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Research Article

Experimental investigation on the correlation between specific gravity and bending properties of tropical timber species

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Abstract

This study investigates the relationship between specific gravity and the flexural properties of twelve tropical wood species with specific gravities ranging from 0.39 to 0.67. An experimental approach was employed to determine three-point bending properties under air-dry or normal moisture conditions in accordance with ASTM D143-22. Bending load–deflection curves were obtained from flexural tests, and regression analysis was performed to develop empirical equations describing the relationships between specific gravity and bending properties. The results demonstrate a significant correlation between specific gravity and wood bending strength, particularly at the proportional limit load and ultimate limit load (modulus of rupture). The consistently low p-values of the developed equations indicate that specific gravity has a statistically significant effect on the flexural mechanical properties of wood. Although the proposed models do not fully account for the inherent variability of wood arising from factors such as tree age, grain orientation, temperature, moisture content, and other natural variations, they effectively describe the overall trends observed in the experimental data. Bending strength can support the design of flexural members using the Load and Resistance Factor Design method, while modulus of rupture can be applied in designs based on the Allowable Stress Design method. The developed empirical equations provide useful predictive relationships between specific gravity and flexural properties and may assist engineers and researchers during the early stages of timber grading. A limitation of this study is the variation in grain angle, which may have contributed to the observed variability in bending strength and modulus of rupture.

1. Introduction

Bending parameters in terms of bending strength (F_b) and modulus of rupture (MOR), are critical mechanical properties used in the design and analysis of flexural members in timber structures [1, 2, 3], such as beams in wooden frame systems and girders in timber bridges. These parameters govern the load-carrying capacity, stiffness, and failure behavior of timber elements subjected to bending loads. The research hypothesis is that there is a significant correlation between the specific gravity and the bending mechanical properties of wood.

This study aims to investigate the relationship between specific gravity and both bending properties bending properties for tropical wood species with a specific gravity range of 0.39 to 0.67. This research employed an experimental methodology to acquire empirical data regarding

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the three-point bending mechanical properties. Regression analysis was then conducted to develop an empirical equation and investigate the correlation between bending properties and specific gravity.

The bending load-deflection curves are compiled from the results of flexural tests of twelve tropical wood species, namely red meranti (*Shorea parvifolia*), white meranti (*Shorea montigena*), padi meranti (*Shorea venulosa*), akasia mangium (*Acacia mangium*), gunung (*Dipterocarpus retusus*), yellow meranti (*Shorea faguetiana*), meranti bunga (*Shorea leprosula Miq.*), kamper sumatra (*Dryobalanops aromatica*), meranti (*Shorea macrobalanos*) keruing (*Dipterocarpus*), kamper (*Cinnamomum camphora*), and kamper kalimantan (*Dryobalanops lanceolata*). The tests were conducted using the three-point bending test method in accordance with ASTM D143-22 [4]. The number of test objects for each species is three specimens. All specimens were made in air-dry or normal moisture content (MC) conditions, ranging from 12% to 18%.

The novelty of this research lies in the development of empirical equations that explicitly account for the influence of specific gravity when predicting bending strength and modulus of rupture of tropical wood species with specific gravities between 0.39 and 0.67. The proposed models are based on a locally derived experimental dataset from selected tropical wood species, providing prediction equations that are specifically applicable to these materials.

2. Previous Research

Armstrong et al. [5] analyzed literature data and reported regression relationships between specific gravity and mechanical properties, including MOR. The results showed that the exact form of the relationship depends on whether the wood is tested green or air-dry, indicating that moisture state modifies the slope and intercept of density–strength models. A study on tropical woods reported specific gravity values ranging from 0.36 to 1.18 and noted a close relationship between specific gravity and mechanical properties, consistent with earlier findings [6]. Tropical hardwoods often have higher density than many temperate softwoods, and this tends to be reflected in higher bending strength.

Flexural testing using the three-point bending test method is highly influenced by the accuracy of the results, especially with the determination of the test point. The test speed has been designed to accommodate tests with the load point in the middle of the span [7]. Yoshihara and Fukuda [8] conducted research by varying the load point conditions and studying the flexural mechanical properties of yellow poplar wood. The results showed that when the specimen had a high depth/span ratio, the strength increased with the increase in the radius of the loading nose.

Green et al. [9] and Ross [10] described in the classical Wood Handbook (USDA Forest Products Laboratory) that static bending strength increases with specific gravity according to power-law relationships for both softwoods and hardwoods. For clear, straight-grained wood at 12% moisture content, MOR is expressed as a function of specific gravity with exponents of about 1.01 for softwoods and 1.13 for hardwoods, indicating a strong positive dependence of bending strength on density-related characteristics. The same source also shows similar density-based relationships for other properties such as modulus of elasticity and work to maximum load, reinforcing the view that specific gravity is a primary predictor of wood mechanics.

