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DEVELOPMENT OF A CORRELATION MODEL FOR TORSIONAL SHEAR MODULUS PROPERTIES BETWEEN STRUCTURAL SIZE SPECIMENS BASED ON EN 384:2016 AND SMALL CLEAR SPECIMENS (MS544: PART 2)

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Abstract

In timber design, the shear modulus of beams is crucial for ensuring torsional stability and minimizing vibrational issues. Traditionally, the ratio of modulus of elasticity (E) to shear modulus (G) is assumed to be 16:1. However, bending tests often combine flexural and shear stresses, making it difficult to assess pure shear properties. The British Standard BS EN 408:2012 now recommends the torsion test as the preferred method for determining the shear modulus of structural-size timber and timber composites. This method has received limited attention in Malaysia. This study investigates the torsional shear modulus of Malaysian tropical timber species across different strength groups (SG), including Balau (SG1), Kempas (SG2), Kelat (SG3), Kapur (SG4), Resak (SG4), Keruing (SG5), Mengkulang (SG5), Light Red Meranti (SG6), and Geronggang (SG7). Torsion tests were conducted in line with BS EN 408, and the results were compared with modulus of elasticity values from MS554: Part 2. The findings showed that the E to G ratio for these species ranged from 17:1 to 29:1, with an average of 21:1—exceeding the conventional 16:1 ratio. This indicates that torsional shear modulus must be experimentally tested rather than inferred from the traditional ratio.

Keywords: Shear modulus, torsion testing, structural dimension, small defect-free samples, tropical hardwood timber

Abstrak

Dalam reka bentuk kayu, modulus ricih balak adalah penting untuk memastikan kestabilan kilasan dan mengurangkan isu getaran. Secara tradisinya, nisbah modulus keanjalan (E) kepada modulus ricih (G) diandaikan pada nisbah 16:1. Walau bagaimanapun, ujian lenturan sering menggabungkan tegasan lenturan dan ricih, menjadikannya sukar untuk menilai sifat ricih tulen. Piawaian British BS EN 408:2012 kini mengesyorkan ujian kilasan sebagai kaedah pilihan untuk menentukan modulus ricih bagi balak bersaiz struktur dan bahan komposit kayu. Kaedah ini masih kurang mendapat perhatian di Malaysia. Kajian ini menyiasat modulus ricih kilasan spesies kayu tropika Malaysia merentasi kumpulan kekuatan yang berbeza (SG), termasuk Balau (SG1), Kempas (SG2), Kelat (SG3), Kapur (SG4), Resak (SG4), Keruing (SG5), Mengkulang (SG5), Light Red Meranti (SG6), dan Geronggang (SG7). Ujian kilasan dijalankan mengikut piawaian BS EN 408, dan hasilnya dibandingkan dengan nilai modulus keanjalan dari MS554: Bahagian 2. Penemuan menunjukkan bahawa nisbah E kepada G bagi spesies ini berkisar antara 17:1 hingga 29:1, dengan purata nisbah 21:1, melebihi nisbah konvensional 16:1. Ini menunjukkan bahawa modulus ricih kilasan perlu diuji secara eksperimen dan tidak boleh disimpulkan berdasarkan nisbah tradisional.

Kata kunci: *Modulus ricih, ujian kilasan, dimensi struktur, sampel kecil bebas kecacatan, kayu keras tropika*

1.0 INTRODUCTION

Shear properties of timber structures encompass two main categories: shear strength and shear modulus. Bending and torsion tests are highly acknowledged as the preferred and optimal methods for acquiring shear properties data for large-sized elements [1].

The shear modulus, also referred to as the modulus of rigidity, represents the flexural resistance of a member generated by shear stress. This rigidity modulus (G) is determined along the longitudinal (L), radial (R), and tangential (T) axes of timber, denoted as GLR, GLT, and GRT [2, 3, 4].

The shear modulus of a structural element holds significant importance in designing dimensions and selecting materials within the fields of structural and mechanical engineering [5, 6]. It plays a crucial role in preventing lateral torsional buckling, a failure mode that arises when an unconstrained beam or beam-column undergoes simultaneous in-plane displacement, lateral displacement, and twisting due to an applied load or moment.

