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STRENGTH PREDICTION OF RSM IN BOLTED CONNECTION OF ALAN BATU WOOD

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Abstract

This study investigates the structural performance of bolted connections in Alan Batu wood to support the development of a local wood database for strengthening wall-diaphragm connections of unreinforced masonry (URM) buildings in Malaysia. Alan Batu wood was selected due to its common use as roof rafters and floor joists in URM buildings. Ten groups, each with ten replicates, were tested to assess bolted connection strength. Brittle failure was observed, confirming row shear failure. Since the material properties of Alan Batu are similar to Meraka wood, this study combines data from both to recommend design parameters (i.e., dry density and calibration factor) for optimising bolted connection strength predictions using the Row Shear Model (RSM). Analysis of the combined data showed that the Malaysian timber code (MS544-5) significantly underestimates bolted connection strength, potentially leading to over-sizing steel bolts and using more fasteners than necessary. The MS544-5 predictions had an average effectiveness of 45% compared to the 5th percentile experimental values, while the RSM showed a much higher average effectiveness of 80%. The design parameters proposed in this study optimise RSM strength predictions for Meraka and Alan Batu woods, offering cost-effective solutions for retrofitting URM wall-diaphragm connections.

Keywords: Alan Batu wood, Bolted connection, Row shear, Strength prediction, Timber code.

1. Introduction

Previous research on bolted connections in Malaysian woods has shown that wood failure can occur in either row shear parallel to the grain (brittle failure) [1-5] or bearing mode (ductile failure) [1, 3, 4, 6, 7], depending on bolt configurations or geometrical detailing. Quenneville [8] noted that the international timber engineering community agrees that design standards for timber bolted connections should be based on models that identify potential failure modes. Thus, the models should be capable of embodying both brittle and ductile failures.

The failure mode that results in the lowest strength should be the one that determines the connection capacity. The brittle failure data in [1-5] shows that the Malaysian timber code, MS544-5 [9], underestimates the bolted connection strength of woods like Bitis [1], Nyatoh [2, 3], and Meraka [4-5]. The article [1] stated that the MS544-5 can only estimate the bolted connections of Bitis wood with an average efficiency percentage of 68%, compared to the actual experimental strengths for connections that failed in brittle mode.

For Nyatoh wood, Ujan et al. [2] and Ujan [3] reported that the MS544-5 gives 44% of an average accuracy in strength prediction for the connections that failed in a similar failure mode. Both published literatures on Meraka wood in [4, 5] reported that the MS544-5 strength predictions give an average effectiveness of 41% for the brittle mode of failure. Table 1 compares the average effectiveness of MS544-5 and the Row Shear Model (RSM) for brittle failure. The comparisons clearly highlight issues with the existing timber standard, which tends to lead designers to over-design steel bolt sizes or quantities due to low strength predictions. Due to a lack of bolted connection data for Alan Batu wood, commonly used in roof rafters and floor joists in unreinforced masonry (URM) buildings, this study was conducted to assess its bolted connection capacity and validate the strength prediction effectiveness of MS544-5 and RSM.

Table 1. Effectiveness of MS544-5 versus RSM [1-5].

Published work	Wood species	Brittle	
		MS544-5	Row Shear Model (RSM)
[1]	Bitis	68%	74%
[2, 3]	Nyatoh	44%	68%
[4, 5]	Meraka	41%	79%

Referring to Section 11.2.3 of MS544-5 [9], it gives an equation to calculate the permissible load, F_{adm}, for a bolt connection system that is loaded parallel to the wood grain, as shown below:

$$F_{adm} = k_1\, k_2\, k_{16}\, k_{17}\, F \quad (1)$$

Refer to Section 11.2.1 of [9] and use Table 12 to estimate the F value by selecting b and d. The F in kN for a single bolt in single shear, either parallel or perpendicular, is determined based on the joint group ($J1$ to $J5$) in Table 1 of [9]. Because a double shear bolted connection was tested in the present study, the F value is required to be multiplied by two and by the number of bolts used in the joint system. The k_1 factor can be ignored in the F_{adm} calculation, as the testing load rate is short-term [10], and the connections are designed for retrofitting URM wall-diaphragm connections to resist short-term earthquake loads [11].