Flexural testing using the three-point bending test is a standard method for obtaining empirical data on the mechanical properties of wood. The modulus of elasticity (MOE), modulus of rupture (MOR), and bending strength (F_b) are some of these mechanical characteristics. This method is not only used for destructive testing on solid wood specimens, but can also be used on engineered wood specimens. Research by Song and Hong [11] demonstrated that the flexural testing method can be used to study the mechanical properties of engineered cross-laminated timber. Pereira et al. [12] also conducted research on the flexural testing of engineered laminated veneer lumber and oriented strand board panels using static bending tests. Vida et al. [13] also conducted a flexural test study to estimate the flexural mechanical properties of glue-laminated engineered wood. Siegel [14] showed that the three-point test method can be used for veneer-based engineered wood.

Static flexural testing actually does not only use the three-point bending method, there is also another method, namely the four-point bending test with the aim of obtaining the span area of the beam that experiences pure bending, in order to determine the bending strength and the modulus of rupture parameters. Hein and Brancheriau [15], through their research, conducted a comparative test of the two methods with the result being an empirical correlation equation between the MOR obtained with the two test methods.

França et al. [16] examined Southern yellow pine samples across several decades and found that the relationship between specific gravity and static bending MOR was moderate but significant, with coefficients of determination (R^2) ranging from 0.41 to 0.50 for different sample groups. Their results are important because they show that specific gravity alone explains a meaningful portion of bending-strength variation, but not all of it. In practical terms, this means specific gravity is useful for strength estimation, though prediction improves when it is combined with stiffness-related variables such as MOE.

3. Methods

3.1 Experimental Tests

This research aims to investigate the relationship between specific gravity and bending properties of tropical timber species. Specimens with dimensions of 50 mm (width) by 50 mm (thickness) by 400 mm (length) were prepared in accordance ASTM D143-22 [4]. ASTM D143-22 specifies standard procedures for testing the bending properties of small clear wood specimens [4]. Table 1 displays the specification of the specimens used in the experimental tests. All specimens were prepared from air-dried timber with a moisture content ranging between 12% to 18%, in accordance with standard practice [1, 3].

Table 1. Specification and species of timber that are used in research

No	Species	Cross-Section area	Number of specimens
1	Red meranti (*Shorea parvifolia*)	50mm by 50mm	3
2	White meranti (*Shorea montigena*)	50mm by 50mm	3
3	Padi meranti (*Shorea venulosa*)	50mm by 50mm	3
4	Akasia mangium (*acacia mangium*)	50mm by 50mm	3
5	Gunung (*Dipterocarpus retusus*)	50mm by 50mm	3
6	Yellow meranti (*Shorea faguetiana*)	50mm by 50mm	3
7	Bunga meranti (*Shorea leprosula Miq*)	50mm by 50mm	3
8	Kamper sumatra (*Dryobalanops aromatica*)	50mm by 50mm	3
9	Meranti (*Shorea macrobalanos*)	50mm by 50mm	3
10	Keruing (*Dipterocarpus*)	50mm by 50mm	3
11	Kamper (*Cinnamomum camphora*)	50mm by 50mm	3
12	Kamper kalimantan (*Dryobalanops lanceolata*)	50mm by 50mm	3

Fig. 1. The three-point bending test according to ASTM D143-22 [4]

Each specimen was simply supported on two supports and subjected to loading using a three-point bending configuration. Figure 1 illustrates the test setup, showing the timber specimen positioned prior to loading. A Universal Testing Machine was used to perform bending tests, and the loading rate was managed in compliance with ASTM D143-22 [4, 17, 18]. The load was applied at a displacement rate of 2.5 mm/min, in accordance with the primary method of ASTM D143-22 [4], until peak or failure occurred. This testing configuration enables the determination of the slope of the elastic region, the proportional (yield) point, the post-elastic behavior, and the ultimate (rupture) point of the specimen.

3.2 Regression Analysis

3.2.1 Linear Regression Analysis

Linear regression analysis is a statistical method used to model the relationship between a dependent variable and one or more independent variables by fitting a linear equation to observed data. The technique estimates the effect of the independent variable on the dependent variable and is used to evaluate the strength, direction, and statistical significance of these relationships. Furthermore, linear regression can be used to predict the value of a continuous dependent variable based on one or more independent variables [19, 20, 21, 22].

$$y = ax + b \tag{1}$$

3.2.2 Quadratic Regression Analysis

A quadratic term that takes into consideration the interaction between two distinct time periods in the functional data is added to a functional linear model to create a functional quadratic model. Basis expansions are used in these models to express both the predictor and coefficient functions [23, 24]. Quadratic regression is a statistical method used to find the best-fitting parabolic equation for a set of nonlinear data points, typically expressed in Equation 2.

$$y = ax^2 + bx + c \tag{2}$$

where y is the response variable, x is the predictor variable, and a, b, and c are constants. This model aims to depict associations where the response variable varies at a pace proportionate to its own value rather than being constant, leading to a nonlinear correlation [25, 26].