In timber design, the widely used ratio of modulus of elasticity to shear modulus (E:G ratio) is 16:1, serving to estimate the shear modulus, especially for design equations concerning torsional rigidity and lateral-torsional stability of timber beams. Nevertheless, researchers [7, 8, 9] have discovered that this ratio varies among different species, particularly when dealing with structural composite timbers. Over the past two decades, several research endeavors have been conducted to estimate the shear modulus through a variety of test methods, such as shear block, bending shear, and torsion tests, with the objective of establishing accurate correlations.

Ukyo *et al*. (2010)[10] conducted a study that delved into the correlation between shear strength and shear modulus of glue-laminated timber, with a particular emphasis on Japanese cedar and Douglas-fir. The research utilized block shear specimens from five layers of glue-laminated timber, adjusting the shear plane to the center of the timber. The study revealed a relatively high correlation coefficient of 0.75 between the computed shear modulus and nominal shear strength. However, it also highlighted the species-dependence of this relationship. Bilko *et al*. (2021)[11] explored the determination of shear modulus and shear strength of pine wood (*Pinus sylvestris L.*) by using Arcan shear tests with digital image correlation (DIC). The usage of the DIC system showed that it is capable of gathering more information on the experiment than typically used measuring techniques. However, conducting and analyzing this technique proves challenging, despite its continued utilization of small clear specimens.

The shear block test has been deemed ineffective in accurately assessing the true shear strength of structural-sized timber. This is due to its neglect of stress concentrations and failure to consider defects and orthotropy [12]. The mechanical behavior of lumber cannot be reliably predicted solely based on qualities of small defectless timber owing to variations in timber properties [13]. MS 544 Part 2 [14] assesses grade stresses (tension, compression, and bending stresses) based on small clear timber stresses (defect-free timber pieces) frequently utilized in standard laboratory testing. Hence there is a need to redevelop the grade stress using structural size specimens.

Previously, the bending test was the preferred test method to determine the shear strength and to derive shear modulus as stipulated in BS EN 408: 1995 [15]. The torsion test has been recognized to be able to produce pure shear values and derive the shear modulus since this technique has been incorporated in the latest revision of BS EN 408:2010 [1]. The torsion test method provides a more consistent and uniform system of shear stresses in the specimen, enabling accurate measurement of pure shear stiffness and strength [5, 16, 17, 18, 19, 20, 21]. Timber exhibits a relatively low shear stiffness. Hence, in load-bearing applications, the shear modulus becomes a crucial consideration when designing for the lateral-torsional stability of beams, as outlined in BS EN 1995-1-1[22]. Additionally, the shear modulus plays a significant role in ensuring the serviceability of wood-joist floors and serves as a vital parameter for establishing analytical and finite element models [8, 23].

Harrison (2006)[24] employed the bending and torsion test methods to determine the shear modulus of timber beams and evaluate the accuracy of the 16:1 E:G ratio. The research unveiled notable fluctuations in the E:G ratio, indicating its non-constant nature. Moreover, the E:G ratio exhibited variability across various test methods and timber species.

Khokhar's (2011)[5] investigated the relationship between the shear modulus and modulus of elasticity of structural timber beams. Torsion tests were executed to determine the shear modulus (G) of Sitka spruce. The findings revealed variations in shear stress across different planes (LT and LR) and with changes in aspect ratio. Notably, the typical E:G ratio was closer to 23:1, which contradicts the assumption of a constant 16:1 ratio.

There is a limited amount of research on the shear properties of structural-sized timber in Malaysia, which has sparked increased interest among timber practitioners in comprehending the stresses of Malaysian timber for structural purposes. To address this gap, a comprehensive experiment was conducted on selected Malaysian tropical structural timber samples to evaluate their shear properties, with a specific emphasis on the shear modulus, in accordance with the EN 408[1] guidelines. The results from large size specimens were correlated with the result from small clear specimens published in MS 544 Part 2[14].

