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Flexural Performance of Glued Laminated Timber Beams Reinforced with Externally Bonded FRP: An Experimental Investigation

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Abstract: The use of hard timber in construction is increasing, but it is quite expensive and its production is slow. As an alternative, laminated timber combining hard and soft quality timber has been proposed. This study utilized rambutan timber (hardwood) and sengon timber (softwood). Structural failure may occur when elements can no longer resist the applied loads; thus, reinforcement is required. This study aims to investigate the flexural strength of laminated timber beams and assess the performance enhancement using a fiber-reinforced polymer (FRP) type SCH-11UP. Composite was applied through the Externally Bonded (EB) method. The flexural capacity was evaluated in accordance with ASTM D143 through four-point bending tests and SNI 7973:2013. Four types of test objects were tested with three samples per type: TP (unreinforced), EB1 (type 1), EB2 (type 2), and EB3 (type 3), with TP as the control group. The experimental results showed that EB3 yielded the highest improvement, with up to 87% increase in the maximum load capacity, displacement, modulus of elasticity (MOE), modulus of rupture (MOR), stiffness, and structural efficiency. The improvements followed in descending order: EB2, EB1, and TP.

Keywords: externally bonded, fiber reinforced polymer, laminate, timber

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1. Introduction

Timber is a natural resource widely utilized across various industries, from small-scale enterprises to large-scale manufacturing industries. Forest plantations are continually expanding, introducing both native and exotic species through community forests, social forestry and industrial plantations. Therefore, understanding timber properties is critical for stakeholders in the timber processing and construction sectors [1]. The physical and mechanical properties of timber are essential for timber design. Among the most commonly monitored physical properties are moisture content and density, whereas flexural strength is a key mechanical property. Flexural strength represents a timber's capacity to resist bending, whereas compressive strength reflects its ability to withstand axial forces in specific applications [2]. According to SNI 7973:2013, glued laminated timber (glulam) is an engineered timber product made from stress-graded lumber that is precisely prepared and bonded using adhesives. Structural strengthening is typically performed to prevent damage or failure of structures [3]. Retrofitting is necessary when structural degradation compromises technical requirements, including strength, stiffness, ductility, stability, and serviceability [4]. The modulus of elasticity (E), as defined by SNI 7973-2013, is a measures a material's ability to resist deformation within its elastic limit. The greater the load, the higher the resulting stress and deformation, up to the elastic threshold [3].

Fiber-reinforced polymer (FRP) is a modern composite material frequently employed as an external reinforcement owing to its ability to enhance ductility in otherwise brittle structures [5]. This study uses the Externally Bonded (EB) technique, where FRP plates are adhered to the outer surface of timber. The EB method offers several advantages, including ease of installation, reduced stress concentrations, improved ductility, and minimal impact on the structural system [6]. Based on this background, this study was conducted to investigate the physical and mechanical properties of sengon and rambutan timbers, determine the flexural capacity of laminated timber beams, and evaluate the strengthening effect of FRP with varying EB-application widths.

2. Methods

2.1. Materials

This study employed various tools and materials during the testing process. The specimens were categorized into control and experimental groups. Control specimens were used to assess the physical and mechanical properties of these materials. Physical tests included moisture content and density measurements, while mechanical tests included compression parallel and perpendicular to the grain. According to SNI 7973-2013, the specimen dimensions for the physical tests were 5 cm × 5 cm × 5 cm, with 10 samples each. For mechanical tests, the dimensions were 5 cm × 5 cm × 20 cm for compression parallel to the grain, and 5 cm × 5 cm × 15 cm for perpendicular compression [3].

Flexural tests were conducted on laminated timber beams composed of sengon and rambutan timber bonded with a polyurethane adhesive (PU). The lamination sequence (from bottom to top) was rambutan – sengon – sengon–rambutan, with each piece measuring 3.8 cm × 2 cm × 75 cm. Thus, the resulting laminated beam measured 3.8 cm × 8 cm × 75 cm. **Figure 1** shows the beam.