Since the present study's wood specimens were tested in dry conditions, based on the MS544-2 [12], the k_2 is equal to one. By considering b = 50 mm and d = 13 mm in this present study, the b/d ratio < 5, so k_{16} equals one. Table 15 of [9] states that the bolted joint is considered brittle when the k_{17} factor is less than one for joints with more than four fasteners. Many previous studies [13-23] have identified that the brittle failure of timber bolted connections is predominantly controlled by the geometrical configurations (i.e., e_t and s_b).

Research works on local Malaysian woods [1-5] and indigenous New Zealand woods [17, 18] reported that even connections with less than four bolts can fail in brittle mode. The timber code [9] assumption on the brittle mode controlled by $n_f \geq 5$ fasteners is totally contrary to the recent findings. Thus, in this present study, the use of k_{17} in the estimation of the permissible load is not considered. Due to MS544-5's misalignment in identifying brittle failure modes, the parameters for brittle failure in Alan Batu wood must be investigated.

This study investigates a single-row connection, so the Row Shear Model (RSM) by Quenneville and Mohammad [13] is used to compare prediction effectiveness with MS544-5 [9]. The connection's potential brittle failure mode is wood failure in row shear, as shown in Fig. 1. The RSM equation is as follows:

$$R_{r\,rs} = (2\;(f_v)\;K_{ls}\;t\;n_f\;a_{cr}\;n_r)/CF \tag{2}$$

The key parameters in the RSM equation for predicting the strength of bolted connections are f_v and CF. Previous work [5] found that using f_v values from Table 4 of [12] led to overly conservative strength predictions. The article recommends using $f_v = 17.8\ G^{1.24}$, according to the Wood Handbook [24], with G determined through a wood density test. Another critical parameter in optimising RSM strength prediction is CF. CF varies by wood species, as shown in studies on Bitis [1], Nyatoh [2, 3], and Meraka [4], so identifying CF for Alan Batu wood is essential. Since Alan Batu wood is comparable to Meraka wood [4, 5, 7], data from both sets were combined and analysed to determine the CF for optimising RSM strength prediction in Meraka+Alan Batu wood.

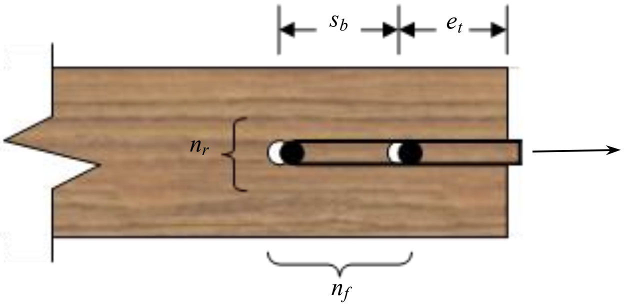


Fig. 1. Brittle failure mode of wood in row shear.

The present experimental study on bolted connection strength in Alan Batu wood aims to support the development of a local wood database for strengthening wall-diaphragm connections of URM buildings in Malaysia. Including Alan Batu in the database enhances the comprehensiveness of URM retrofit guidelines, offering more design parameters for various wood species. Expanding the database helps engineers select appropriate design parameters. Validating the prediction equations with laboratory results ensures the optimisation of timber bolted connections, promoting cost-effective and sustainable designs by reducing steel material usage (i.e., optimising bolt sizing and quantities).

2. Material Used and Method

2.1. Materials used

This research was conducted to develop an optimised retrofitting design for wall-diaphragm connections of unreinforced masonry (URM) buildings, specifically focusing on the bolted joints of timber floor joists or roof rafters. Details of typical wall-diaphragm connections, including wall anchorages and diaphragm connections, are available in [25, 26]. The selection of wood species for this study is crucial, and Alan Batu was chosen to improve genus identification with microscopic anatomy data, which was lacking for Meraka [4, 5, 7]. This investigation on Alan Batu enables a more comprehensive analysis of wood properties (density, embedding strength) and bolted connection strength, providing insights into potential variations despite similar property ranges. According to the Malaysian Timber Industry Board [27], wood strength groups suitable for structural use are classified from SG1 to SG4. The woods selected in this study are commonly used as structural rafters and joists for roof and floor diaphragms in URM buildings, falling within the strength groups described in [27].

