3	24.70	11.12	23.71
Mean	21.75	10.02	24.83
Stdev	2.75	0.96	5.30
CoV (%)	12.66	9.61	21.36
FFML.1	26.20	11.79	23.78
FFML.2	26.73	12.03	26.94
FFML.3	25.93	11.67	27.75
Mean	26.29	11.83	26.16
Stdev	0.41	0.18	2.10
CoV (%)	1.55	1.55	8.02
FBTL.1	24.43	10.99	19.57
FBTL.2	22.03	9.91	20.78
FBTL.3	24.88	11.20	29.62
Mean	23.78	10.70	23.32
Stdev	1.53	0.69	5.49
CoV (%)	6.44	6.47	23.52
FBML.1	27.88	12.55	30.04
FBML.2	29.27	13.28	31.27
FBML.3	26.82	12.07	25.60
Mean	27.99	12.63	28.97
Stdev	1.23	0.61	2.98
CoV (%)	4.39	4.82	10.30
FFTRL.1	31.64	14.24	25.80
FFTRL.2	34.52	15.54	27.63
FFTRL.3	30.91	13.91	25.89
Mean	32.36	14.56	26.44
Stdev	1.91	0.86	1.03
CoV (%)	5.90	5.92	3.90
FFMRL.1	32.17	14.48	28.70
FFMRL.2	37.60	16.92	39.19
FFMRL.3	34.16	15.37	31.61
Mean	34.64	15.59	33.17
Stdev	2.75	1.23	5.42
CoV (%)	7.93	7.92	16.33
FBTRL.1	36.54	16.44	33.69
FBTRL.2	34.40	15.48	33.83
FBTRL.3	24.68	11.11	21.83
Mean	31.87	14.34	29.78
Stdev	6.32	2.84	6.89
CoV (%)	19.83	19.81	23.13
FBMRL.1	32.17	16.74	48.59
FBMRL.2	36.01	16.20	30.34
FBMRL.3	38.78	17.45	52.66
Mean	35.65	16.80	43.86
Stdev	3.32	0.63	11.89
CoV (%)	9.31	3.73	27.10

When analyzing the mid-span deflection (Δmax) in detail, a different character is easily noticed regarding the moment capacity increase that has been observed. It is already apparent from the beginning that the deflection of the CFRP reinforced beams eventually surpasses the corresponding failure of these beams. In the finger face configuration, the deflection increased by 6.5% for three laminates (from 24.83 mm to 26.44 mm) and by 26.8% for five laminates (from 26.16 mm to 33.17 mm). On the contrary, the face butt configuration gave a larger increase of 27.7% for three laminates (from 23.32 mm to 29.78 mm) and the highest of 51.4% for five laminates (from 28.97 mm to 43.86 mm). The increase shows that the use of CFRP reinforcement has the potential to make beams more ductile, thereby allowing for much greater deformation before they eventually fail. This is a design advantage in the structural perspective, as it would provide a clear visual warning before the actual collapse.

The trustworthiness of the test outcomes was assessed by means of descriptive statistical methods comprising mean values, standard deviations, and coefficients of variation (CoV) for every beam configuration, using three specimens per group as a basis. The CoV values represent the inherent variance of wood materials as well as the discrepancies in joint quality and adhesive bonding. The consistency in the performance trends which were observed across specimens with the same joint orientations, laminations, and reinforcements indicates that the test results are quite reproducible and can be replicated. Because of the small number of specimens in each configuration, the results of the study are interpreted by means of a comparison of performance trends. This is a more suitable approach for exploratory experimental studies on wooden structural elements, rather than making probabilistic statistical inferences.

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

The four-point bending test results, as shown in Fig. 14, *a*, suggest that the MOR (Modulus of Rupture) of laminated wood beams differ significantly with respect to joint orientation, the number of laminations and the use of CFRP reinforcement. The three-laminate beams with face finger orientation (FFTL) had a MOR value of 33.00 MPa, while the face butt orientation (FBTL) gave a slightly higher value of 35.23 MPa. Thus, it can be inferred that the face butt orientation, without reinforcement, has greater flexural strength than the face finger orientation.