Figure 1. Laminated Beam (TP Specimen)

The reinforcement material used was SCH-11UP Fiber Reinforced Polymer (FRP) with tensile strength and tensile modulus of 4.0 Gpa and 240 GPa, respectively, produced by PT. Fyfe Fibrwrap Indonesia. The FRP was applied using three different EB configurations, resulting in four timber beam types for flexural testing, as illustrated in **Figure 2.**

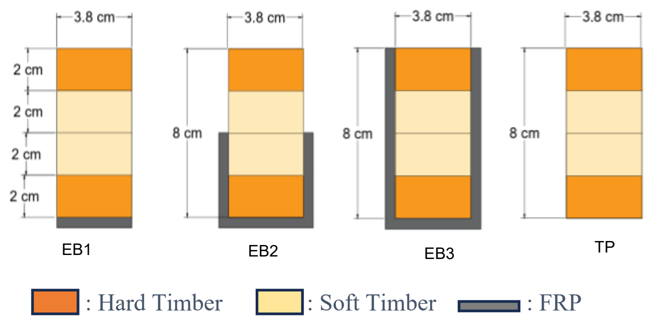


Figure 2. FRP Application Types

Flexural tests were conducted using a Universal Testing Machine (UTM) with a 2-ton capacity, equipped with a load cell and displacement gauge. The testing procedure followed PN-EN 408 + A1:2012 "Timber Structures – Structural Timber and Glued Laminated Timber.” The test setup is illustrated in **Figure 3.**

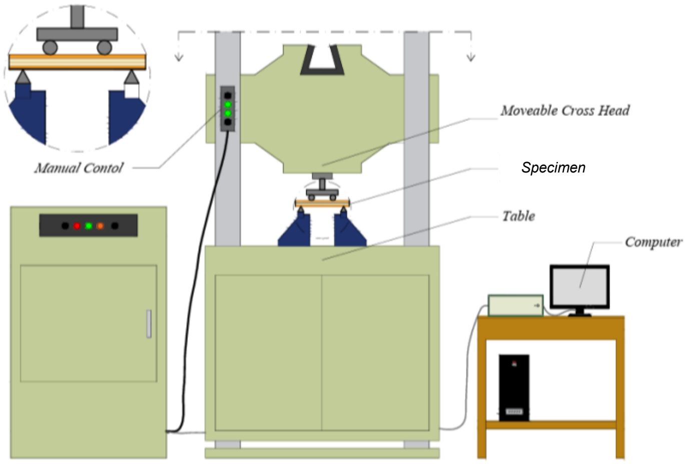


Figure 3. Flexural Test Setup

2.2. Research Procedure

The study began with a literature review, gathering and analyzing relevant journal articles and standards. The research workflow is summarized in **Figure 4**.