2.0 METHODOLOGY

To evaluate the torsional shear modulus, an experimental procedure involving three laboratory stages was utilized. Initially, timber logs were obtained, processed, and classified based on MS 1714 [25], then cut to specific sizes for torsion testing following BS EN 408 [1].

In the subsequent phase, data collection occurred as part of the laboratory process to determine the moisture content, density, and shear properties of the specimens.

During the third phase of the study, a detailed analysis was conducted on the data gathered in the second phase to identify potential correlations between the results of the torsional shear modulus test and the data acquired from MS544: Part 2 [14]. The EN 408:2010 [1] standard was utilized to determine the shear modulus, meanwhile the mean strength, strength grade and characteristic value were carried out according to the guidelines provided in [26, 27, 28, 29, 30]. Following this, statistical analysis and cumulative distribution function were employed to comprehensively analyze all the collected data.

2.1 Material

According to EN 384[28], a minimum of 40 specimens must be collected from a single growth region, and the more growth regions selected, the smaller the penalty factor. When samples are collected from five (5) different sampling locations, there is no penalty. The penalization factor is the incremental transmission loss factor used to adjust the mechanical properties of the timber in order to achieve the specified total number of samples and areas as outlined in EN 384[28].

Considering lumber's high cost, this study utilized four (4) sample locations strategically spread across several sampling areas, representing both the East and West Malaysian regions. To ensure comprehensive coverage of East Malaysia, three (3) locations were chosen, spanning the north, central, and southern regions. The selected sample growth zones included Kelantan (A1), Pahang (A2), Johor (A3), and Kelantan (A4) (Sarawak). Details regarding the distribution of specimens used in the shear test can be found in Tables 1. The investigation encompassed a total of 1800 samples.

All timber species from strength group SG1 to SG7 were included in the study [14]. The species used in this study are; Balau (SG1), Kempas (SG2), Kelat (SG3), Kapur (SG4), Resak (SG4), Keruing (SG5), Mengkulang (SG5), Light Red Meranti (SG6), and Geronggang (SG7). The selection process took into account the availability of these species in the market and their commercial viability in Malaysia. For all these timbers, a chain of custody (CoC) certificate was deemed necessary to ensure the traceability of certified material from the forest to the final product. This approach simplifies the monitoring of timber throughout all stages of processing and distribution, thereby ensuring the identification of certified forests from which the timber originated.

In order to achieve the desired dry timber state, adhering to Malaysian standards specifying a moisture level between 12 and 19 percent, the specimens underwent kiln drying.

2.2 Specimens Preparations and Measurements

2.2.1 Sample Preparation

The specimens were manufactured to meet the dimensions of 90 x 45 x 1900 mm and 120 x 80 x 2280 mm, following the standards outlined in EN 408[1]. Afterward, the timbers underwent kiln drying, followed by a visual grading process conducted by an accredited grader from the Malaysian Timber Industry Board (MTIB). This grading process adhered to guidelines from MS 1714 [25], resulting in the assignment of an HS (Hardwood Structural) grade to the samples.

2.2.2 Testing Procedure

As illustrated in Figures 1 and 2, all timber beams underwent torsion testing using a 5 kN-m torsion testing machine. This machine was employed specifically for the torsion testing of the timber beams.

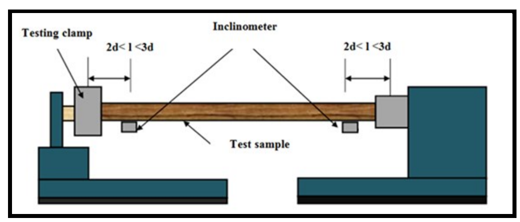

Figure 1 Schematic diagram for test setup

Figure 2 The actual equipment and test set-up for torsion test

Table 1 Specifications for the samples used in the torsion test

Species	Torsional testing of mechanical properties for structural-sized (mm) samples in parallel to the grain.		SG
	Size (mm) **90 X 45 X 1900** **Amount and Region**	**Size (mm)** **120 X 80 X 2280** **Amount and Region**	
Balau	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	1
Kempas	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	2
Kelat	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	3
Kapur	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	4
Resak	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	4
Keruing	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	5
Mengkulang	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	5
Light Red Meranti	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	6
Geronggang	30(A1) + 25(A2) + 35(A3) +30 (A4) = 120	20(A1) + 25(A2) + 15(A3) +20 (A4) = 80	7
	Total = 1080	**Total = 720**	

Torsional deformation along the longitudinal axis was induced by placing the test sample between supports spaced over 16 times wider than its largest cross-sectional dimension."