3.3 Determining the Yield Point

The approach developed by Yasumura and Kawai [*27*] was used to determine the initial stiffnesses, yielding, and maximum moments because it was found to produce the most consistent findings for various types of timber beam connections when compared to other published methods [*28*].

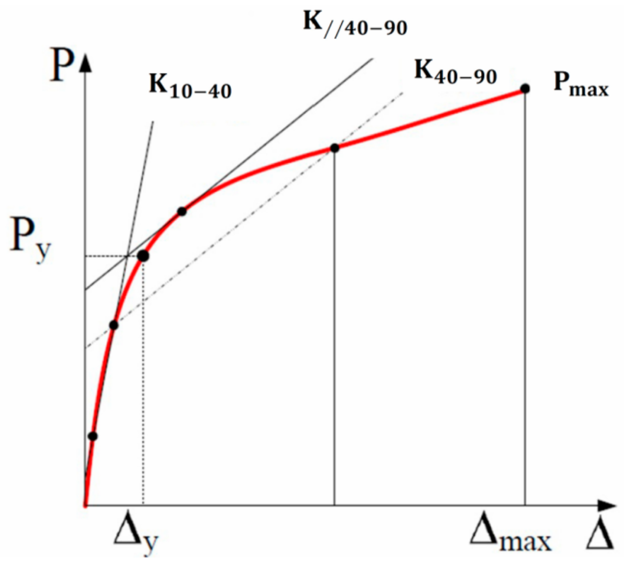


Fig. 2. Method for finding the yielding point of a load-deflection curve [27]

Using this technique, the initial stiffness (K10–40) of the beam connection was first determined to be between 10% and 40% of the maximum applied load. The initial stiffness line (K10–40) and a straight-line drawn tangent to the moment-rotation curve that is offset and parallel to the secant line plotted between 40% and 90% of the peak load were then used to estimate the yielding moment of the connection. The yielding rotation of the link was then found by projecting this point of intersection horizontally onto the moment rotation curve. Figure 2 shows how to find the point of intersection.

3.4 Method of Analysis

This study employed an experimental laboratory method to obtain the relationship between load and specimen deflection. ASTM D143-22 [4] was used as the reference standard for the flexural test, which was conducted using the three-point bending method. The load corresponding to the proportional (yield) limit was converted into bending strength (F_b) using elastic mechanics formulations [29] as seen in Equation 3 and Equation 4.

$$F_b = \frac{M_y y}{I_x} \quad (3)$$

Where M_y is the bending moment at mid-span in terms of P_y, I_x is the moment of inertia of the specimen cross-section, and y is the distance from the center of gravity of the cross-section to the outermost fiber edge. Using the same approach, the ultimate or peak load was converted into the modulus of rupture (MOR).

$$MOR = \frac{M_u y}{I_x} \quad (4)$$

where Mu is the bending moment at mid-span in terms of P_u. The transition point from elastic to plastic behavior, required to calculate the yield load (P_y), was determined using the Yasumura and Kawai method [27]. The ultimate load (P_u) was defined as the maximum load at which the specimen began to exhibit a reduction in load-carrying capacity after reaching the peak. Quadratic regression analysis was then performed to establish relationships between the specific gravity of timber and its bending properties, namely bending strength (F_b) and modulus of rupture (MOR).

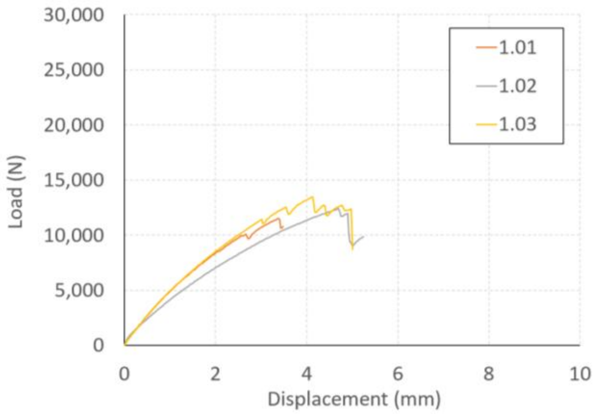
4. Results and Discussion

The bending tests were performed using the three-point loading method in accordance with ASTM D143-22 [4]. This method allows for the evaluation of both stiffness and strength characteristics under controlled loading conditions.