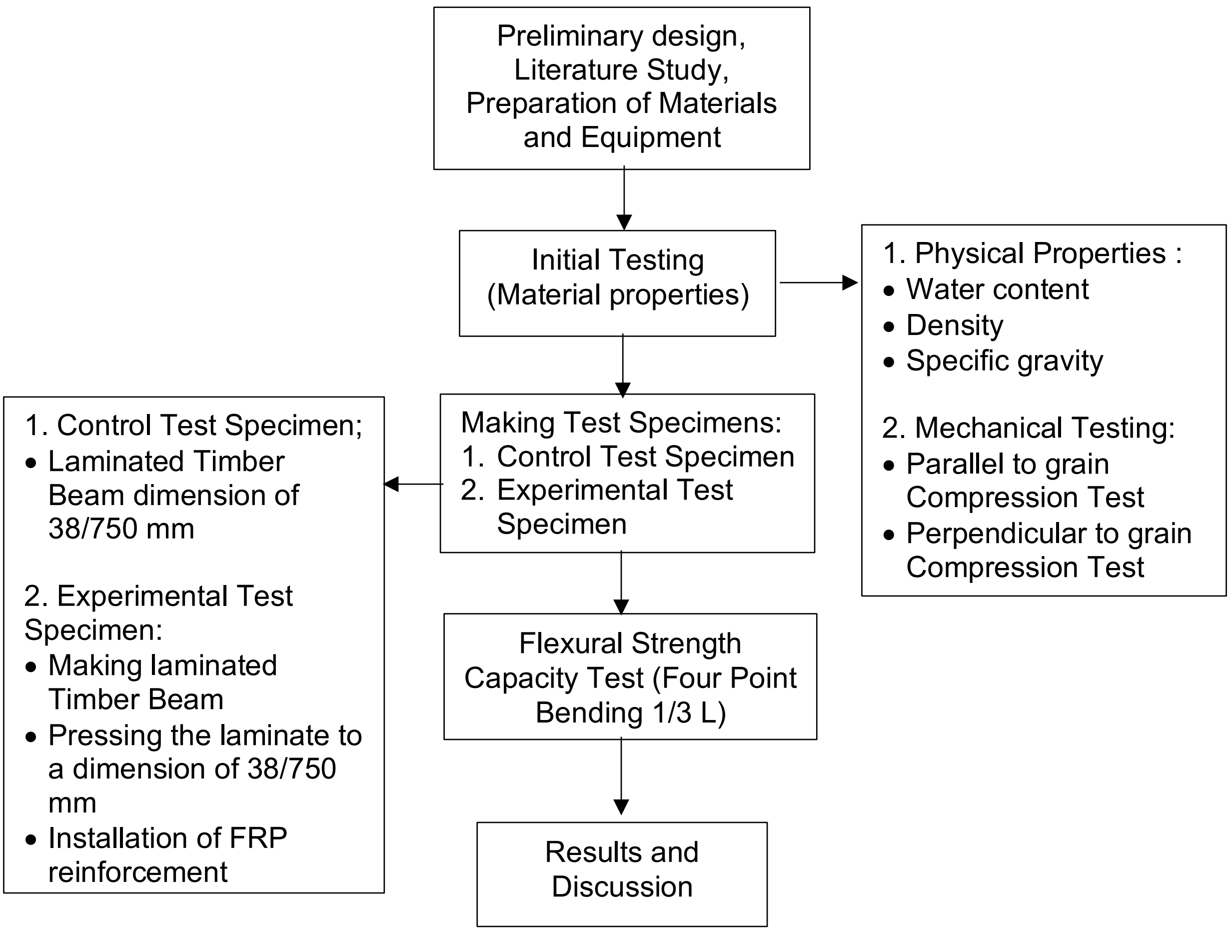


Figure 4. Research Procedure

2.3. Physical Properties of Timber

The physical properties of timber include moisture content, density, shrinkage, and specific gravity (SG) [8]. In this study, the evaluated physical properties were moisture content and specific gravity. According to the Indonesian Standard SNI 7973-2013, the moisture content of timber used for structural purposes should be below 30% [3]. The moisture content test aims to determine the amount of water in timber by comparing the mass of the specimen before and after oven drying. The moisture content (MC) was calculated using Equation (1):

$$\text{Moisture content (\%)} = \frac{BB - BK}{BB} \; x \; 100 \qquad (1)$$

where :
$W_{initial}$ = weight before oven-drying (g)
W_{oven} = weight after oven-drying (g)

Based on ASTM D4442-92, the specific gravity of timber is typically determined at a moisture content of m% (where m should be less than 30%) [9]. The following equations are used to determine specific gravity

a. Density at current moisture content (ρ), as expressed in Equation (2)

$$\rho = \frac{BA}{V} \qquad (2)$$

where:
W = mass of specimen (g)
V = volume of specimen (cm³)

b. Specific gravity at *m%* moisture content (G_m) is calculated using Equation (3):

$$Gm = \frac{\rho}{1000 \; x \left(1 + \frac{m}{100}\right)} \qquad (3)$$

c. Basic specific gravity (G_b) is calculated using Equation (4) :

$$G_b = \frac{Gm}{1 + 0{,}265 \; x \; \alpha \; x \; Gm} \qquad (4)$$

$$\alpha = \frac{30 - m}{30}$$

d. Specific gravity at 15% moisture content (G_{15}) is calculated using Equation (5):

$$G_{15} = \frac{Gb}{1 - 0{,}133 \; x \; Gb} \qquad (5)$$

2.4. Mechanical Property Testing

The mechanical properties assessed in this study included the compressive strength parallel to the grain, compressive strength perpendicular to the grain, and shear strength parallel to the grain. According to ASTM D143-2008, the compressive strength of timber depends on the orientation of the timber fibers relative to the direction of the applied force [10]. The ultimate compressive stress (σult) was calculated using Equation (6):

$$\sigma_{ult} = \frac{F_{ult}}{A} \qquad (6)$$

where :
σ_{ult} = ultimate compressive stress (MPa or N/mm²)
F_{ult} = maximum applied load (N

A = cross-sectional area of specimen (mm²)