Each test specimen was placed into a torsion tester and exposed to torsion via a displacement control procedure. The torsion tester's measures of twist, including the specimen's own twist, were exclusively used to regulate the applied torque; they were not employed for data analysis. Two (2) inclinometers were employed to measure torsional displacements in these experiments. These inclinometers were mounted on the underside of the device to gauge the actual rotational displacement. Gupta *et al*. (2002a) [31] demonstrated that the end effect can be minimized by a distance of 2d (where d is sample depth). Consequently, the inclinometer was positioned 180 mm from the end of the specimen for a 90 mm x 45 mm x 1900 mm beam and 240 mm for a 120 mm x 80 mm x 2280 mm beam. The test specimens underwent torsional testing at a rate of 20° to 30° per minute until they fractured, with the rate varying according to the species.

2.2.3 *Assessment of the Torsional Shear Modulus*

When subjected to torsional force (against the grain), the timber specimen undergoes two stages of linear elasticity, followed by rapid failure after reaching the maximum torque T_r. The shear parameters were determined following the EN 408 [1]:

i) By plotting the applied torque against the relative twist of each sample, the maximum torque can be identified.

ii) The maximum applied torque, which causes the sample to break, is referred to as the final applied torque.

The sample stiffness K_{Tor} is calculated through regression analysis, which involves correlating the applied torque with the relative twist per length in the elastic region as shown in Figure 3.

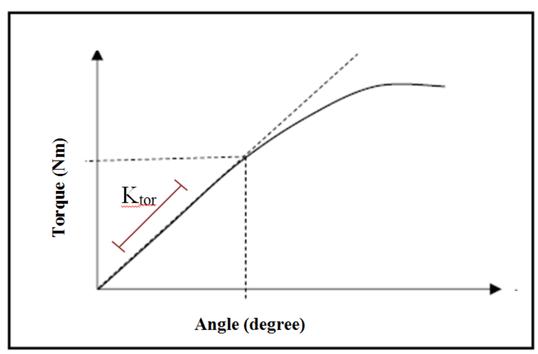

Figure 3 Torque vs Angular Displacement Graph for Timber Specimen Under Torsion Test

The shear modulus, $G_{tor,t}$, is subsequently calculated in accordance with EN 408 [1] guidelines, employing the following formula:

$$\frac{K_{tor}}{nhb^3} \times l_1 \qquad \text{Equation 1}$$

Where,

$G_{tor,t}$	=	Torsion-based shear modulus, in newtons per square millimetre.
K_{tor}	=	Newton-meters per radian, or torque stiffness.
l_1	=	Gauge length.
η	=	Shape factor (Table 3.6)
b	=	The cross-section's smaller dimension.
H	=	The cross-section's larger dimension.

Table 2 Shape factor values for the torsional shear modulus of isotropic rectangular cross-sections (EN 408 [1]).

h/b	1.0	1.2	1.5	2.0	2.5	3	4	5
η	0.14	0.17	0.20	0.23	0.25	0.26	0.28	0.29

The characteristic shear modulus was calculated in accordance with BS EN 384 [28].

2.2.4 Statistical Analysis

Every material has a unique shear modulus, including homogeneous materials like steel and concrete. However, timber is a material that exhibits significant variety between species and even within a single species. This is because timber is a biological substance. It should be noted, though, that statistical techniques can be used to detect strength variations in any species of timber.

The means and standard deviation of all shear modulus of timbers were computed using Minitab v 16.0 software to produce a normal distribution, which is shown in Figure 4, in order to establish a statistically estimated shear modulus.

