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The Effect of Size Factors on the Mechanical Strength of Meranti Wood

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Abstract— The use of wood as a construction material has been increasing in recent years. However, wood has limitations in terms of availability and size, which can affect the strength capacity of structural materials. Therefore, the efficient use of raw materials must be carefully considered in structural and construction planning. One important parameter related to this efficiency is the size factor of wood samples. The objective of this study was to analyze the effect of different sizes of meranti wood (*Shorea* spp.) used as structural elements on its mechanical properties, such as flexural properties (stiffness and strength) and compressive strength parallel to the grain. The results showed that both empirical observations and theoretical standards indicate a decrease in MOE values as the size of the test samples increases. Larger samples tend to produce lower MOR, bending strength, and compressive strength values. These findings indicate that the size factor plays an important role in determining the mechanical performance of wood and should be considered in structural design using wood materials.

Keywords: Mechanical Strength, Meranti Wood, and Size Factor.

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1. Introduction

Wood is one of the most commonly used construction materials by the communities, for both light and heavy construction. According to the previous study [1], wood as a construction material offers several advantages, including high strength, easy processing, good durability, and low operational costs. In addition, another study [2] also states that wood is an environmentally friendly material that generates low carbon emissions. Despite these advantages, the demand for wood continues to increase each year, while its availability is limited. Moreover, the size of wood directly affects its strength for structural applications. Therefore, efficient use of raw material needs to be considered during construction planning to address the limitations of wood resources. One of the crucial aspects of efficiency in structural construction is the size factor.

The size factor is defined as a coefficient used to calculate the effect of the size of structural elements, as determined by relevant product standards [3]. This factor is essential for calculating structural design strength, which is a key component in setting engineering design standards and ensuring structural safety [4]. In practice, larger structural elements may exhibit different mechanical properties compared to smaller specimens due to factors such as inherent material flaws, load distribution, and stress concentrations. Therefore, neglecting the influence of size effects may lead to inaccurate estimates of the actual load-carrying capacity, resulting in over- or under-design [5]. By quantifying the size factor appropriately, engineers and designers can optimize the use of raw materials, minimize waste, and enhance cost efficiency while maintaining structural integrity [6]. Based on these explanations, understanding the effect of size on structural strength is necessary to establish appropriate design values and advance standardization in construction. Furthermore, incorporating practices by promoting the efficient utilization of timber resources, which are inherently limited and subject to increasing demand.

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This research used meranti wood (*Shorea* spp.) as raw material. Meranti wood is widely used in construction, especially in housing and shipbuilding [7]. It is also considered a viable alternative to more expensive species such as teak wood because it is more readily available and relatively affordable [8]. Meranti wood can be used for light construction and furniture [9]; however, it is not recommended for outdoor applications due to its limited weather resistance. Generally, meranti wood is classified into strength classes II-IV, with a specific gravity of 0.55 (0.29 – 1.09) and durability classes of II-III [10]. Meranti wood has a modulus of elasticity (MOE) of 37719.93 kg/cm^2, and a modulus of rupture (MOR) of 308.8 kg/cm^2 [11]. Additionally, this wood has the potential to be used as veneer for plywood production [7]. Therefore, this study aims to analyze the effect of the size factor on the structural strength of meranti wood (*Shorea* spp.), thereby optimizing its utilization as a construction material and supporting the development of more efficient and standardized design practices.

2. Method

2.1 Wood Sample Preparation

The primary material used in this study was red meranti wood (*Shorea* spp.) measuring 8 cm × 12 cm × 400 cm as many as four beams. These beams were then cut according to the dimensions listed in Tables 1 and 2. For the bending test, the wood sample was given an additional length of 10 cm, except for standardized test specimens (following existing standards). The specimens were dried to air dry moisture content (12 – 18%).

Table 1. The size of wood samples used in the flexural test parallel to grain

No	Sample size (mm) b × h × l	Span (mm)	Loading speed (mm/min)
1	20 × 20 × 380	280	5
2	25 × 25 × 410	360	5
3	30 × 30 × 520	440	5
4	40 × 40 × 660	560	5
5	50 × 50 × 760	710	5
6	60 × 60 × 940	840	5
7	70 × 70 × 1080	980	5
8	80 × 80 × 1220	1120	5

Table 2. The size of wood samples used in the compression test parallel to grain

Width (mm)	Thickness (mm)	Length (mm)	Loading speeds (mm/min)
10	10	40	5
20	20	80	5
25	25	100	5
30	30	120	5
40	40	160	5
50	50	200	5
60	60	240	5
70	70	280	5
80	80	320	5

2.2 Mechanical Properties Evaluation

The mechanical properties evaluation carried out included fiber parallel bending (static bending) and fiber parallel compressive testing. Flexural testing refers to the ASTM D-143 standard [12]. Fiber parallel flexure testing was carried out by loading the tangential cross-section of the test sample with a

loading speed of 5 mm/minute. Flexural testing was performed by analyzing the modulus of elasticity (MOE) and modulus of rupture (MOR) values obtained through the following formulas (Equations 1 and 2).

$$MOE\ (N/mm^2) = \frac{PL^3}{4\Delta bh^3} \ldots\ldots\ldots (1)$$

$$MOR\ (N/mm^2) = \frac{3PL}{2bh^2} \ldots\ldots\ldots (2)$$

where P is the maximum load (N), L is the span length (mm), b is the test sample width (mm), and h is the test sample thickness (mm).