From the pre-scanning wood identification using a 10X portable lens during the delivery of the present study wood supply, the wood material used was identified as Alan Batu or by other names like Meraka, Meraka Alan, Alan Batu, Sengawan, or Seringawan [12, 28]. This wood was found to be comparable to the Meraka wood investigated in [4, 5, 7], as both Alan Batu and Meraka belong to the *Shorea Albida* species in the *Dipterocarpaceae* family [12, 28]. One should note that the Meraka wood of [4, 5, 7] was also identified using the same pre-scanning method. To further verify the wood material, its average density was compared with that of Meraka wood from [4, 5, 7], as well as the density values reported by MS544-2 [12] and the Forest Department Sarawak (FDS) [28]. Table 2 shows the comparison between Alan Batu and Meraka wood, while Table 3 provides the average densities from [12] and [28]. The pre-scanning and density comparisons confirm that the wood used in this study is comparable to both Meraka wood [4, 5, 7] and Alan Batu wood [12, 28].

Table 2. Average density of Alan Batu and Meraka.

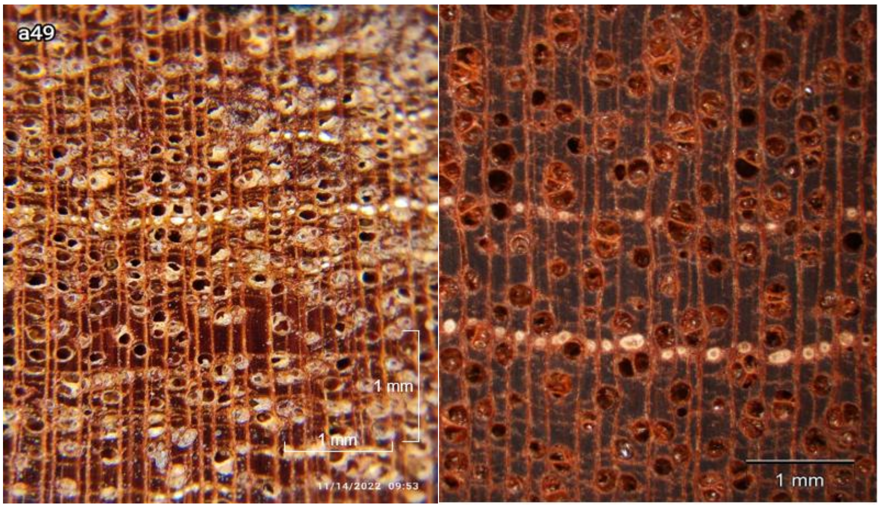
Source	Wood material used	Average density
Present study	Alan Batu	740 kg/m^3 at 16% moisture content
[4, 5, 7]	Meraka	827 kg/m^3 at 18% moisture content

Table 3. Average density of Alan Batu from [12, 28].

Source	Standard name	Other common name	Average density
MS544-2 [12]	Alan Batu	Meraka, Meraka Alan, Seringawan	850 kg/m^3 at 19% moisture content
FDS [28]	Alan Batu	Meraka, Sengawan, Seringawan	732 kg/m^3 at 18% moisture content

To confirm the genus of the wood material used, a comparison of the microscopic end grain sections from the present study (Fig. 2(a)) and the wood database library developed by the FDS (Fig. 2(b)) was conducted using the Xyloric Inspector WIDK-24X01. The anatomical similarities between the two figures, such as pore size, frequency, arrangement, pore contents, wood parenchyma, rays, and ray spacing, are evident. Readers may refer to [6, 29] for common anatomical features of hardwoods.

The comparison of Figs. 2(a) and 2(b) reveals medium-sized pores (50-100 µm), with a moderately numerous frequency (20-40 pores/mm²). The pores are mostly solitary or arranged in radial pairs, with occasional radial multiples (up to three pores). Tyloses, bubble-like structures, are abundantly present in both figures. Wood parenchyma appears in a wing-like shape (aliform) and is often confluent with neighbouring parenchyma. Scattered parenchyma strands are also visible. Rays, which run radially or vertically, are clearly identified, with normal spacing (4-12 rays/mm). Axial resin canals, filled with whitish deposits and arranged in short tangential concentric series, are also observable.



(a) Present study wood samples. (b) Dipterocarpaceae - *Shorea* ALAN BATU *albida* (Source from Wood Library, FDS).

Fig. 2. Endgrain microscopic sections (20x).