The use of CFRP strengthening has been shown to yield a remarkable improvement in both orientations of the joint. The FFTRL beam (face finger with reinforcement) reached a modulus of rupture (MOR) of 48.30 MPa, which is a rise of 46.4% compared to the unreinforced condition, while the FBTRL beam (face butt with reinforcement) reached 47.61 MPa, which is a rise of 35.1%. It is worth mentioning that even though the face butt performed best in the unreinforced condition, the face finger orientation beam still had a mor slightly higher value after being reinforced with CFRP.

The addition of CFRP reinforcement (FBMRL) in the five-lamina configuration with face butt orientation significantly raised the flexural strength (FBML) from 41.87 MPa to 55.85 MPa, which is a 33.4% hike. By comparing the FBTL (35.23 MPa) and FBML (41.87 MPa) values, it can be inferred that the flexural strength has been enhanced by 18.9% when the number of laminates was increased from three to five. The findings confirm that using CFRP reinforcement

is a very effective and economical method to increase the flexural strength of laminated wood beams regardless of their configurations. Among the various configurations, the five-lamina face butt orientation beam strengthened with CFRP showed the highest MOR value, which indicates that the method could effectively improve the flexural load performance of laminated wood beams.

The findings of the four-point bending test (Fig. 14, *b*) show that the finger-jointed laminated wood beams have a wide range of Elasticity Modulus (MOE) values, which are 18.80 GPa to 20.46 GPa. The three-lamina face butt beam configuration with CFRP reinforcement (FBTRL) showed the best performance with the MOE of 20.46 GPa. On the contrary, the configuration without any reinforcement (FBTL) had the lowest MOE of 18.80 GPa. This result suggests that the direction orientation of wood, which was combined with the reinforcement laid down in that direction, significantly affects beam.

The assessment made through comparison shows that the efficiency of CFRP reinforcement is influenced by the positioning of the joints. In the case of three-lamina face butt orientation, the mixture of CFRP results in a substantial increase in MOE of 8.8% (from 18.80 GPa to 20.46 GPa), which indicates a good interaction between the reinforcement and the joint configuration. Conversely, in the three-lamina face finger orientation, only a slight increase of 1.2% in MOE (from 19.52 GPa to 19.76 GPa) is provided by CFRP reinforcement. In the case of five-lamina beam with a face butt orientation, the MOE together with CFRP resulted in a minute lowering of the MOE value by 0.6% (from 19.20 GPa to 19.09 GPa). This case can be explained by a complicated interaction between multiple tape layers and reinforcement materials.

The study results amount to that they can be viewed as major factors in the structural design of laminated beams. The face finger orientations without any reinforcement (FFTL and FFML) gave stable performance with MOEs of 19.52 GPa and 20.36 GPa, respectively, thus revealing the good natural stiffness of the finger joint orientation. In contrast, the face butt orientation exhibited a higher degree of sensitivity to the application of reinforcement, especially lessening the impact of three-lamina configuration as the five-lamina configuration was reached. Consequently, the research results imply that the choice of the best configuration has to be made by taking into account the complicated interplay between joint type, the number of laminas, and the reinforcement system in order to accomplish the required structural performance.

The variation in MOR and MOE values of the eight laminated timber beam configurations is presented in Fig. 14. The highest MOR was obtained for the FBMRL specimen, reaching 55.85 MPa, while the lowest value was recorded for FFTL at 33.00 MPa, indicating the best and weakest flexural performance, respectively. Meanwhile, the MOE values ranged from 18.80 to 20.46 GPa, reflecting relatively similar stiffness among all configurations. These results indicate that the joint configuration and CFRP reinforcement have a more pronounced influence on flexural strength than on the elastic stiffness of the beams.