2.5. Flexural Strength Testing

The flexural strength test was conducted on the experimental beams following ASTM D198, Standard Test Methods of Static Tests of Lumber in Structural Sizes. A two-point bending test configuration was used. The Modulus of Elasticity (MOE) was calculated using Equation (7) [13], [14]:

$$MOE = \frac{Pa}{48\,\delta I} x\,(3L^2 - 4a^2) \quad (7)$$

The Modulus of Rupture (MOR) represents the bending stress at the extreme fiber (top or bottom) of the beam section farthest from the neutral axis at the point of failure [8], [15]. MOR is calculated using Equation (8).

$$MOR = \frac{3\,Pmax\,.\,a}{bh^2} \quad (8)$$

2.6. Stiffness and Structural Efficiency

The stiffness of the beam (k) was calculated using Equation (9)

$$k = \frac{P}{\delta} \quad (9)$$

where :
k = stiffness (N/mm)
P = applied load (N)
δ = mid-span deflection (mm)

The structural efficiency (λ) is defined as the ratio between the maximum moment capacity and the self-weight of the structural element. FRP reinforcement contributes significantly to structural efficiency, which is especially important in seismic-prone regions, where lightweight yet strong materials are preferred to minimize eccentricity from lateral loads [12]. The structural efficiency is calculated using Equation (10):

$$\lambda = \frac{Mmax}{w} \quad (10)$$

Where :
M_{max} = maximum moment capacity (N·mm)
w = self-weight of the structural element (N)

3. Result and Discussion

3.1. Physical Properties Test Results

Moisture Content

The results of the analysis of the moisture content of sengon and rambutan timbers are presented in **Tables 1 and 2**, respectively.

Table 1 Moisture Content of Sengon Timber

Object Code	Water Content (%)	Average (%)
BK-S1	15.49	14.98

Table 2 Moisture Content of RambutanTimber

Object Code	Water Content (%)	Average (%)
BK-R1	16.52	16.18

Object Code	Water Content (%)
BK-S2	15.12
BK-S3	14.14
BK-S4	14.35
BK-S5	14.56
BK-S6	14.71
BK-S7	14.75
BK-S8	14.92
BK-S9	16.02
BK-S10	15,76

Object Code	Water Content (%)
BK-R2	16.17
BK-R3	15.98
BK-R4	16.25
BK-R5	15.91
BK-R6	15.91
BK-R7	16.09
BK-R8	16.02
BK-R9	16.58
BK-R10	16.45

Density

The results of the analysis of the density of sengon and rambutan timber are presented in **Tables 3 and 4**, respectively.

Table 3 Density of Sengon Timber

Object Code	Before Oven-Drying		Density (kg/m^3)	Average (kg/m^3)
	Weight (gram)	Volume (cm^3)		
BK-S1	52.3	125	418.4	381.04
BK-S2	46.3	125	370.4	
BK-S3	49.5	125	396	
BK-S4	43.2	125	345.6	
BK-S5	47.4	125	379.2	
BK-S6	47.6	125	380.8	
BK-S7	46.1	125	368.8	
BK-S8	47.6	125	380.8	
BK-S9	48.7	125	389.6	
BK-S10	47.6	125	380.8	

Tabel 4 Density of Rambutan Timber

Object Code	Before Oven-Drying		Density (kg/m$^{3)}$	Average (kg/m^3)
	Weight (gram)	Volume (cm^3)		
BK-R1	120.4	125	963.2	942.08
BK-R2	116.2	125	929.6	
BK-R3	118.2	125	945.6	
BK-R4	120	125	960	
BK-R5	116.9	125	9352	
BK-R6	116.9	125	935.2	
BK-R7	116.8	125	934.4	
BK-R8	116.1	125	928.8	
BK-R9	118.2	125	945.6	
BK-R10	117.9	125	943.2	

Specific gravity

The results of the calculation analysis of the specific gravities of sengon and rambutan timbers are presented in **Tables 5 and 6,** respectively.

Table 5 Specific gravity of Sengon Timber

Object Code	Specific gravity (%)	Average (%)
BK-R1	0.317	0.331
BK-R2	0.317	
BK-R3	0.319	
BK-R4	0.319	
BK-R5	0.318	
BK-R6	0.318	
BK-R7	0.318	
BK-R8	0.318	
BK-R9	0.316	
BK-R10	0.316	

Tabel 6 Specific gravity of Rambutan Timber

Object Code	Specific gravity (%)	Average (%)
BK-R1	0.818	0.818
BK-R2	0.818	
BK-R3	0.818	
BK-R4	0.818	
BK-R5	0.818	
BK-R6	0.818	
BK-R7	0.818	
BK-R8	0.818	
BK-R9	0.818	
BK-R10	0.818	