Fiber parallel compressive testing also refers to the ASTM D-143 standard [12]. The loading speed used was 5 mm/min. Fiber parallel compressive testing is carried out by applying a load to the cross-section of the test sample (parallel to the fibers). The fiber parallel compressive strength value is calculated using the following formula (Equation 3).

$$Compressive\ strength\ parallel\ to\ grain\ (N/mm^2) = \frac{Maximum\ load\ (N)}{Cross-sectional\ area\ (mm^2)} \ldots\ldots (3)$$

2.3 Data Analysis

The effect of the size factor in this study was analyzed using Microsoft Excel software and Curve Expert 1.4 to find the coefficient value of the equation model.

3. Result and Discussion

Modulus of elasticity (MOE) is an indicator to determine the stiffness properties of a material. The results regarding the MOE of meranti wood with various sizes, which are shown in Figure 1, indicate that the highest MOE is found in the 30 mm × 30 mm × 520 mm wood sample. It means that this sample also shows the highest stiffness compared to the other wood samples. Nevertheless, the lowest MOE was obtained by the 80 mm × 80 mm × 1220 mm wood sample, which means this sample exhibits low stiffness properties or is more elastic than the other samples. Herein, Figure 1 below shows the results of MOE testing for various wood sample sizes.

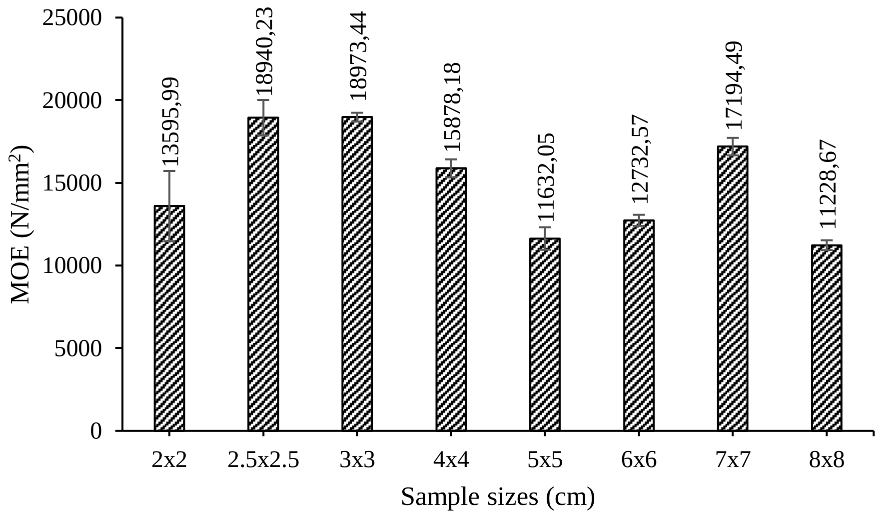


Figure 1. The MOE of meranti wood in various sizes

Figure 1 also illustrates that the MOE obtained exhibits considerable fluctuation. The MOE increases from the wood sample size of 20 mm × 20 mm × 380 mm, but then declines at the dimension of 50 mm × 50 mm × 760 mm. The MOE rises again for the 70 mm × 70 mm × 1080 mm and drops once more at the size of 80 mm × 80 mm × 1220 mm. These variations suggest that the size factor does not significantly affect the MOE across the wood samples. The findings of this study contradict the observations reported by the previous study [13]. However, larger structural dimensions are expected to produce lower MOE due to the presence of more defects or stress concentrations, and vice versa [14]. This discrepancy could be attributed to the heterogeneity or variability inherent in the wood samples.

The flexural strength or modulus of rupture (MOR) is one of the wood mechanical properties that needs to be examined, as it represents the maximum capacity of a material to withstand bending loads before failure occurs [15]. Theoretically, the larger the cross-sectional area of a wood sample, the lower the MOR tends to be. This relationship is further supported by the results of prior research [16], who stated that the MOR is influenced by the size of the cross-sectional area, indicating that an increase in cross-sectional size generally results in a lower MOR. This phenomenon is believed to be related to the presence of defects within the wood. Wood with larger cross-sections (approaching full-scale sizes) has a higher probability of containing defects compared to smaller wood samples. Small wood samples can be prepared in such a way that they are free from visible defects, whereas in structural-sized wood, the presence of natural defects is unavoidable. Related research [17] also stated that structural-sized timber is often affected by internal defects such as cracks, splits, knots, and other irregularities that can reduce its strength.