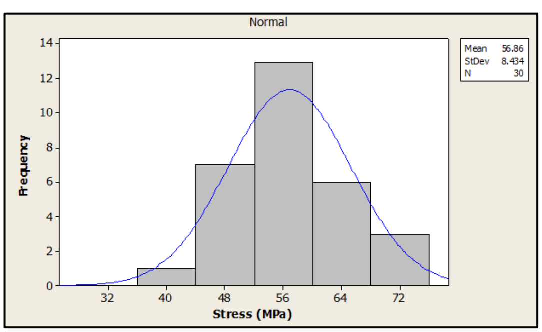

Figure 4 Histogram of Normal Distribution Function in determining means and standard deviation of all shear modulus of timbers

3.0 RESULTS AND DISCUSSIONS

3.1 Shear Failure Characteristics of Structural Size Specimens

Figure 5 illustrates the load versus displacement graph of the structural-size specimen under torsional shear parallel to the grain. The slopes on the graph represent the change in torque with respect to angular displacement, which is linked to the materials' shear modulus. Instead of comparing the strength features, its goal is to show the specimens' behavioral tendency. Due to the specimen's rapid fracture when it reached the maximum force, the entire graph displays brittleness.

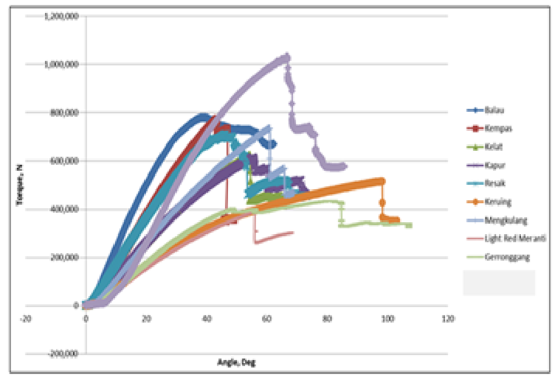

Figure 5 Torque vs Angular Displacement Graph for Timber Specimen Under Torsion Test

3.2 Shear Failure Characteristics (Structural Size)

Load and displacement for each specimen were continuously recorded throughout the entire test. Torsional failure instances, patterns, and reasons are shown in Figure 6 and Table 3 respectively.

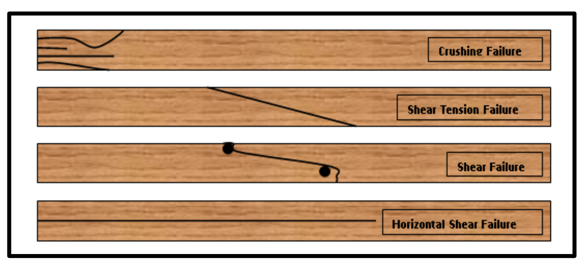

Figure 6 Torque vs Angular Displacement Graph for Timber Specimen Under Torsion Test

Table 3 Timber Species

Failure Modes	Pattern	Causes
Crushing	The initiation of cracks occurred in the earlywood zone of the radial-tangential (RT) plane and then extended towards the long side (LR) plane.	Compressive stress applied to the cross-sectional area of the test clamps.
Shear Tension	Shear fracture commenced at the center of the LT plane, advanced towards the LR plane, and terminated there as a result of tension.	Due to the cross-grain that is present.
Shear	The fractures leading to this failure mode usually initiated either on the top or bottom side	Both internal and external flaws, such as decay and knots, are present.
Horizontal Shear	Shear fractures commonly originated in the clear wood within the LR plane and propagated parallel to the longitudinal direction towards the supports.	Shear tension was the sole cause.

Table 4 provides a comprehensive breakdown of the failure characteristics expressed as a percentage for the mean torque parallel to grain observed in the structural size specimens used in this study.