The findings of the tests indicate that the joint orientation and the amount of laminations play a major role on the MOR, with the face-butt arrangement and a larger number of laminations (5 layers) offering more bending strength than face-finger and 3 layers. Stress concentration in the tension zone is reduced and stress across the beam's cross-section is more evenly distributed, which is the case of the joint ori-

entations mentioned above. On the other hand, the effect of these two factors on MOE is quite small in comparison, as the wood's intrinsic properties dominate the elastic stiffness of the beam, thus variations in joint configuration and number of lamellas do not have a major impact on MOE.
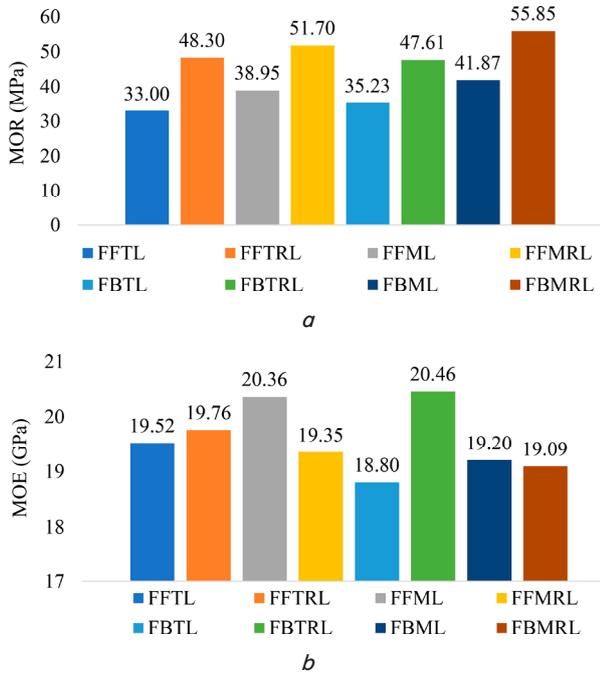

Fig. 14. Comparison of mechanical properties of different finger-jointed timber beam configurations: a — MOR (modulus of rupture) graph with the eight types of finger-jointed timber beams; b — MOE (modulus of elasticity) graph of eight types of finger-jointed timber beams

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

The load-deflection relationship curves indicated in Fig. 15 show that the finger-jointed laminated wood beams which were not reinforced have similar characteristics during the elastic phase. It is apparent that all the samples, regardless of their face-finger orientation (FFTL and FFML) or face-butt orientation (FBTL and FBML), have a linear relation between the applied load and the measured deflection until a deflection of about 12–15 mm is reached. The almost common slope of the curve during this time indicates that the initial stiffness of all the beam variations was comparable with an elastic load range of 10–22 KN. This implies that the orientation of the joints and the number of laminations have a relatively insignificant impact on the elastic behavior of the beams.

The studies on the beams showed a continuous increase in their maximum load capacity until a total of up to 30 KN with specimen FBTL.1 being the highest with a value of about 30 KN as of a 25 mm deflection. It became apparent that face-butt orientation beams usually can carry slightly more than face-finger orientation ones. Although the number of laminations (3 or 5) did not have an obvious correlation with the ultimate load capacity, the variations among specimens with similar configurations indicated the effect that the dif-

ferences in wood material properties and finger-joint quality had on the bending strength of the beams.

The orientation of the joints has been demonstrated to exert a significant influence on the collapse mode of the beams. Beams with a face-finger orientation (FFTL and FFML) exhibited a substantial decline in load capacity upon reaching the maximum load at a deflection of 25–30 mm, suggesting that the observed collapse was of a brittle nature. The beams with a face-butt orientation (FBTL and FBML), however, demonstrated a more gradual decline in load and were able to maintain some capacity at larger deflections, which indicates a more ductile behavior. The results highlight that the orientation of the finger joints is a decisive factor in the failure mechanism of laminated wood beams without reinforcement. In such situations, the face-butt orientation provides a more favorable post-peak response in terms of structural performance.

The load-deflection characteristics of the twelve specimens that were tested and shown in Fig. 15, were classified into four categories (FBTL, FBML, FFTL, and FFML), each consisting of three samples. The performance of all specimens was similar and resembled a pattern of first a linear rise in load followed by a peak of about 20–30 KN at a deflection of 20–28 mm and then a post-peak decline. The load drop rate differed according to the joint position, with face-butt joints (FBTL and FBML) having a softer decline and thus reflecting higher ductility, while face-finger joints (FFTL and FFML) showed a rapid drop in load indicating a more brittle way of failure.