(a) (b)

Fig. 3. The three point bending test [4] (a) Red meranti (*Shorea parvifolia*) and (b) Kamper kalimantan (*Dryobalanops lanceolata*)

Three bending failure modes were identified, namely simple tension, cross-grain tension, and splintering tension. Simple tension failure is characterized by a brittle fracture and typically occurs in straight-grained timber at the location of peak bending moment. Splintering tension involves progressive fibre separation, where failure develops gradually rather than occurring instantaneously. Cross-grain tension failure occurs when tensile stresses act perpendicular to the grain angle, often leading to crack initiation and propagation across the grain. is indicates a cross-grain tension failure, where tensile stresses act perpendicular to the wood fibres, leading to separation along weaker transverse planes. In several specimens (e.g. specimens 4.2, 4.3, 7.2, 7.3), the cracks are not perfectly straight but show progressive and irregular propagation, suggesting splintering tension failure. In this mode, failure does not occur instantaneously; instead, fibres fail progressively, producing a rough and uneven fracture surface.



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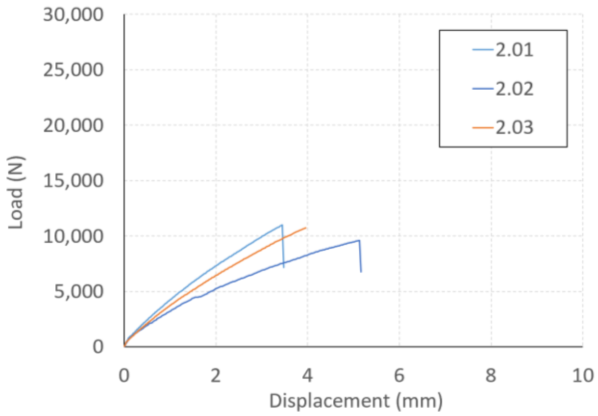

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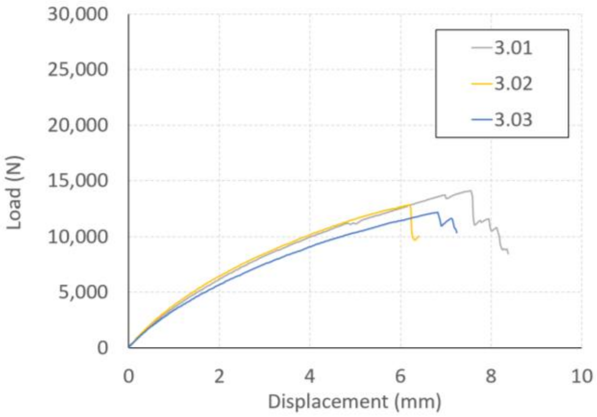

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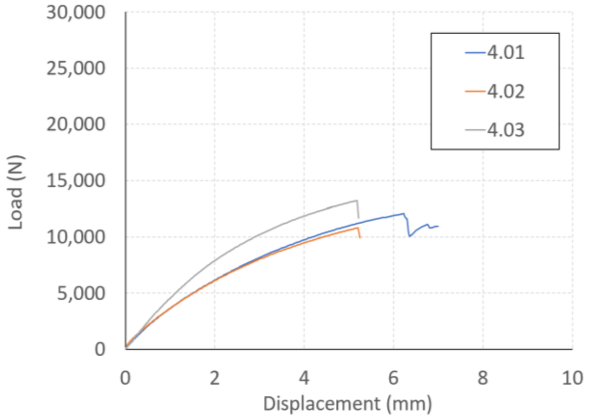

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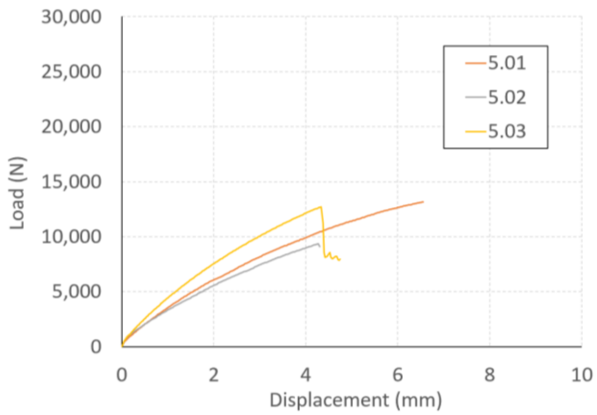