Table 4 Summary of failure characteristics observed in structural size specimens under shear parallel to grain

Failure Type	Number	Failure Modes (%)	Mean Torque (N)
Crushing	9	0.5	1128500
Shear tension	118	6.6	1108303
Shear	66	3.7	1056437
Horizontal Shear	1607	89.3	1314969

According to the data in Table 4, horizontal shear failure exhibited a mean torque value of 1314969N. Horizontal shear cracks in clear timber typically initiated in the LR plane and propagated parallel to the longitudinal direction until they reached the end supports. Pure shear stress caused this type of breaking to occur since the sample was defect-free, resulting in significantly higher stress levels than other failure types. Crushing registered the highest mean torque (1128500 kN) among the four types of shear failure, followed by shear tension (1108303 kN), and shear (1056437 N). This suggests that the types of failures and their causes align with the mean torque levels.

Horizontal shear emerges as the predominant failure mode, with shear tension, shear, and crushing following as the other observed failure modes. The findings reveal that horizontal shear failure was observed in over 80% of all species, a promising result for our study. Less than 10% of all failures are attributed to shear tension and other flaws. The classification of these timbers as Hardwood Structural (HS) grade led to the conclusion that the likelihood of failure due to faults was low. Bodig and Jayne (1982) [32] posit that this behavior stems from the typical complex distribution of stresses in the material induced by internal inhomogeneities or defects, and that this deficiency in mechanical properties in timber will likely result in a decrease in mechanical properties.

3.3 Characteristic of Shear Modulus

Table 5 provides an overview of the shear modulus and physical characteristics of large-sized specimens. The moisture content for all species falls within the range of 12% to 15%. Since the average moisture content is below 19 percent. According to MS 544: Part 2 [14], the samples can be categorised as dry. This suggests that the moisture content in the samples does not have an effect. This enables the examination of the impact of density on the shear properties.

As depicted in Table 5 and Figure 5, the shear modulus values for all timbers exhibit the following order: Balau > Kempas and Resak > Kelat, Kapur, Keruing, and Mengkulang > Geronggang > Light Red Meranti. The shear modulus also not highly correlated with density (R^2 = 0.65) which is reflected by the order of shear modulus for all species.

Based on shear modulus values (as shown in Table 5 and Figure 7, there is notable differentiation in the distribution of species among the higher strength groupings of Resak, Mengkulang, and Geronggang, as evidenced by the strength distributions of Resak and Mengkulang, which tend to shift toward SG 2 and SG 5 species, respectively. Resak, on the other hand, exhibits a stronger strength distribution compared to the SG 4–5 species, Kelat, Kapur, and Keruing. Additionally, the strength groups of Mengkulang and Geronggang tend to surpass the values outlined in MS 544: Part 2 [14] (SG5 and SG6, respectively). These results demonstrate significant variation when compared to the strength groups specified in MS 544: Part 2 [14].

Table 5 Summary of Mean Shear Modulus for Large Size Specimens

Species	Shear Modulus			Density (kg/m³)	MC(%)
	Mean (MPa)	Standard Deviation (MPa)	COV %		
Balau	952.36	129.96	13.67	1018.93	12.71
Kempas	910.86	151.81	16.48	915.00	12.36
Kelat	590.11	90.78	15.50	980.76	14.13
Kapur	601.81	96.70	16.06	834.55	13.60
Resak	828.71	103.55	12.63	1028.53	12.47
Keruing	551.83	96.80	17.53	822.02	13.18
Mengkulang	597.68	88.00	14.51	743.38	13.06
Light Red Meranti	396.44	72.93	18.37	482.90	12.55
Geronggang	483.83	65.21	13.58	586.82	13.06