The load-deflection curve in Fig. 16 shows that the different CFRP-reinforced laminated wood beam configurations have almost the same initial stiffness in the linear elastic phase no matter how the laminates are arranged or how many layers there are, with the curves staying practically linear until a deflection of about 20–28 mm is reached. The similarity implies a uniform elastic behavior of the specimens and also points to the effective role of the CFRP reinforcement in all beam types.
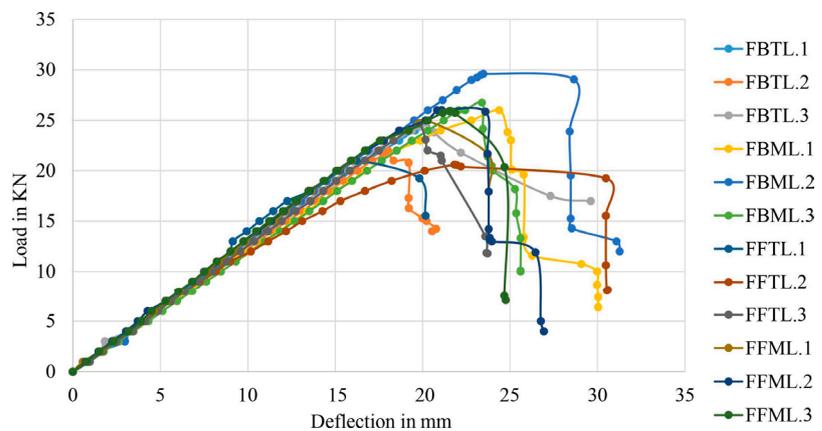

Fig. 15. The graph presented below demonstrates how the load and deflection of finger-jointed laminated wood beams correlate with each other considering no carbon fiber reinforced polymer reinforcement is applied

Maximum load capacity wise, the various beam configurations gave off quite similar ultimate loads of 35 to 38 KN, with pretty much only slight differences due to joint orientations and numbers of laminates. This indicates that the CFRP strengthening was successful in uniformly increasing the flexural strength of all the tested beam configurations. On the other hand, the post-peak behavior and failure modes were quite different from

each other. The FBMRL.1 beam suffered the most ductile failure, which was the case when the load decreased gradually until a deflection of almost 50 mm was reached, while the three-laminate beams (FFTRL and FBTRL) showed more brittle behavior with a sudden load drop just after the peak at around 32–35 mm, thus the load drop was characterized by the peak at around 32–35 mm.

ration (Fig. 17, *a, b*), crack propagation follows a longitudinal pattern along the wood grain, with relatively sudden failure, while the face butt configuration (Fig. 17, *c, d*) shows more localized damage with brittle failure characteristics, marked by sudden lamina separation.

The mode in which the beams failed is mainly affected by the combination of the orientation of the joints and the number of laminates. The three-laminate beams (FFTRL and FBTRL), based on the visual inspection of the failed specimens, were the ones that mostly suffered delamination and direct damage at the wood-CFRP interface, thus confirming this mechanism as the main one for the sudden post-peak failure. On the other hand, the five-lamina beams exhibited a wider range of failure responses, with the face-butt configuration (FBMRL) even showing the ability to preserve post-peak load through a more effective stress redistribution mechanism. The different behavior of the specimens with the same configurations observed here only adds weight to the argument that the quality of fabrication and the bonding conditions at the interface play a major role in determining the overall structural performance of CFRP-reinforced laminated beams.

The load-deflection traits of the 12 specimens in the four test groups (FBTRL, FBMRL, FFTRL, FFMRL) are presented in Fig. 16. All specimens exhibited similar linear elastic behavior up to approximately 20–28 mm of deflection, after which they reached peak loads in the range of 35–38 KN at around 30–33 mm. Beyond the peak, the three-lamina beams experienced a sharp drop in load capacity, whereas the five-lamina beams showed a more gradual strength reduction up to 45–50 mm. Of the specimens, the FBMRL beams collectively bore the highest peak loads, with FBMRL 3 being one of those better loads tested. In general, the enhanced strength and deformation capacity of the laminated timber beams with finger joints reinforced with CFRP are due to the interplay of stress redistribution mechanisms at the macro scale and crack control at the micro scale. The CFRP reinforcement not only postpones the tensile failure by lowering the stress concentration at the finger joints but also the laminate configuration and joint direction govern the effectiveness of crack containment and post-peak energy dissipation. It is the combined effect of the wood microstructure, adhesive interface, and CFRP bond that determines the transformation from brittle to more ductile behavior in the reinforced beam system. The failure mechanisms of laminated beams with no and with CFRP reinforcement are shown in Fig. 17, 18, respectively.