Based on the findings from the pre-scanning procedure, wood density comparisons, and anatomical characteristics of the microscopic end grain section, the wood material used in this study can be confirmed as Alan Batu. Therefore, throughout this paper, the term "Alan Batu" is used to refer to the wood material. The analysis in this study combines bolted connection test data from both the present study and the Meraka wood study [4, 5, 7] to provide optimized design strength for Alan Batu wood using the Row Shear Model (RSM) equation. The cross-sectional area of 50 mm (width) × 100 mm (height) for Alan Batu wood was selected, following the recommendation in Table B1 of MS544-2 [12] for common commercial timber sizes of Malaysian structural bare sawn timbers.

Other materials used in this study include 13-mm-diameter steel bolts and 15-mm-thick side steel plates. The bolted connection tests were conducted in a double shear configuration, with bolts of 85 mm shank length to ensure that the threaded bolt section did not contact the wood piece or the side steel plates.

A steel-wood-steel (SWS) type was applied to eliminate eccentricity complexities during testing and to ignore any moment resistance between the wood specimen and side steel plates. The bolts used were grade 4.6 mild steel, with an ultimate tensile strength of 400 MPa and yield strength of 240 MPa. The 15-mm-thick side steel plates, with an ultimate strength of 400 MPa, were used to ensure they did not fail in bearing during testing, allowing accurate evaluation of the timber bolted connection strength.

2.2. Method

To investigate the strength performance of bolted connections in Alan Batu wood, eighteen different connection groups, each with ten duplicate specimens, were prepared, resulting in 180 bolted connection samples. This sample size enabled a statistical analysis to determine the 5th percentile experimental strength for comparison with the characteristic strength of MS544-5 [9]. The 5th percentile serves as the basis for many international timber standards regarding characteristic strength determination [30-33], considering that timber is a highly variable material with significant strength variation.

This basis translates to at least 95% of the tested specimens exceeding the characteristic strength value, which ensures the structural reliability of bolted connections. Table 4 provides the configuration details for each group tested. The configuration details of e_t, s_b and n_f were chosen based on the possible bolted connections applied for roof rafters and floor joists that seated on or embedded into the masonry wall of URM buildings [17, 18].

Table 4. Specimens configuration details.

Group	End distance, e_t (mm)	Bolt spacing, s_b (mm)	Number of bolts, n_f
1	150	-	1
2	125	-	1
3	100	-	1
4	75	-	1
5	50	-	1
6	150	100	
7	125	100	2
8	100	100	2
9	75	100	2
10	50	100	2
11	150	50	2
12	125	50	2
13	100	50	2
14	75	50	2
15	50	50	2
16	100	50	3
17	75	50	3
18	50	50	3

Each test specimen was purposely prepared to have an identical bolted configuration at both ends to enable the capacity of the bolted connection governed by the joint's extremity that failed first. To ensure both ends function as a separate bolted joint, a minimum distance of 400 mm was fabricated in each test specimen as shown in Fig. 3, which is in accordance with the minimum 30*d* criteria in ISO/DIS 10984-2 [34]. For connections with a single row of fasteners ($n_r = 1$), a minimum edge distance (*a*) of 3*d* was maintained, as per [34]. The number of fasteners (n_f) varied from 1 to 3 bolts across the groups. Connections with either e_t or s_b set to 50 mm were prepared to maximise the occurrence of row shear failure in Alan Batu wood.

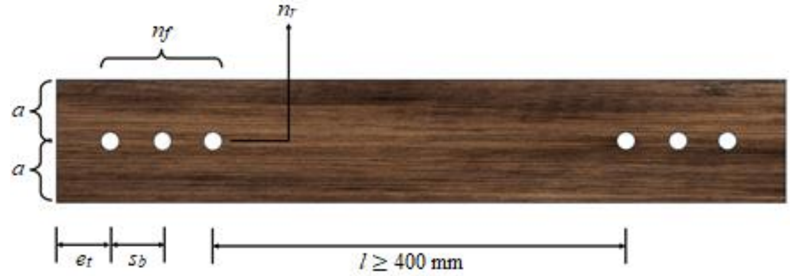


Fig. 3. Timber bolted connection configuration.

All connection specimens were loaded in monotonic tension parallel to the timber grain using a 300 kN Universal Testing Machine with a displacement-controlled loading rate of 1 mm/min [35]. To minimize friction between the wood and the side steel plates, and between the steel plates and bolt heads/nuts, the bolts were only finger-tightened to allow self-alignment of the bolted connection during loading. Specimens were loaded to failure, identified by a sudden drop in load from the load-displacement curve, which was plotted using the recorded load and displacement data. Failure modes observed in the wood specimen were marked, and any bolt bending failure was also noted.