Based on Figure 2, the MOR of meranti wood increases by up to a size of 3 cm × 3 cm, and then decreases as the size reaches 8 cm × 8 cm. This trend is likely caused by the non-uniformity of the wood samples used. Bazant [18] explains that the size factor can be understood by the heterogeneity within the structure. There are varying strength chains within the structural elements, and the more strength chains can lower the structural element's strength. In addition, a prior study [19] said that smaller structural elements have superior strength compared to larger structural elements. For more details, the MOR values obtained from wood samples in different sizes are illustrated in Figure 2.

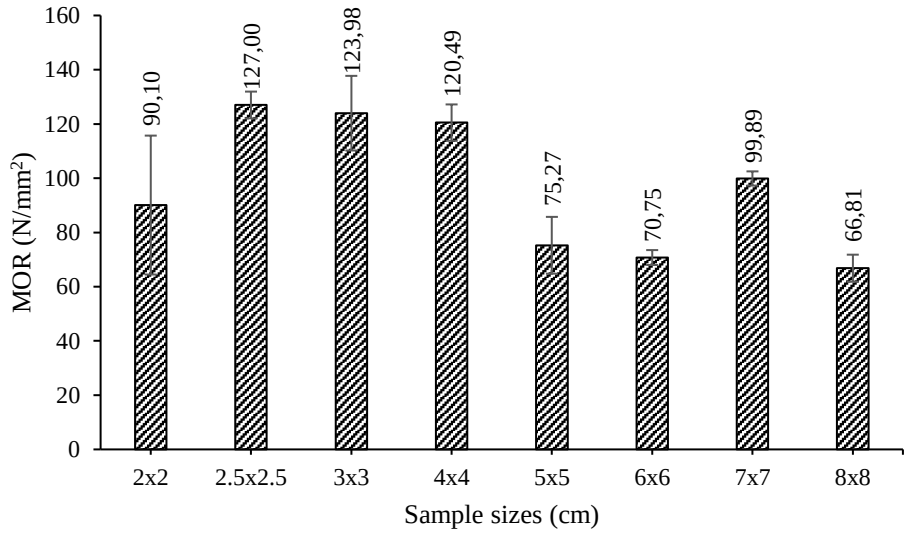


Figure 2. The MOR of meranti wood in various sizes

Besides determining MOE and MOR, this study also evaluated other mechanical properties, namely compressive strength, which becomes one of the essential parameters that must be known regarding its use as a construction material [15]. This evaluation was carried out in the direction parallel

to grain received by the wood until the failure point. The results showed that the compressive strength parallel to grain ranged from 29.78 – 39.43 N/mm^2. These values are slightly different from the results of the previous study [20] who obtained a meranti wood's compressive strength parallel to grain of 23 N/mm^2, which is linear with the reference value from SNI 7973 [21], namely 4.94 N/mm^2. One factor that can influence this parameter is the size factor of the construction wood used. Another study [22] also stated that the larger wood size results in the lower compressive strength parallel to grain of the wood.

Based on the previous research [23], the use of parameters or assumptions of the basic unit is identical for the strength of the wood sample taken on average to estimate the size factor, the use of the average to size factor of the basic unit is expected to be in accordance with the actual theoretical situation. However, the presence of defects in the different sizes can affect the wood's strength after the compressive strength parallel to grain evaluation; hence, the wood cannot be categorized identically in this condition. The presence of defects can influence the fluctuation obtained in this study, as shown in Figure 3. In addition to the results of existing literature [24], the wood size for structural use affects the presence of water content; therefore, the evaluation conducted using small samples, which did not represent the actual size, cannot accurately reflect the actual moisture content of the wood. The higher compressive strength parallel to grain obtained, the wood with high strength will be used as a construction material. According to early study [25], the parallel compressive strength is the maximum capacity of wood to withstand loads parallel to the direction of the wood grain.