The moisture content test was initiated by weighing the specimen before oven-drying for approximately 24 h at a temperature of 100°C, followed by weighing after oven-drying to obtain the dry weight. Based on the calculation using Equation (1), the moisture content of sengon was 14.98%, and that of rambutan was 16.18%. Density measurements were performed on the composite beams in their wet condition prior to oven-drying, as the flexural strength tests were conducted using laminated beam specimens in the same wet state. Based on Equation (2), the density of sengon was 381.04 kg/m3, and that of rambutan was 942.08 kg/m3. After conducting moisture content and density tests, the next step was to calculate specific gravity. Moisture content data were used to determine the actual specific gravity (Gm) of the specimens. The actual specific gravity (Gm) was then used to calculate the basic specific gravity (Gb), which was subsequently used to estimate the specific gravity at 15% moisture content (G15). Based on the calculations using Equations (3)–(5), the specific gravity of sengon was 0.331%, and that of rambutan was 0.818%. The obtained specific gravity values were used to calculate the modulus of elasticity, which allowed the classification of timber quality based on the Design Value and Reference Bending Modulus of Elasticity in accordance with SNI 7973:2013. Table 7 presents the reference modulus of elasticity and timber strength grades.

Table 7 Modulus of Elasticity and Timber Strength Classification of the Test Specimens

Timber Specimen	Modulus of Elasticity (E =16000$G^{0,17}$)	Timber Strength Grade Classification	Reference Modulus of Elasticity(E)
Sengon	7304,718	E7	7000
Rambutan	15463,189	E15	15000

3.2. Mechanical Properties Test Results

Test Results of Parallel to grain

Compressive Strength The compressive strength of sengon and rambutan timbers parallel to the grain is shown in **Tables 8 and 9**, respectively.

Table 8 Compressive Strength Test Results Parallel to grain Sengon Timber

Object Code	Maximum Load (N)	Compressive Strength (N/mm^2)	Average (Mpa)
SS-1	38300	16.0	
SS-2	38700	16.1	18.1
SS-3	51200	22.2	

Table 9 Compressive Strength Test Results Parallel to grain Rambutan Timber

Object Code	Maximum Load (N)	Compressive Strength (N/mm^2)	Average (Mpa)
SR-1	84700	36.8	
SR-2	75000	31.2	36.4
SR-3	94800	41.1	

Perpendicular to grain Test Results

The results of testing the compressive strength perpendicular to the grain of sengon and rambutan timbers are shown in **Tables 10 and 11**, respectively.

Table 10 Compressive Strength Test Results Perpendicular to grain Sengon Timber

Object Code	Maximum Load (N)	Compressive Strength (N/mm^2)	Average (Mpa)
TLS-1	53000	22.1	19.6
TLS-2	45600	18.2	
TLS-3	46000	18.4	

Table 11 Compressive Strength Test Results Perpendicular to grain Rambutan Timber

Object Code	Maximum Load (N)	Compressive Strength (N/mm^2)	Average (Mpa)
TLR-1	45200	19.6	27.3
TLR-2	75200	32.6	
TLR-3	74200	29.7	

Compression Strength Testing Results The parallel-to-grain compression strength test of the wood specimens yielded the maximum load capacity and the corresponding compressive strength values. Based on Equation (6), the average parallel-to-grain compressive strength of sengon was 18.1 MPa, whereas rambutan exhibited an average value of 36.4 MPa. Additionally, the average compressive strength of sengon in another set of tests was 19.6 MPa, whereas that of rambutan was 27.3 MPa.

3.3 Flexural Strength Test Results

The results of the flexural strength test are presented in the form of **Table 12.**

Table 12 Flexural Strength Test Results

Object Code	Max Flexural Strength (N)	Displacement (mm)
TP1	573.550	5.097
TP2	973.550	17.060
TP3	373.550	4.873
EB1a	1073.550	18.496
EB1b	873.550	15.219
EB1c	873.550	18.726
EB2a	4173.550	15.759
Eb2b	3473.550	15.331
Eb2c	4873.550	16.126
EB3a	5023.550	15.974
EB3b	4473.550	24.597
Eb3c	5573.550	14.832

Based on **Table 13**, the data on flexural strength and displacement when presented in graph form can be seen in **Figure 5**.