As illustrated in Fig. 17, the failure characteristics of unreinforced beams demonstrate that crack initiation predominantly occurs in the tensile zone at the finger joint area. This observation indicates significant stress concentration at the point of material discontinuity. In the face finger configu-
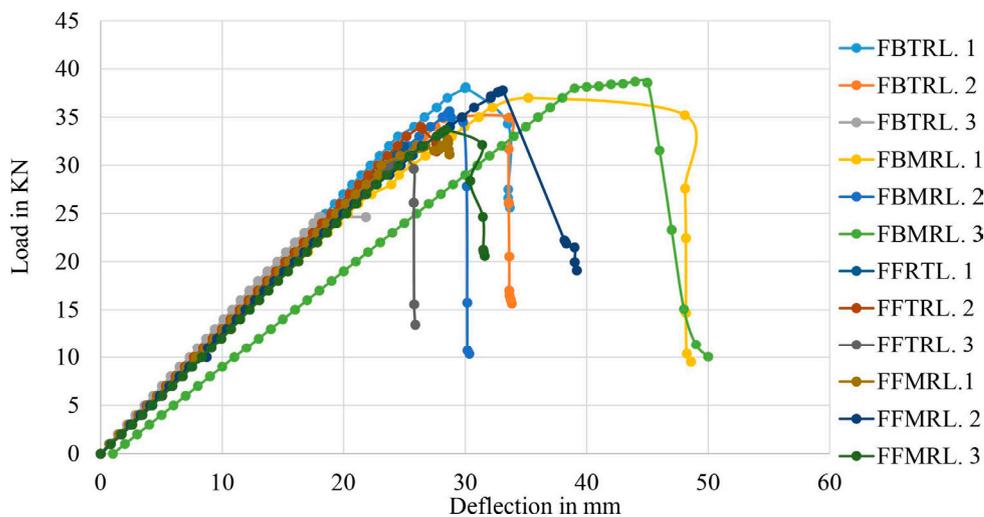

Fig. 16. The following graph illustrates the relationship between load and deflection of finger-jointed laminated timber beams that have been reinforced with carbon fiber reinforced polymer

a

b

c

d

Fig. 17. Damage to laminated wood beams with finger joints without CFRP reinforcement: *a* — three-lamina face finger without CFRP reinforcement; *b* — five-lamina face finger without CFRP reinforcement; *c* — three-lamina face butt without CFRP reinforcement; *d* — five-lamina face butt without CFRP reinforcement
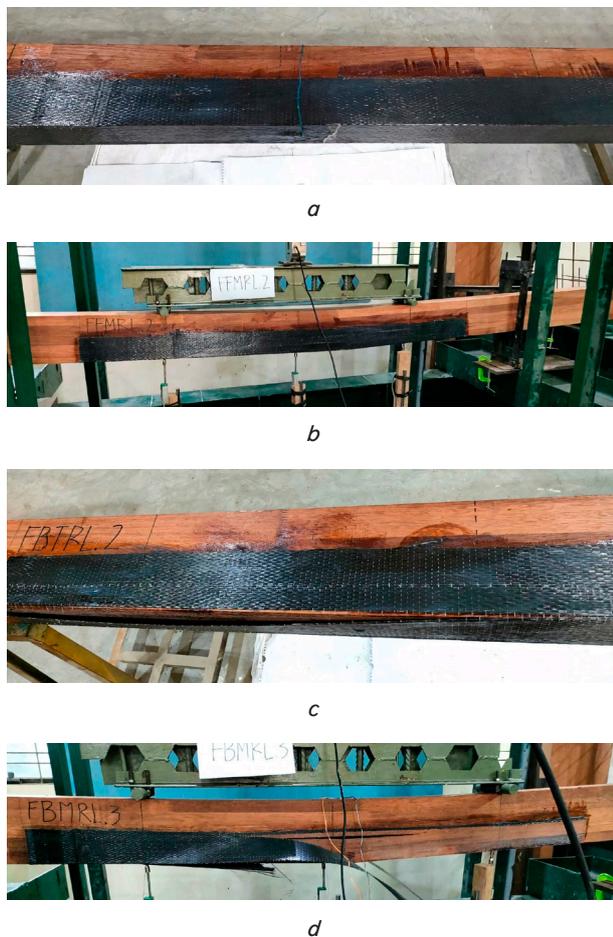
Fig. 18. Damage to laminated wood beams with finger joints reinforced with CFRP: *a* — Three-lamina face finger with CFRP reinforcement; *b* — Five-lamina face finger with CFRP reinforcement; *c* — Three-lamina face butt with CFRP reinforcement; *d* — Five-lamina face butt with CFRP reinforcement