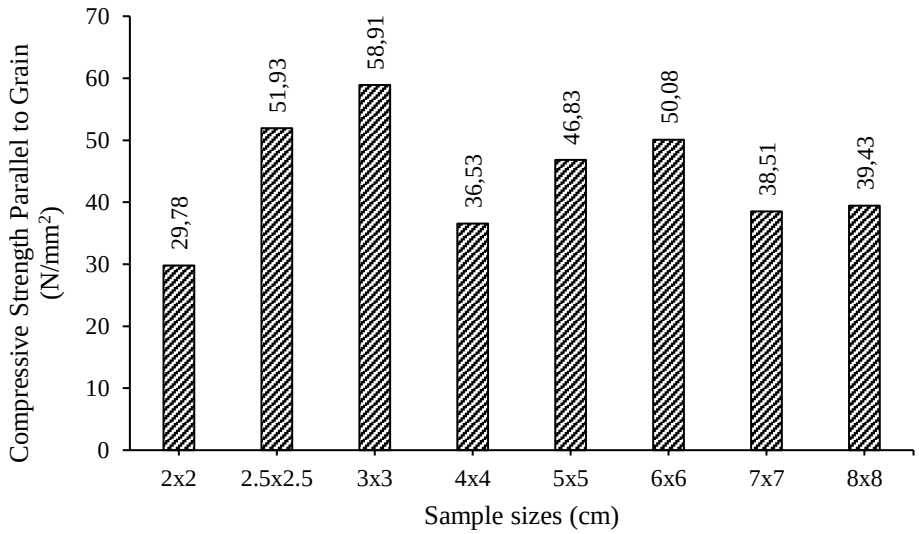


Figure 3. The compressive strength of meranti wood in various sizes

Based on the size factor for MOE (empirical F), the result is significantly different from the theoretical size factor (theoretical F) for both ASTM D245 and ASTM D5456 (P(T<t)), two-tailed less than 0.05. However, the size factor, both empirically (research) and theoretically (standard), shows a decreasing value along with the increasing size of the test sample studied. This indicates that larger wood samples tend to have lower stiffness compared to smaller samples. The relationship between MOE and wood sample size is displayed in Figure 4, which clearly describes the decreasing trend of MOE values as the dimensions of the test samples increase.

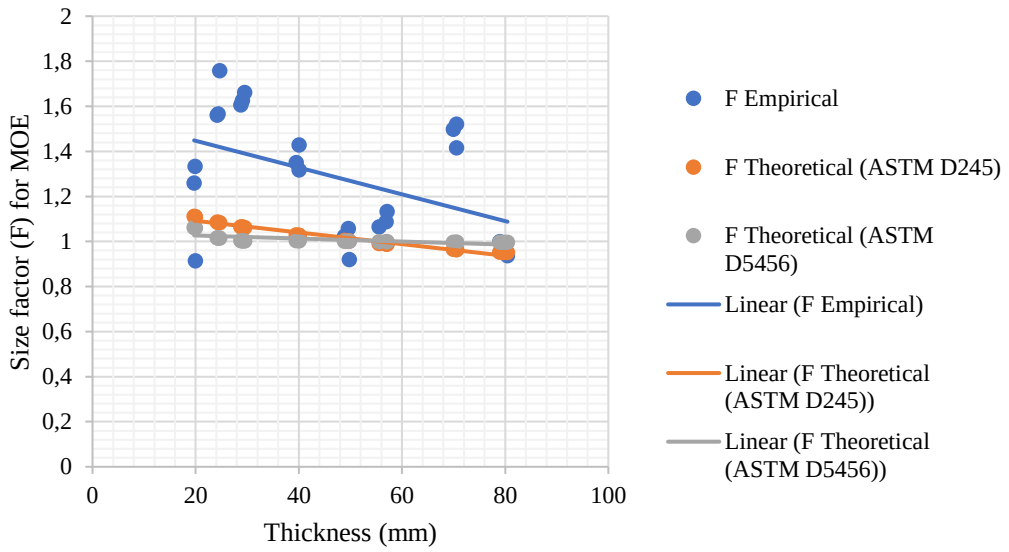


Figure 4. Size factor for the MOE of meranti wood

The same results are also shown in the MOR values. The two-tailed P(T<t) for the MOR of the size factor is also less than 0.05. This indicates that the size factor for MOR is also not significantly different from the theoretical F based on ASTM D245 and ASTM D5456. The relationship between MOR and the size factor is presented in Figure 5, which shows that larger test sample sizes tend to result in lower MOR values, indicating a negative relationship. This trend suggests that the size of the wood specimen has an influence on its bending strength, where larger specimens generally exhibit lower MOR values compared to smaller ones.