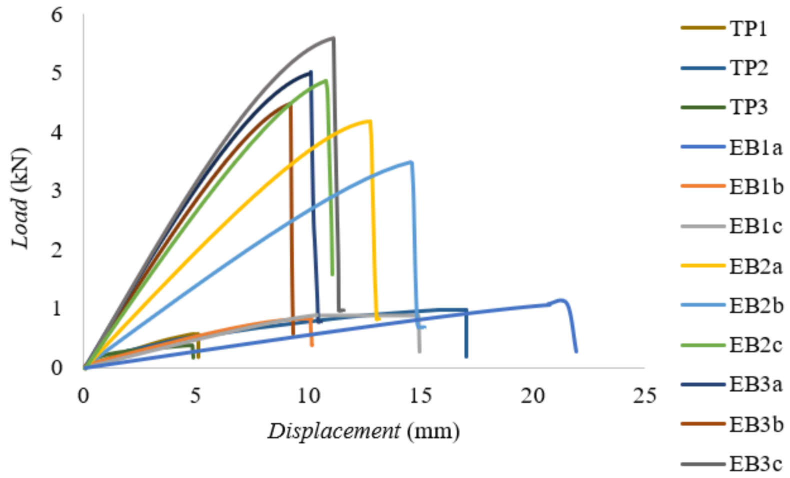


Figure 5 Load-Displacement Graph of Laminated Beams

The average value can be calculated based on the load-displacement results obtained. These results show the extent to which FRP can be compared to laminated beams with TP as the control variable. The average comparison is shown in **Table 14** and **Figure 6**.

Table 14 The Average Flexural Strength Test Results

Object Code	Max Flexural Strength (N)	Displacement (mm)
TP	640.217	9.010
EB1	940.217	11.978
EB2	4173.550	12.752
EB3	5023.550	10.143

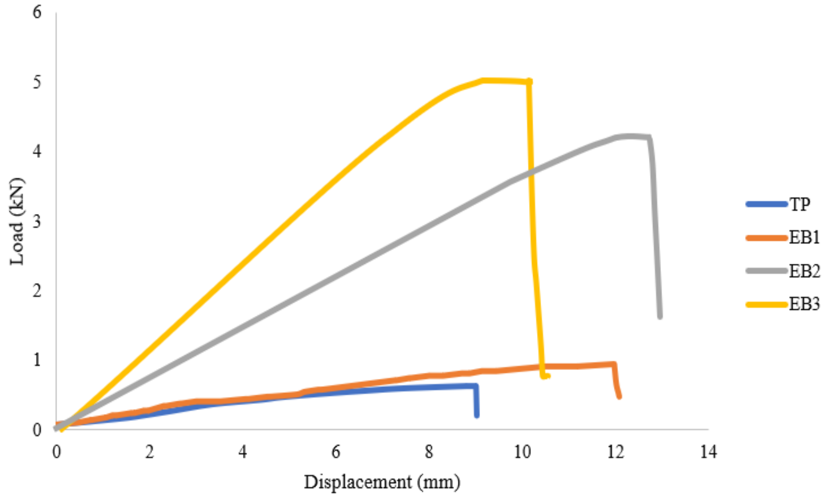


Figure 6 Graph of Test Results of Laminated Beams Without FRP Reinforcement and with FRP

According to the results presented in **Table 16** and **Figure 6**, the average maximum load sustained by the unreinforced laminated timber beams was 640.217 N. After reinforcement with FRP, the EB3 specimen withstood an average maximum load of 5023.550 N, representing an increase of approximately 87%. The average maximum deflection (displacement) of the unreinforced timber beams was 9.01 mm, whereas the reinforced laminated timber beams exhibited an average displacement of 10.143 mm, indicating an 11% increase.

3.4. Flexural Strength Parameters

Flexural strength testing was conducted in the laboratory with 12 laminated beam samples to obtain data on flexural strength and displacement. The data were then analyzed to determine the maximum value for each sample. Based on these data, the research continued by reanalyzing the data to calculate several other review parameters, including load-deflection graph data, flexural elasticity (MOE), modulus of rupture (MOR), flexural stiffness, and structural efficiency. The results of the data analysis are presented in **Table 15.**

Table 15 Parameter Analysis Results of Flexural Strength

Object Code	MOE (MPa)	MOR (Mpa)	Stiffness (k)	Efficiency (λ)
TP	281.1	1.80	82.10	41.50
EB1	273.8	2.61	79.94	596.96
EB2	1156.7	1156.70	337.69	2649.90
EB3	1694.6	13.94	494.75	3189.50

3.5. Effect of FRP Reinforcement Laminated Beams

The results of the comparative analysis between laminated beams without FRP reinforcement and laminated beams with FRP reinforcement were reviewed based on several observations. The review parameters can be used to determine the extent of improvement in laminated beams with FRP reinforcement based on Equations (7)–(10). The review is used as a material that will be compared with the laminated beams without reinforcement. The reviews that have been tested and the results of the analysis are presented in **Tables 16**, **17**, and **18**.