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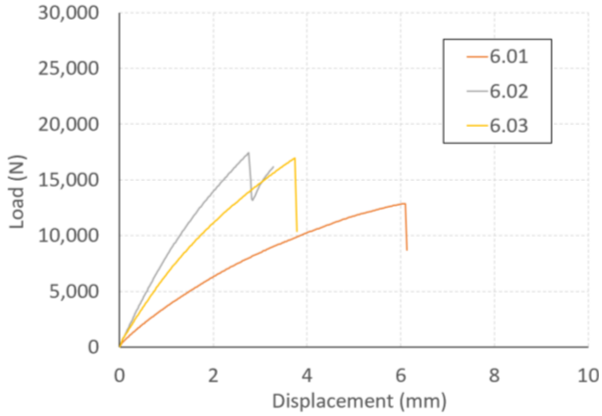
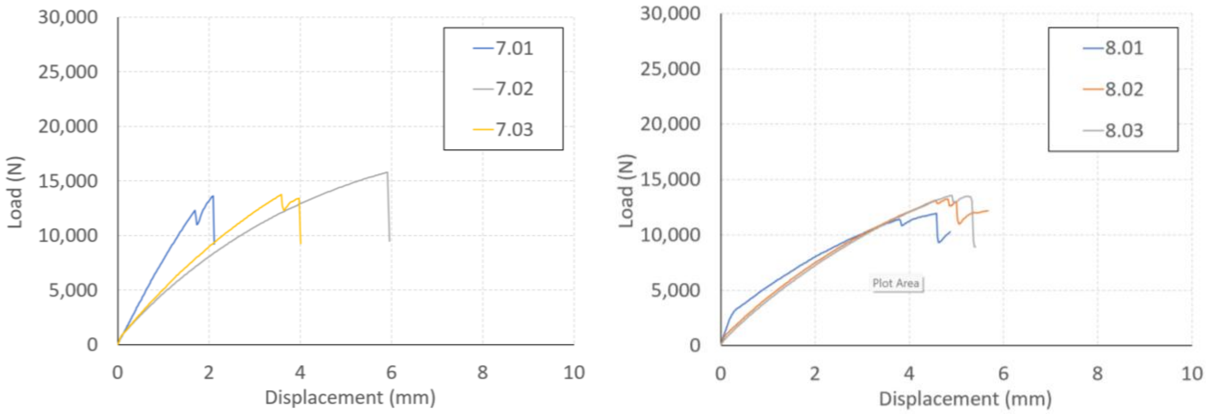
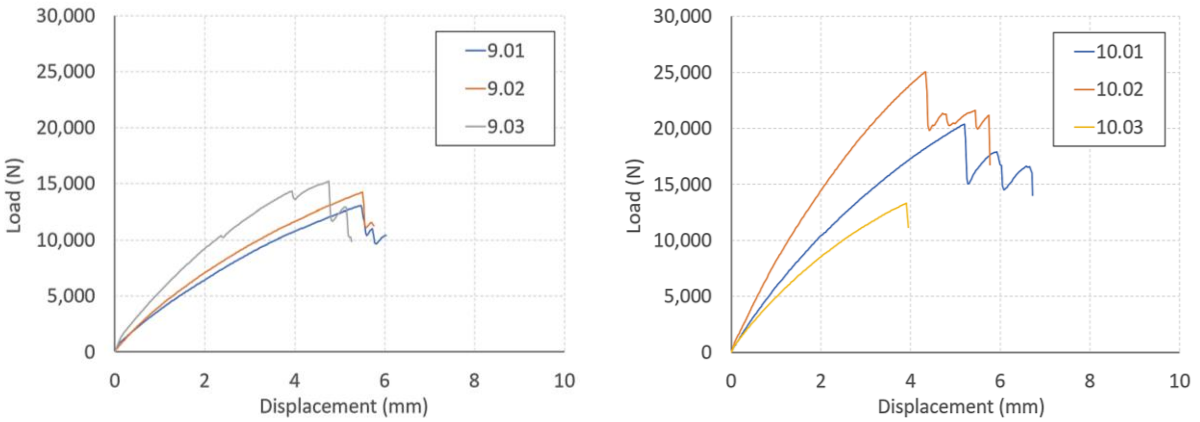


(f)



(g) Bunga meranti (h) Kamper sumatra



(i) (j)