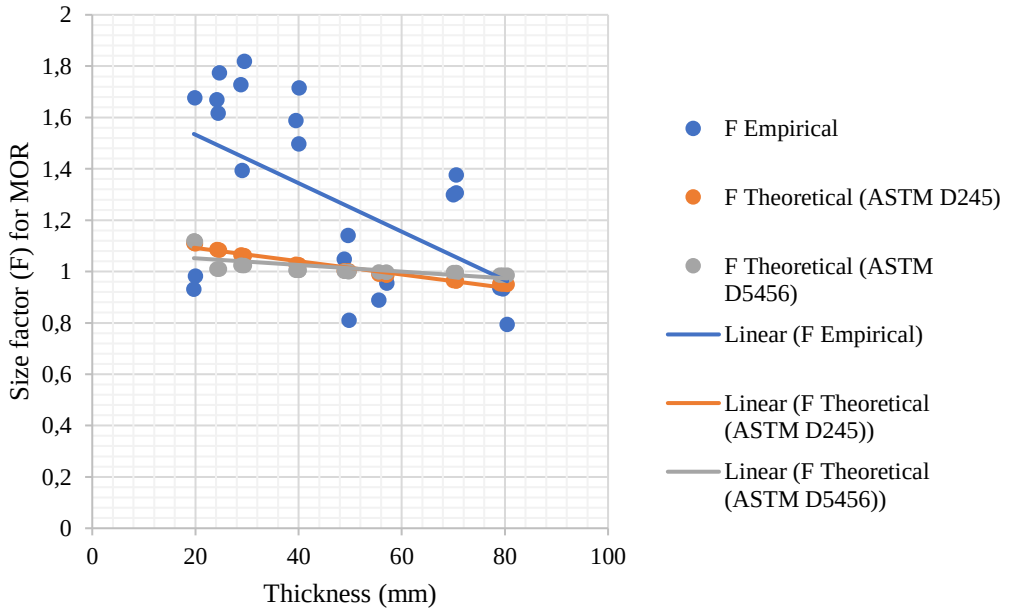


Figure 5. Size factor for MOR of meranti wood

Table 3. The size factor for MOE, MOR, and compressive strength parallel to grain

Test	Model	Result	Literature
Flexural strength (MOE)	$F = \left(\frac{51}{d}\right)^{a}$	$F = \left(\frac{51}{d}\right)^{0.397}$	$F = \left(\frac{51}{d}\right)^{\frac{1}{9}}$
	$F = 1 + a - a\left(\frac{d}{51}\right)^{0.5}$	$F = 1.054 - 0.054\left(\frac{d}{51}\right)^{0.5}$	$F = 1.07 - 0.07\left(\frac{d}{51}\right)^{0.5}$
	$F = \left(\frac{51^2 + b}{51^2 + a}\right)\left(\frac{d^2 + a}{d^2 + b}\right)$	$F = \left(\frac{51^2 + 680.301}{51^2 + 1677.515}\right)\left(\frac{d^2 + 1677.51}{d^2 + 680.301}\right)$	$F = 0.625\left(\frac{d^2 + 143}{d^2 + 88}\right)$
Flexural strength (MOR)	$F = \left(\frac{51}{d}\right)^{a}$	$F = \left(\frac{51}{d}\right)^{0.465}$	$F = \left(\frac{51}{d}\right)^{\frac{1}{9}}$
	$F = 1 + a - a\left(\frac{d}{51}\right)^{a}$	$F = 2.203 - 1.203\left(\frac{d}{51}\right)^{0.5}$	$F = 1.07 - 0.07\left(\frac{d}{51}\right)^{0.5}$
	$F = \left(\frac{51^2 + b}{51^2 + a}\right)\left(\frac{d^2 + a}{d^2 + b}\right)$	$F = \left(\frac{51^2 + 1158.208}{51^2 + 3513.705}\right)\left(\frac{d^2 + 3513.705}{d^2 + 1158.208}\right)$	$F = 0.625\left(\frac{d^2 + 143}{d^2 + 88}\right)$
Compressive strength	$F = \left(\frac{{b_0}^3}{b^3}\right)^{-s_\tau}$	$F = \left(\frac{{b_0}^3}{b^3}\right)^{-(-0.033)}$	$F = \left(\frac{{b_0}^3}{b^3}\right)^{-0.047}$

Table 3 presents the size factor models for MOE, MOR, and compressive strength parallel to grain, including the results obtained in this study and those reported in the literature. This table compares the empirical results of the current research and several theoretical models previously developed by other researchers. Through this comparison, it can be observed how the size factor values obtained in this study relate to the values predicted by established models in the literature.

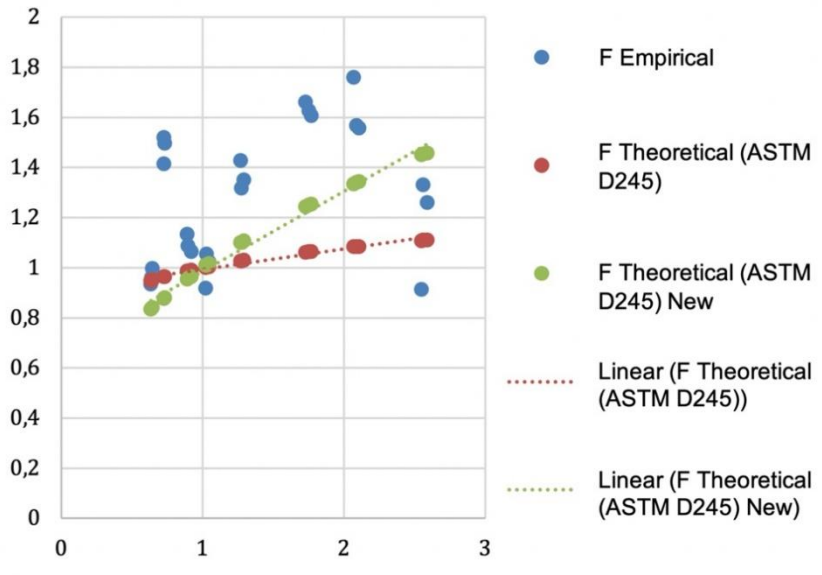
Based on the results of the analysis of flexural test data influenced by the size factor, the R^2 values obtained for MOE and MOR were respectively; firs model of MOE: 0.46; second model of MOE: 0.43; and third model of MOE: 0.37; and first model of MOR: 0.02; second model of MOR: 0.07; and third model of MOR: 0.07. The results show that the model chosen for MOE is the calculation using the first model, with a value of 0.46 closest to one, which means that if the R^2 value is small, the ability of the independent variables to explain the variation of the dependent variable is very limited. However, if the value is close to one, the independent variables provide almost all the information needed to predict the variation of the dependent variable [26], while the MOR value closest to one is obtained by using the calculation of the second model with a value of 0.08. Thus, the MOE value with the first model and the MOE value with the second model have independent variables in the form of size, which can provide information to predict the variation of the dependent variable, namely F (size factor). The results of the analysis of the compression test data with the influence of the size factor obtained an R^2 value using the Weibull theory of 0.08. For more details, the comparison of the coefficient of determination among models can be seen in Table 4.