Table 16 Calculation of Improvement Without FRP Reinforcement and FRP type EB1

Parameters	TP	EB1	Improvement (%)
Load (N)	640.217	940.210	32%
Displacement (mm)	9.010	11.978	25%
MOE(MPa)	281.147	273.810	-3%
MOR (MPa)	1.777	2.610	32%
Stiffness (k)	82.083	79.942	-3%
Eficiency (λ)	41.450	596.960	93%

Table 17 Calculation of Improvement Without FRP Reinforcement and FRP type EB2

Paramaters	TP	EB2	Improvement (%)
Load (N)	640.220	4173.550	85%
Displacement (mm)	9.010	12.752	29%
MOE(MPa)	281.150	1156.660	76%
MOR (MPa)	1.777	11.584	85%
Stiffness (k)	82.083	337.690	76%
Eficiency (λ)	41.450	2649.87	98%

Table 18 Calculation of Improvement Without FRP Reinforcement and FRP type EB3

Paramaters	TP	EB3	Improvement (%)
Load (N)	640.200	5023.550	87%
Displacement (mm)	9.010	10.143	11%
MOE(MPa)	281.100	1694.580	83%
MOR (MPa)	1.777	13.943	87%
Stiffness (k)	82.080	494.749	83%
Eficiency (λ)	41.450	3189.550	99%

The use of fiber-reinforced polymers (FRP) has a significant effect on the strengthening of laminated timber beams. A notable difference was observed between the beams strengthened with FRP and those without reinforcement. The maximum load capacity (EB3) increased by 87%, displacement increased by 11%, and Modulus of Elasticity (MOE) of unreinforced timber beams was 281.100 MPa, whereas the MOE of FRP-reinforced laminated timber beams reached 1694.580 MPa, reflecting an increase of 83%. The Modulus of Rupture (MOR) for unreinforced beams was 1.777 MPa, while the MOR of the EB3 reinforced beam reached 13.943 MPa, showing an 87% improvement. The stiffness of the unreinforced beams was 82.8 MPa, and the stiffness of the FRP-reinforced laminated beams was 494.749 MPa, which is an increase of 83%. The structural efficiency of the unreinforced beams was calculated to be 41.882, whereas the FRP-reinforced laminated beams achieved a structural efficiency of 3189.555, indicating a 99% enhancement. These results indicate that the highest improvements in the maximum load capacity, displacement, MOE, MOR, stiffness, and structural efficiency were observed in the beams reinforced with FRP (EB3). The next most effective reinforcements were found in EB2, followed by EB1, with the smallest increase. The application of FRP significantly influenced the failure mechanism of the beams, demonstrating the effects of FRP width and size on the structural performance. Bonding FRP to the tensile side (bottom surface) of the beam allowed for better stress absorption and elongation, resulting in a notable increase in the load-bearing capacity and overall flexural performance of the laminated timber beams.

3.6. Classification of Damage Patterns

In this study, the grouping of structural failures was based on ASTM D143 [11]. The criteria for static bending flexural failures of beams with a four-point loading test specimen model consist of several classifications, depending on the condition of the timber surface cracks. The beam failure classification is shown in **Figure 7**.

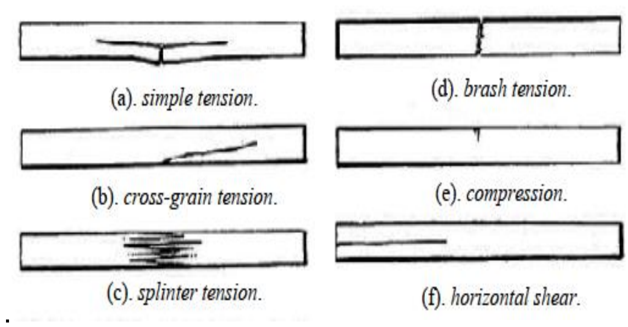


Figure 7 Failure Classification according to ASTM D143 [11]

Testing was performed on each laminated beam at the speed and settings set on the computer so that the UTM tool operated according to the settings. When a certain load is reached, the timber beam will fail because it is no longer able to withstand the force, and the failure will be classified according to

ASTM D143 [11].