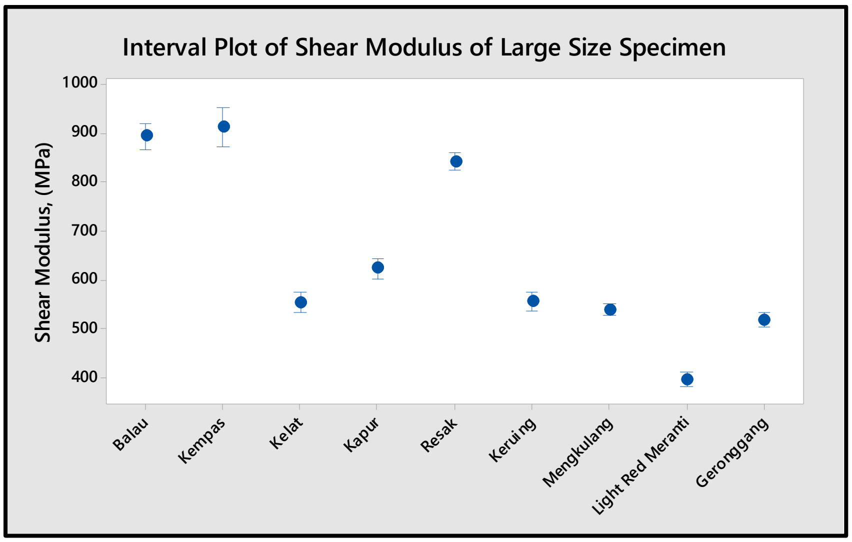

Figure 7 Interval Chart Depicting Shear Strength Properties of Large Size Specimens

3.4 Correlation Analysis between Torsional Shear Modulus (Experimental) and Modulus of Elasticity (MS544: Part 2)

To establish the correlation between the characteristic value of the mean shear modulus of structural-size specimens and the small clear specimens, the characteristic value of the bending modulus of elasticity taken from MS 544: Part 2 [14] was employed as a representative of the small clear specimen sample. Accordingly, the bending modulus of elasticity data sourced from MS544: Part 2 [14], were obtained through bending tests on small clear specimens.

The mean shear modulus, G_{mean}, is determined by substituting the mean modulus of elasticity (MOE) value of the bending strength (E_{mean}) into the formula provided by EN 384 [28] which is $G_{mean} = E_{mean}/16$. The correlation analysis between torsional shear modulus properties of structural size specimens, based on EN 384 [24], and small clear specimens (MS544: Part2 [14]) reveals variations in shear modulus distribution, as depicted in Figure 8.

Figure 8 illustrates the correlation analysis examining the relationship between the mean modulus of elasticity in bending and the mean torsional shear modulus value. The figure presents two sets of correlations. The first projected value is obtained by correlating the shear modulus (E_{mean} from MS544: Part 2 / 16) and modulus of elasticity (MS544: Part 2), showing $G_{mean} = 0.0625(E_{mean})$ or $1/16(E_{mean})$ with a correlation coefficient (R^2) of 1.

The second correlation equation, $G_{mean} = 0.0423(E_{mean}) + 80.773$, which represents the relationship between the torsional shear modulus (experimental) and modulus of elasticity (MS544: Part 2 [14]), is found to differ from the model presented in EN 384:2016, with a correlation coefficient (R^2) of 0.565. The strong E:G correlation coefficient observed, as depicted in Figure 8, supports this conclusion, given that the correlation coefficient (R^2) between these two parameters is 0.565. It can be inferred that a significant correlation coefficient is established when the correlation coefficient for timber mechanical characteristics exceeds 0.5, owing to timber being a non-homogeneous, organically grown material [33, 34, 35].

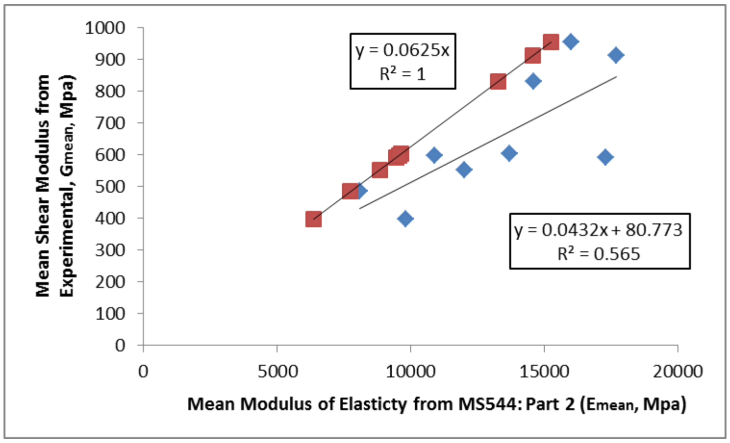

Figure 8 Correlation Analysis between Torsional Shear Modulus Properties of Structural Size Specimens Based on the EN 384 and Small Clear Specimens (MS544: Part2)

Table 6 illustrates the correlation between the torsional mean shear modulus and the bending mean modulus of elasticity. In the realm of timber design, the widely employed EG ratio of 16:1 is utilized to compute the shear modulus of timber. Consequently, this study compares the ratio of the bending mean modulus of elasticity to the shear modulus, as well as the EG 16:1 ratio, to assess the appropriateness of using 16:1 as a reliable ratio when calculating the shear modulus.