Fig. 18 illustrates that the use of laminated finger-jointed timber beams with CFRP reinforcement not only changes the mode of failure but also improves ductility. It has been proved that CFRP can completely stop the propagation of cracks and at the same time transfer the stress till the last moment when debonding occurs. The CFRP cutting from the wood substrate takes place only after very large deformation, thus giving the visual warning before total failure of the structure. The picture clearly shows that the placement of the joints and the CFRP reinforcement are the main factors to influence the course of failure of the structure. If CFRP had not been used, the structural failure would have been determined by the weak point of the finger joint in the tension area, which would give rise to a brittle failure pattern. The CFRP addition led to failure moving towards the compression area and thus the dramatic increase of ductility. In the end, the leading failure mode was defined as the wood-CFRP interface being separated, which resulted in a considerable improvement in post-peak performance and the guarantee of greater structural safety.

6. Discussion of the results of mechanical performance of finger-jointed laminated timber beams

The influence of CFRP reinforcement, joint orientation, and lamination number on the ultimate load capacity, maxi-

mum bending moment, and mid-span deflection is discussed based on the results presented in Table 3. The experimental research revealed that the application of carbon fiber reinforced polymer (CFRP) has dramatically enhanced the structural performance of finger-jointed laminated timber beams in terms of ultimate load, maximum bending moment, and ductility. The increase of ultimate load ranging from 27.4% to 48.8% and that of maximum moment going to 45.3% at the most serve as proof for the efficient load transfer from timber to CFRP, resulting in a significant improvement of the entire flexural performance. Such findings corroborate those of [9, 11], who found that over 30% increase in bending capacity and stiffness was achieved in finger-jointed glulam beams reinforced with CFRP. Besides, the deflection at mid-span which increased 6.5–51.4%, is a measure of ductility improvement and thus beam can sustain larger deformations before its failure, as [13] have also evidenced for FRP-reinforced laminated timber beams.

The increase in flexural performance seen is due to the combining of different physical mechanisms, which are the changing of the finger joint configuration, the number of laminas, and the area of CFRP reinforcement. In the case of unreinforced finger-jointed laminated timber beams, there is a stress concentration occurring in the joint area due to the discontinuity in material, as well as the adhesive interfaces. This leads the cracking process to be the most tedious in the tension zone, to be the kind of brittle failure that is controlled by the weakness at the joints. The external CFRP reinforcement is utilized to change the internal stress distribution by taking up the role of an extra tensile element on the tension side of the beam. It is said that CFRP support has been able to attenuate the stress concentration at the finger joint, postpone the formation of cracks, and take the cracks longer to grow. This means that the beam can bear up to a point ready load and will take longer even to be deformed in the failure process. Performance gains can be linked to better stress transfer within the wood–adhesive-CFRP system and in addition, the stress homogeneity effect brought about by the integration of laminate layers. The latter effect will help the local defects and joint irregularities to be less severe and in turn, the system will be more rigid and reliable. The combining of these mechanisms explains the rise in flexural strength, ductility, and failure behavior of Merbau finger-jointed laminated wood beams that were studied.