Table 4. The comparison of the coefficient of determination (R^2) among models

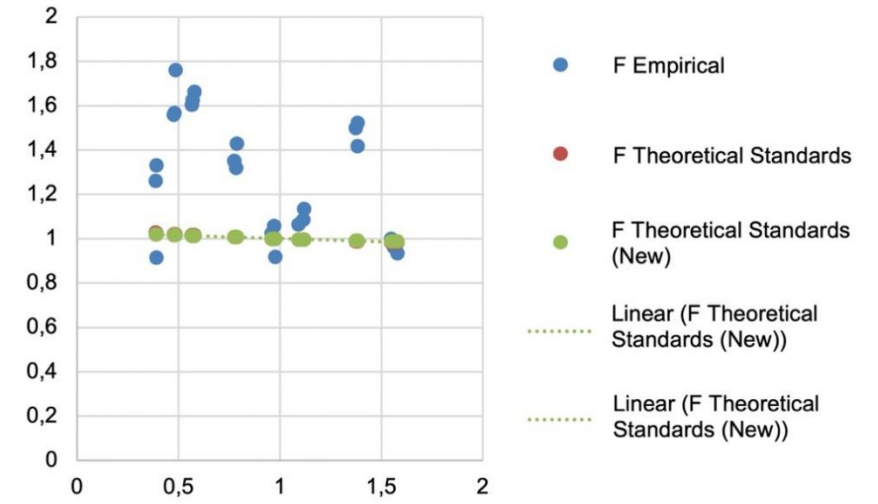
Test	Model	Coefficient of determination (R^2)
Flexural strength (MOE)	$F = \left(\frac{51}{d}\right)^{a}$	0.46
	$F = 1 + a - a\left(\frac{d}{51}\right)^{0.5}$	0.43

	$F = \left(\frac{51^2 + b}{51^2 + a}\right)\left(\frac{d^2 + a}{d^2 + b}\right)$	0.37
Flexural strength (MOR)	$F = \left(\frac{51}{d}\right)^a$	0.02
	$F = 1 + a - a\left(\frac{d}{51}\right)^a$	0.07
	$F = \left(\frac{51^2 + b}{51^2 + a}\right)\left(\frac{d^2 + a}{d^2 + b}\right)$	0.04
Compressive strength	$F = \left(\frac{{b_0}^3}{b^3}\right)^{-s_\tau}$	0.08

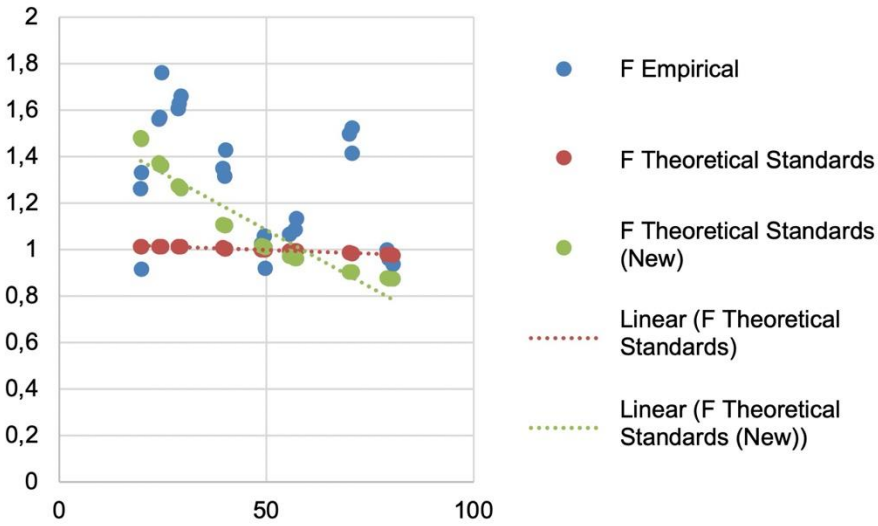
Further analysis of the size factor models presented in Figures 6 and 7. Figure 6 illustrates the comparison between the empirical size factor and several theoretical models for MOE, including the ASTM D345 model, the Newlin & Trayer model, and the Dawley & Youngquist model. Based on the comparison, the empirical values show a decreasing trend as the wood samples' size increases, which have lower stiffness due to the higher probability of internal defects and heterogeneity within the wood structure [27]. A similar pattern is also observed for the bending strength analysis. Figure 7 shows the comparison between the empirical size factor for MOR and the theoretical models proposed by ASTM D345, Newlin & Trayer, and Dawley & Youngquist. The results indicate that the MOR size factor decreases with increasing specimen size. This relationship confirms the negative correlation between specimen size and bending strength, where larger wood size generally exhibits lower MOR values.