Kelat has the highest E:G ratio of 29:1 among all species, followed by Light Red Meranti (25:1), Kapur (23:1), Keruing (22:1), Kempas (19:1), Resak and Mengkulang (18:1), Balau and Geronggang (17:1), as shown in Table 6. This demonstrates that the E:G ratio is not constant. When the strength grouping and density of the samples are taken into account, the E to G ratio varies dramatically. The E:G ratio of all species was discovered to range from 17:1 to 29:1, with an average of 21:1.

The study's findings reveal a modulus of elasticity to shear modulus ratio of 21:1, which significantly surpasses the conventional 16:1 of E:G ratio. This result aligns with the E:G ratios of 23:1 and 26:1 documented by Khokhar [5] and Harrison [24], respectively. Based on these findings, the fluctuation in the E to G ratio suggests that using the mean modulus of elasticity value of structural timber for prediction could potentially underestimate the shear modulus value. Furthermore, a notable difference is observed when comparing the two correlations from Figure 8: $G_{mean} = 0.0625(E_{mean})$ and $Gmean = 0.0423(E_{mean}) + 80.773$.

Hence, the findings of this study do not offer evidence backing a correlation between the shear modulus and elasticity modulus at the conventional E:G ratio of 16:1. Instead, they suggest that the E:G ratio is inconsistent. Given the common use of thin and deep beams as continuous beams without lateral supports, it is strongly advised to determine the shear modulus through a torsion test. This is crucial for design purposes, as the pure shear modulus result (from torsion) tends to be smaller than the anticipated value obtained from the bending test shear modulus test.

Table 6 Characteristic Values of Torsional Shear Modulus and Bending Modulus of Elasticy

Species	Shear Modulus and Modulus of Elasticity			
	Mean Shear Modulus from Experimental, G_{mean} (MPa)	Experimental Mean Modulus of Elasticity , $G_{mean}\ x\ 16$ (MPa)	MS 544 Part 2 Mean Modulus of Elasticity E_{mean} (MPa)	Ratio, E_{mean}: G_{mean}
Balau	952.36	15237.76	16000	17:1
Kempas	910.86	14573.76	17700	19:1
Kelat	590.11	9441.76	17300	29:1
Kapur	601.81	9628.96	13700	23:1
Resak	828.71	13259.36	14600	18:1
Keruing	551.83	8829.28	12000	22:1
Mengkulang	597.68	9562.88	10900	18:1
Light Red Meranti	396.44	6343.04	9800	25:1
Geronggang	483.83	7741.28	8100	17:1

4.0 CONCLUSION

In conclusion, the study highlights the torsional shear modulus assessment of Malaysian Tropical Timber. Four distinct failure patterns were identified, with horizontal shear being the most common, followed by tension shear, shear, and crushing.

The shear modulus values for all timbers from torsion test exhibit the following order: Balau > Kempas and Resak > Kelat, Kapur, Keruing, and Mengkulang > Geronggang > Light Red Meranti. These sequences do not align with the strength grouping order in MS 544 Part 2. This provides evidence that the strength properties of large-size specimens may differ from those of small, clear specimens.

The ratio of the modulus of elasticity to shear modulus for all species are in the range of 17:1 to 29:1 with an average ratio of 21:1, which significantly surpasses the conventional 16:1of E:G ratio. Hence, the findings of this study do not offer evidence backing a correlation between the shear modulus and elasticity modulus at the conventional E:G ratio of 16:1. Therefore, further research needs to be conducted to investigate the torsional properties for other species.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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