The effects of joint orientation, number of laminations, and CFRP reinforcement on flexural strength and stiffness are discussed with reference to the MOR and MOE results shown in Fig. 14. The arrangement of joints and the number of laminations together influenced the mechanical response remarkably. After the application of CFRP reinforcement, the beams with face-butt joints exhibited the highest modulus of elasticity (MOE) of 20.46 GPa, which was an 8.8% increase over the unreinforced samples. On the contrary, beams with face-finger joints reached the highest modulus of rupture (MOR = 48.30 MPa) which was a 46.4% increase due to the excellent distribution of stress and bonding at the wood-CFRP interface [8]. On the other hand, the influence on stiffness was not linear, which could be due to the complex inter-laminar interactions and adhesive behavior; this was pointed out by [6, 16] in a similar way.

The numerical values of modulus of elasticity (MOE) and modulus of rupture (MOR) reveal a significant difference in the mechanical performance of the beam configurations under test. The difference in MOR values is more pro-

nounced than that of MOE, suggesting that flexural strength is more susceptible to varying joint orientation and number of laminations than elastic stiffness. In general, beams with face-butt joint orientation have higher MOR values than the face-finger joint, and this can be attributed to the better stress transfer paths and lesser stress concentration in the joint area. All configurations of beams, both without and with CFRP reinforcement, showed an increase in the MOR values with the increase in the number of laminates from three to five layers. This is indicative of a stress homogenization effect, wherein tensile forces are distributed over more layers, thereby minimizing the impact of local defects and joint irregularities. The differences in MOE values between configurations, on the other hand, are small, which means that the global stiffness of the beams is predominantly determined by the elastic properties of the wood and the overall cross-sectional geometry.

The load-deflection behavior of the laminated beams is interpreted based on the response curves presented in Fig. 15, 16. The third research objective was focused on the load-deflection relationship which illustrated that all the unreinforced beams displayed linear elasticity until about 15 mm of deflection when there was a sudden drop in load at failure, especially in the case of the face-finger configuration, which was indicative of brittle fracture. Conversely, the face-butt joint exhibited a post-peak response that was slower and thus afforded better load redistribution and consequently exhibited more ductile failure [8, 14]. The incorporation of CFRP reinforcement not only increased the load-deflection curves' stability but also prolonged the pseudo-plastic phase, during which the greatest loads were achieved at deflections of 30–45 mm and were in the range of 35–38 KN. The mode of failure was switched from brittle rupture at the finger joints to controlled delamination along the CFRP-timber interface, thereby slowing down crack propagation and improving overall load transfer [10].

To sum up, the bonding of haphazardly distributed block-type finger joints reinforced with external CFRP in tropical hardwoods such as Merbau revealed a considerable chance to manufacture high-quality engineered timber products from industrial wood by-products. This result endorses that modern laminated timber composites can be still classified as eco-friendly and structurally efficient materials for the future of construction, thus facilitating the global transition to low-carbon and renewable building materials [1, 2].

The utilization of finger-jointed Eucalyptus globulus bonded with 1C-PUR adhesive has led to the development of a new wood type with remarkably high flexural strength (50–76 N/mm^2) depending on the geometry of the joint and the pressure inside the assembly [4]. This wood has exhibited significant potential as a material for high performance structural laminated wood products. On the other hand, the MOR values for CFRP-reinforced Merbau laminated beams in this research were found to be in the low to medium range of those reported for hardwood-based systems. This result is an indirect reflection of the quality of finger joints made and the block assembly configurations used during the experiment. A study done on the Northern hardwoods [16] shows a dramatic range of laminated areas made from white ash, yellow birch, and white oak, that can reach characteristic tensile strengths of up to 36.4 MPa, 33.6 MPa, and 35.8 MPa respectively. Full size Glulam beams with optimized finger-joint profiles could exhibit flexural strengths of up to 47.0 MPa (white ash) and 41.6 MPa (yellow birch), demonstrating a significant potential for glulam structural applications. Being in another example, the tropical hybrid CLT consisting Acacia mangium with bamboo core has exhibited superior mechanical properties with an MOE of 21.83 GPa, which is approximately 2.76 times higher than SPF CLT (7.91 GPa), and an MOR of 39.41 MPa as compared to 28.60 MPa for SPF CLT, thus confirming that bamboo boards used as the core layer play a major role in enhancing the stiffness and flexural capacity of the CLT system [18].