(a)

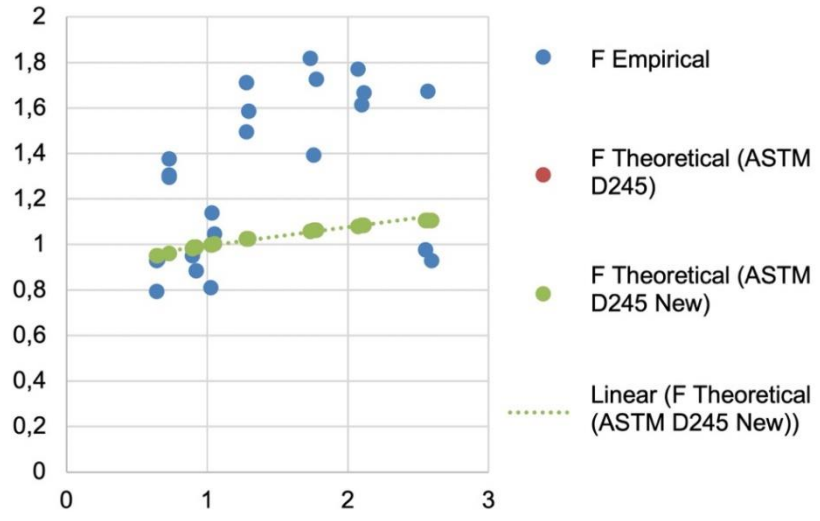


(b)

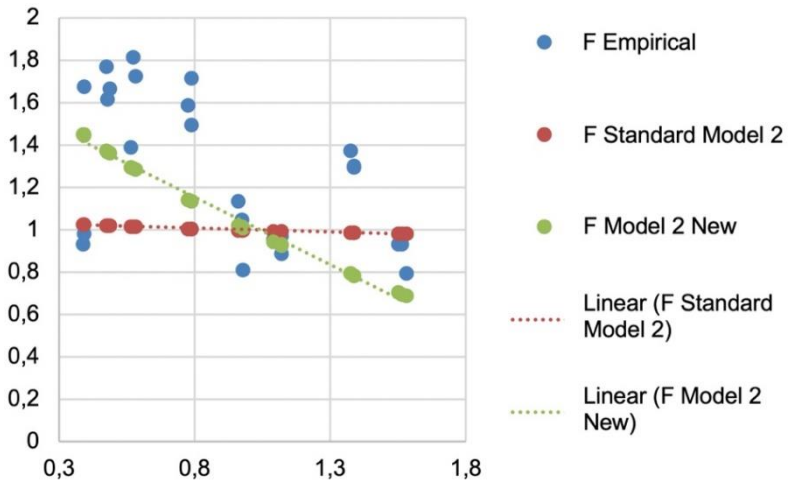


(c)

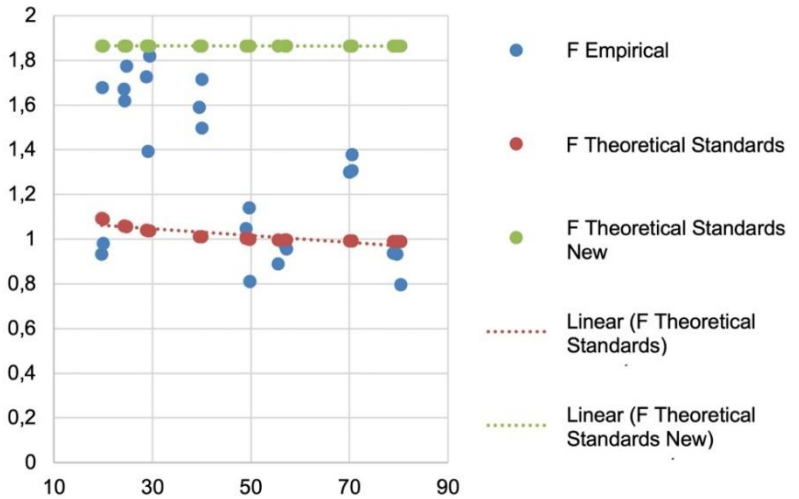
Figure 6. Size factor for MOE flexural testing (a) comparison of empirical F and ASTM D345 first model formula, (b) comparison of empirical F of Newlin & Trayer second model formula, and (c) comparison of empirical F and Dawley & Youngquist third model formula.