The classification of cracking patterns was first performed on test specimens without reinforcement or test specimen code TP with three pieces. The results of the cracking pattern and its classification will be shown in **Table 19**, **20**, **21** and **22**

Table 19 Classification Results of Crack Patterns without Reinforcement FRP (TP)

Crack Patterns of Test Objects	Classification of Crack Types
 TP1	 *Simple Tension*
 TP2	 *Simple Tension*
 TP3	 *Simple Tension*

Table 20 Classification Results of Crack Patterns Reinforcement FRP EB1

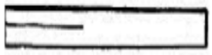
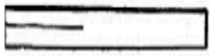
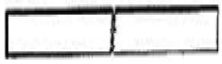
Crack Patterns of Test Objects	Classification of Crack Types
 EB1a	 *Cross-Grain Tension*
 EB1b	 *Horizontal Shear*
 EB1c	 *Horizontal Shear*

Table 21 Classification Results of Crack Patterns Reinforcement FRP EB2

Crack Patterns of Test Objects	Classification of Crack Types
 EB2a	 *Simple Tension*
 EB2b	 *Simple Tension*
 EB2c	 *Simple Tension*

Table 22 Classification Results of Crack Patterns Reinforcement FRP EB3

Crack Patterns of Test Objects	Classification of Crack Types
 EB3a	 *Simple Tension*
 Eb3b	 *Splinter Tension*
 EB3c	 *Brash Tension*

Failure Mechanisms of Laminated Timber Beams In the TP specimen, the initial crack appeared in the bottom layer. As the applied load increased, the crack propagated in length and width, followed by cracking in the middle layer, compressive failure in the top layer, and, ultimately, fracture of the bottom layer. EB1 specimen, the initial crack occurred in the middle layer of the specimen. As the load increased, the cracks grew longer and wider. This was followed by cracking in the bottom layer above the FRP, compressive failure in the top layer, and delamination between the middle layers of the strengthened beams. The failure progressed until the specimen reached its ultimate load. EB2 specimen, the initial crack appeared in the middle layer. With increasing load, the cracks propagated and led to the end splitting of the sengon timber. This was followed by cracking in the bottom layer above the FRP and compressive failure in the top layer. EB3a specimen, the initial crack occurred in the middle layer. As the load increased, the crack widened and propagated, followed by cracking in the bottom layer and compressive damage in the top. Delamination was observed between the middle and bottom layers. EB3b specimen, the initial crack also appeared in the middle layer of the specimen. As the load increased, it was followed by cracking in the bottom layer, eventually tearing the FRP reinforcement and compressive failure in the top layer. Delamination also occurred between the middle and bottom layers. For the EB3c specimen, the initial crack again initiated in the middle layer. As the load increased, the crack extended and led to the fracture of the bottom layer, including tearing of the FRP and compressive failure in the top layer, culminating in the complete rupture of the wood. In addition, delamination occurred between the middle and top layers. The damage in this specimen progressed until the ultimate load was reached.

4. Conclusion

Based on the research and data analysis that has been carried out, a fiber-reinforced polymer (FRP) affects the reinforcement of laminated timber. A significant comparison occurred in beams reinforced with FRP with no FRP, for maximum load increased 32%-87%; displacement increased 11-29%; MOE value increased 75%-83% but there was a decrease in type EB1 by 3%; MOR value increased 31%-87%; stiffness increased 76%-83% but there was a decrease in type EB1 by 3%; and beam efficiency increased 93%–99%. There was an increase in capacity both in terms of the maximum load that the beam can withstand, displacement, MOE value, MOR value, stiffness, and structural efficiency of the four types of beams, it can be seen that the biggest increase occurred in beams with FRP reinforcement type 3 or EB3. Furthermore, the sequential increase after EB3 is EB2 and the smallest increase is in EB1. There are several types of collapse that occur in laminated beam structures based on the classification according to ASTM D143. The cracks that occur include simple tension, cross-grain tension, horizontal shear, splinter tension and brash tension.

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