The findings of this study indicate that the combination of finger joint optimization, number of laminations, and CFRP reinforcement has the potential to improve the structural performance of engineered wood beams made from wood industry waste. The use of block-assembled beams with random finger joint placement reflects actual manufacturing conditions and supports the practical application of this approach.

This study's findings can be utilized in structural parts like floor and roof beams of low to medium wood buildings, especially under indoor short-term static loading conditions, provided that the right adhesive is chosen and adequate environmental protection is in place to guarantee structural durability. The current study has not been carried out without its fair share of limitations, one such being that it focused only on the four-point bending test in the short term and under controlled lab conditions. Other factors like creep, fatigue, cyclic loading, temperature and humidity changes, adhesive aging, and the inherent differences in Merbau wood were completely ignored. Furthermore, the study employed just a single CFRP and epoxy system, which means that the findings are not readily transferable to other reinforcing materials or adhesives. It is important to carry out further investigations to assess the long-term performance under environmental exposure and cyclic loading, one such method being the use of numerical modeling and digital image correlation to study stress distribution. Hybrid reinforcement systems (CFRP-GFRP), finger joint geometry optimization for hardwoods, and the use of bio-based adhesives are further areas that require exploration in order to produce eco-friendly wood composites that are high in performance.

7. Conclusion

1. The experiment's results definitively showed that the CFRP reinforcement on the outside greatly enhanced the bending performance of finger-jointed laminated Merbau timber beams. The load's ultimate capacity was raised by 27.4–48.8%, while the maximum bending moment increased by 31.8–45.3% when compared to the unreinforced specimens. This enhancement is an unmistakable sign of CFRP's ability to handle tensile stress and inhibit crack growth in the finger-joint area, thus resulting in the overall rise in structural capacity and ductility.

2. The orientation of finger joints, the number of laminations, and the CFRP reinforcement have a very significant effect on the mechanical behavior of laminated wood beams. The effect of CFRP reinforcement on wood with face-finger configuration is that it has the highest modulus of rupture (MOR) of 48.30 MPa-increased by 46.4% as compared to the un-reinforced one. However, the face-butt configuration with CFRP reinforcement has the highest modulus of elasticity (MOE) of 20.46 GPa, which is an 8.8% increase in the stiffness of the section. The flexural strength was also raised by 18.9% when three laminations were increased to five; this

indicates that the stress distribution and section homogeneity were improved. The research, in general, identifies the joint orientation, laminate number, and CFRP reinforcement as major factors for the improvement of laminated timber beams' structural performance.

3. The load-deflection curves indicated that all beams exhibited linear elastic behavior up to a deflection of 15 mm, after which the unreinforced beams lost their load-carrying capacity suddenly, particularly the beam with a face-finger configuration. In contrast, the CFRP-reinforced beams showed pseudo-plasticity for a longer time and thus reached the maximum loads of 35–38 KN at the deflections of 30–45 mm, which is indicative of increased ductility and energy absorption. The failure mode in unreinforced beams changed from brittle tension rupture to controlled delamination and gradual crack propagation along the CFRP-timber interface, thus indicating a more favorable and safer structural behavior.

The considerable increase in flexural strength resulting from joint configuration, lamination number, and CFRP reinforcement is nevertheless affirmed throughout the quantitative results. However, the strengthening mechanisms proposed in this research, besides the previously stated, are to a limited extent by a direct stress distribution analysis or detailed material-level investigations. Hence, the conclusion is, to a large degree, based on experimental-based mechanistic interpretation at the structural level, while further numerical and microstructural studies are suggested to quantitatively validate the underlying stress transfer mechanisms.

Conflict of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Authors' contributions

Lilis Nurhayati: Conceptualization, Methodology, Investigation, Writing – Original Draft; **Sri Murni Dewi:** Supervision, Validation, Review & editing; **Wisnumurti:** Data curation, Formal analysis; **Devi Nuralinah:** Visualization, Project administration.

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