2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0
1
2
3
F Empirical
F Theoretical (ASTM D245)
F Theoretical (ASTM D245 New)
Linear (F Theoretical (ASTM D245 New))

(a)


2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
0,3
0,8
1,3
1,8
F Empirical
F Standard Model 2
F Model 2 New
Linear (F Standard Model 2)
Linear (F Model 2 New)

(b)


2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
10
30
50
70
90
F Empirical
F Theoretical Standards
F Theoretical Standards New
Linear (F Theoretical Standards)
Linear (F Theoretical Standards New)

(c)

Figure 7. Size factor for MOR flexural testing (a) comparison of empirical F and ASTM D345 first model formula, (b) comparison of empirical F of Newlin & Trayer second model formula, and (c) comparison of empirical F and Dawley & Youngquist third model formula.

Figure 8 shows the relationship between the empirical size factor and the standard size factor for the compressive strength parallel to grain based on the Weibull theory. The empirical data points exhibit some variability, indicating fluctuations in the compressive strength values of the wood samples. However, the overall trend shows that the empirical values generally follow the pattern of the standard models. The empirical trend lines for both the standard model and the new standard model indicate a slight increasing tendency of the size factor with respect to the parameter studied. Although the empirical data are more scattered, they still fall within the range predicted by the theoretical models. This variation may be influenced by the natural heterogeneity of wood, including differences in fiber structure, moisture content, and the presence of internal defects [28]. Overall, the comparison suggests that the Weibull-based model can reasonably represent the behavior of the compressive strength size factor, although some deviations occur due to the inherent variability of the wood material.

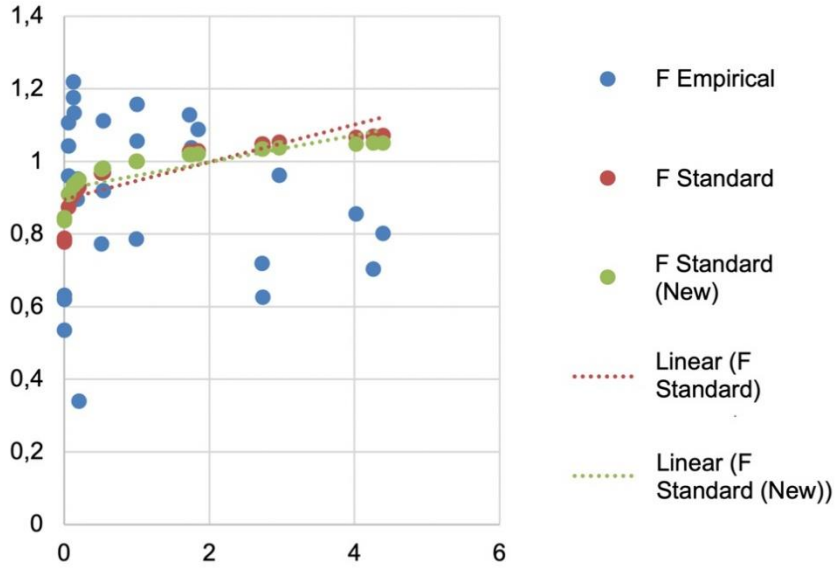


Figure 8. Size factor for the compressive strength using Weibull theory.

4. Conclusion

In the meranti wood flexural test, the MOE and MOR values obtained for each sample size indicated no significant difference in size between each sample, due to the non-uniformity of all test samples. The compressive strength parallel to grain of meranti wood ranged from 29.78 to 39.43 N/mm2. The size factor, both empirically (research) and theoretically (standard), showed a decreasing MOE with increasing sample size. The size factor also showed that the larger the sample size used, the lower the MOR produced. Likewise, the compressive strength size factor showed the same results as the MOE and MOR size factors. The MOE size factor can be calculated using the formulas $F = (51/d)^{0.397}$, $F = 1.054\text{-}0.054(d/51)^{0.5}$, or $F = (51^2+680.301/51^2+1677.515)\ (d^2+1677.51/d^2+680.301)$. The MOR size factor can be determined using the following formula: $F = (51/d)^{0.465}$, $F = 2.203\text{-}1.203(d/51)^{0.5}$, or $F = (51^2+1158.208/51^2+3513.705)\ (d^2+3513.705/d^2+1158.208)$. The compressive strength factor can be calculated using $F=(b0^3/b^3)^{-(-0.033)}$.

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