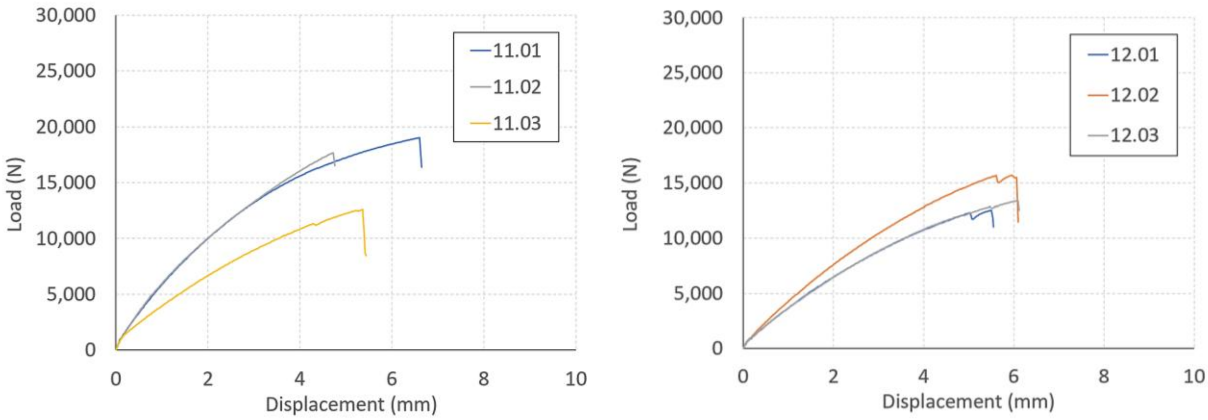


Fig. 4. The three point bending test results (*continued*) (a) Red meranti, (b) White meranti, (c) Padi meranti, (d) Akasia mangium, (e) Gunung, (f) Yellow meranti, (i) Meranti, (j) Keruing, (k) Kamper and (l) Kamper kalimantan

The presence of splintering (specimen 4.2) also indicates some degree of energy absorption and ductility, although overall behavior remains relatively brittle compared to engineered wood products. The location of failure near the midspan region confirms that the failure occurred at or near the maximum bending moment zone, which is consistent with flexural loading behavior. The absence of clean, straight fractures indicates that the timber likely contains grain deviation (specimen 4.3) or minor defects, contributing to stress redistribution and non-uniform crack paths.

Figure 4 presents the load–deformation curves obtained from the bending tests for specimens representing all twelve timber species. These curves were used as the basis for determining the bending strength and modulus of rupture (MOR). The bending stress was calculated using Equation

3, while the proportional limit (yield) point was determined using the method proposed by Yasumura and Kawai [27].

The Yasumura and Kawai method is one of the established approaches for determining the yield point, alongside the European Yield Model (EYM) method [30]. The modulus of rupture was calculated using Equation 4, where the ultimate bending stress was determined from the maximum (peak) load sustained by each specimen, as illustrated in Figure 4. The complete results of the yield point and ultimate point calculations for all specimens are presented in Table 2.

Table 3 shows the results in terms of bending stresses. Load, in terms of proportional or yield point, is then converted into bending strength (F_b) by using the elastic mechanics of the material formula (Equation 3). The load in terms of the ultimate or peak point is then transformed into a modulus of rupture using the same technique (Equation 4). The modulus of rupture in this study was calculated using the mechanics of materials equation [29], so it is called engineered stress, based on the consideration that this parameter is actually in the post-elastic range.

Table 2. Results obtained from research: load and deflection

No	Species	G	P_y (N)	D_y (mm)	P_u (N)	D_u (mm)
1	Red meranti (*Shorea parvifolia.*)	0.57	10616.85	3.10	12468.14	4.12
2	White meranti (*Shorea montigena*)	0.44	9133.25	3.51	10449.99	4.16
3	Padi meranti (*Shorea venulosa*)	0.41	11611.13	5.38	13038.49	6.84
4	Akasia mangium (*acacia mangium*)	0.43	9896.59	3.69	12035.11	5.51
5	Gunung (*Dipterocarpus retusus*)	0.40	9650.87	3.64	11744.39	5.03
6	Yellow meranti (*Shorea faguetiana*)	0.42	12605.47	2.92	15751.61	4.19
7	Meranti bunga (*Shorea leprosula Miq*)	0.53	12797.83	3.08	14398.02	3.84
8	Kamper sumatra (*Dryobalanops aromatica*)	0.51	11866.11	3.90	12883.83	4.77
9	Meranti (*Shorea macrobalanos*)	0.47	12041.15	3.90	14153.57	5.22
10	Keruing (*Dipterocarpus*)	0.66	16353.87	3.37	19591.78	4.45
11	Kamper (*Cinnamomum camphora*)	0.59	14248.69	4.22	16427.70	5.56
12	Kamper kalimantan (*Dryobalanops lanceolata*)	0.64	12348.96	4.52	13869.15	5.84

Specific gravity is one of the most important physical parameters used to describe wood quality because it reflects the amount of solid cell-wall substance present relative to void space. In timber engineering, bending strength is commonly expressed as the modulus of rupture (MOR), which represents the maximum stress developed in a specimen at failure during bending. Across many species, a higher specific gravity is generally associated with higher bending strength because denser wood contains more load-bearing material per unit volume. This relationship has long been recognized as a fundamental basis for estimating timber performance and for classifying wood for structural use.

Table 3. Results obtained from research: bending strength and modulus of rupture

No	Species	G	F_b (MPa)	MoR (MPa)
1	Red meranti (*Shorea parvifolia.*)	0.57	38.22	44.89
2	White meranti (*Shorea montigena*)	0.44	32.88	37.62
3	Padi meranti (*Shorea venulosa*)	0.41	41.80	46.94
4	Akasia mangium (*acacia mangium*)	0.43	35.63	43.33
5	Gunung (*Dipterocarpus retusus*)	0.40	34.74	42.28
6	Yellow meranti (*Shorea faguetiana*)	0.42	45.38	56.71
7	Meranti bunga (*Shorea leprosula Miq*)	0.53	46.07	51.83
8	Kamper sumatra (*Dryobalanops aromatica*)	0.51	42.72	46.38
9	Meranti (*Shorea macrobalanos*)	0.47	43.35	50.95
10	Keruing (*Dipterocarpus*)	0.66	58.87	70.53
11	Kamper (*Cinnamomum camphora*)	0.59	51.30	59.14
12	Kamper kalimantan (*Dryobalanops lanceolata*)	0.64	44.46	49.93

Bending parameters in terms of bending strength (F_b) and modulus of rupture (MOR), are mechanical characteristics that are utilized when designing beam or flexural members for timber frame structures or or main/longitudinal girders in wooden bridges. A quadratic regression analysis was performed [24] to obtain the correlation equation between the specific gravity (G) parameter with bending strength (F_b) and G with modulus of rupture (MOR). The results of the quadratic regression analysis are shown in Equation 5, Equation 6, and Figure 5.

$$F_b = 55.46 - 102.8\,G + 149.9\,G^2 \qquad (R^2 = 0.31;\ p\text{-value} = 0.002) \tag{5}$$

$$MOR = 126.6 - 360\,G + 400.3\,G^2 \qquad (R^2 = 0.29;\ p\text{-value} = 0.003) \tag{6}$$

Empirical equations were developed through linear regression analysis, with the complete results presented in Equations 7 and 8.

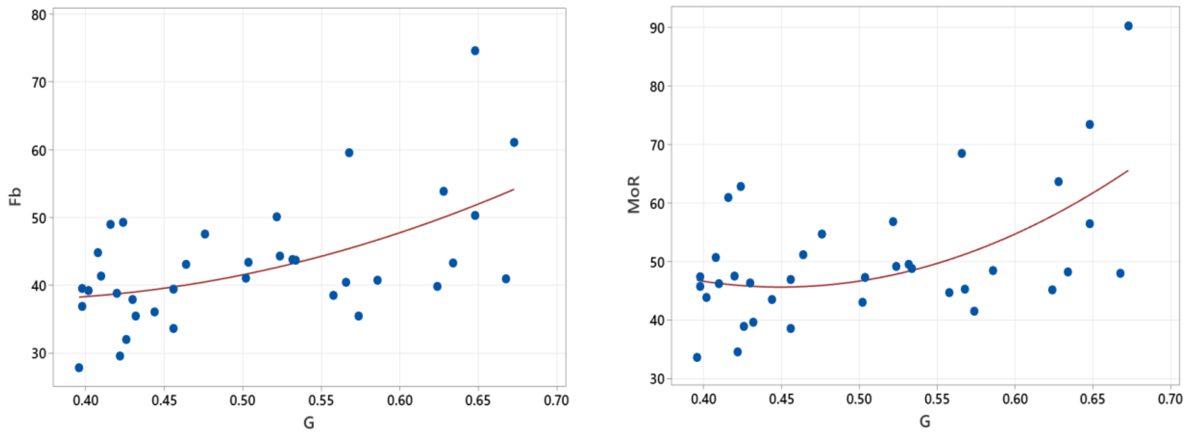
$$F_b = 15.45 + 54.5\,G \qquad (R^2 = 0.296;\ p\text{-value} = 0.044) \tag{7}$$

$$MOR = 19.71 + 60.1\,G \qquad (R^2 = 0.24;\ p\text{-value} = 0.044) \tag{8}$$

The results indicate that the coefficients of determination (R^2) obtained from the linear regression analyses, as presented in Equations 7 and 8, are lower than those obtained from the quadratic regression analyses (Equations 5 and 6), indicating that the quadratic models provide a better fit to the data. Furthermore, the p-value for the linear regression model was 0.044, which exceeds the significance threshold of 0.005, indicating that the model is not statistically significant at this level.

The consistently low p-values (≤ 0.005) for Equations 5 and 6 indicate that the predictor variables have a statistically significant influence on the flexural mechanical properties of wood at both the yield and peak points. However, the models do not adequately capture the inherent variability of wood specimens under field conditions, including differences in tree age, temperature, and moisture content. These uncontrolled factors likely contribute to the models' limited explanatory power. Nevertheless, the equations remain valuable for identifying statistically significant relationships and underlying patterns among the variables.

Equation 5, Equation 6, Figure 5.a, and Figure 5.b show there is a correlation between specific gravity and the flexural strength of wood in the context of proportional limit load (F_b) and ultimate limit load or modulus of rupture (MOR). The R^2 value for both equations is around 30%. Figure 6 compares the modulus of rupture (MOR) values obtained from the experimental tests, the empirical equation developed in this study (Equation (6)), and the MOR equation reported in the Wood Handbook [10], which is MOR = 171.2 $G^{1.13}$. Overall, the results indicate that the empirical equation developed in this study predicts MOR values that are 25.5% to 67.3% lower than those calculated using the Wood Handbook equation over the specific gravity range of 0.39 to 0.67. Consequently, the proposed empirical equation provides more conservative estimates of MOR.



(a) (b)

Fig. 5. Results of quadratic regression analysis(a) Analysis of F_b and (b) Analysis of MOR

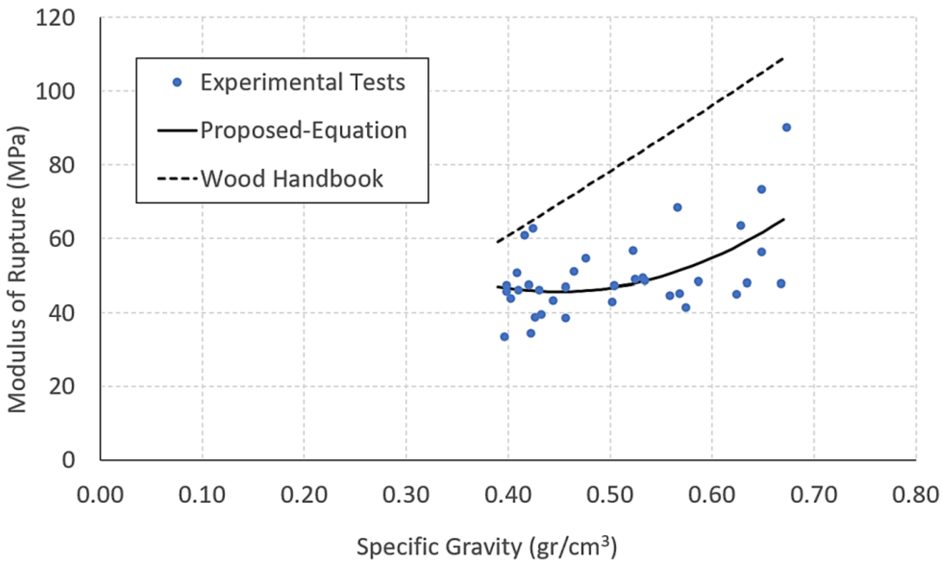


Fig. 6. Comparative study of modulus of rupture values: Experimental test results, proposed equations, and Wood Handbook [10]

This study has several limitations. Although efforts were made to obtain specimens with a relatively uniform specific gravity, it was not possible to ensure that the grain orientation along the longitudinal axis of all specimens was perfectly parallel to the grain direction (0° grain angle). Variations in grain angle may have influenced the flexural strength measurements and contributed to the observed variability in the test results.

5. Conclusions

The following conclusions can be made based on the results of the research:

- There is a correlation between specific gravity and the bending strength of wood in the context of proportional limit load (F_b) and ultimate limit load or modulus of rupture (MOR).
- The consistently low p-values obtained for the bending strength and modulus of rupture equations indicate that the predictor variables have a statistically significant effect on the flexural mechanical properties of wood at both the yield and peak points. However, the proposed models do not fully capture the inherent variability of wood under practical conditions, where factors such as tree age, grain orientation, temperature, moisture content, and other natural variations may influence its mechanical behavior. These uncontrolled

factors likely contribute to the models' limited explanatory power. Nevertheless, the proposed equations remain valuable for identifying statistically significant relationships between the predictor variables and the flexural properties of wood and for describing the overall trends observed in the experimental data.

- Bending strength (F_b) is a mechanical property of bending that can be used in the design of flexural elements (beams) using the Load and Resistance Factor Design (LRFD) method, while the modulus of rupture can be used in the design of flexural elements using the Allowable Stress Design (ASD) method.
- The outcomes of this research include the development of empirical equations relating to bending strength and modulus of rupture as a response to specific gravity as a predictive parameter. These relationships provide a practical and efficient means of estimating bending properties based on easily measured physical characteristics. The results should help both engineers and researchers, particularly during the early stages of timber grading.
- This study has several limitations. It was not feasible to guarantee that every specimen's grain orientation was precisely parallel to the longitudinal axis, despite efforts to choose specimens with a rather consistent specific gravity. Variations in grain angle are known to influence the flexural properties of wood and may have contributed to the variability observed in the bending strength and modulus of rupture measurements.

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