The dry density of Alan Batu wood was determined, as it is an essential parameter for predicting bolted connection strength using the RSM equation. The density test followed the method outlined in Australian/New Zealand Standards [36], while moisture content was also monitored due to its impact on timber bolted connection resistance, following the procedures in Australian/New Zealand Standards [37]. As stated by the standards, both samples of density and moisture content tests shall be extracted from each tested timber specimen of the bolted connection tests for monitoring of the wood's physical properties.

A wood sample of 50 mm (width) × 50 mm (height) × 50 mm (length) was prepared, and its initial mass was recorded to 0.001 g accuracy (see Fig. 4). The sample was oven-dried at 103 °C ± 2 °C for 24 hours, then weighed to obtain the first day's oven-dry mass. The drying process was repeated in 24-hour cycles until a constant mass was achieved, typically after 3 days. The final constant mass and initial mass were used to calculate the moisture content. The oven-dry density was determined by subtracting the Day 0 mass from the Day 3 mass and dividing by the specimen volume. It is important to note that over-drying the wood sample beyond 3 days can result in the loss of wood oil content, leading to inaccuracies in the density measurement.

Fig. 4. Electronic scale with 0.001 g accuracy.

3. Results and Discussion

From Table 5, the oven-dry density and moisture content of Alan Batu wood were analysed based on data from all 180 specimens across groups 1-18. For comparison, similar data for Meraka wood from [4, 5] are also provided in Table 5. Since Alan Batu wood is comparable to Meraka wood, both dry density and moisture content data were combined and analysed to determine the average and 5th percentile Meraka+Alan Batu dry density for predicting bolted joint capacity using the Row Shear Model (RSM) equation. Note that all 5th percentile density values were calculated assuming a normal data distribution.

Table 5. Moisture content and dry density of Meraka [4, 5], Alan Batu, and Meraka+Alan Batu.

Species	No of specimens	ρ_{avg} (kg/m^3)	CoV	$\rho_{5th\%}$ (kg/m^3)	MC_{avg} (%)
Meraka [4, 5]	180	696	15	524	18
Alan Batu [present study]	180	636	11	523	16
Meraka+Alan Batu [present study]	360	666	14	513	17

Determining the moisture content of the wood samples is crucial, not only to ensure that the bolted connection specimens were tested in dry conditions but also because it significantly affects failure mode identification and connection capacity determination. Higher moisture content leads to softer wood, which causes crushing around the bolt hole and complicates failure mode interpretation. It also reduces the timber's strength in resisting bolt penetration, making the connection capacity assessment inaccurate. Moisture content monitoring revealed that all specimens had moisture contents ranging from 14% to 19%, confirming compliance with the MS544-2 [12] criterion of ≤ 19%.

From Fig. 5, it is evident that the specimens predominantly failed in row shear, with only minor bending of the steel bolts, which was occasionally unnoticeable.

Row shear failures were observed in timber bolted joints with geometrical parameters e_t = 50 mm or s_b = 50 mm. This highlights that the design parameters, a_{cr} = minimum of e_t and s_b, used in the RSM equation are more closely related to the connection failure mode than the k_{17} used by MS544-5.

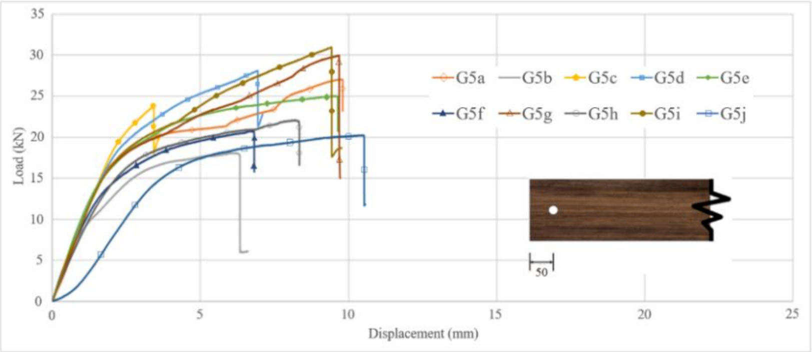
(a) e_t = 50 mm **(b) e_t = 100 mm, s_b = 50 mm** **(c) e_t = 50 mm, s_b = 50 mm**

Fig. 5. Observed brittle row shear failures of the tested specimens.

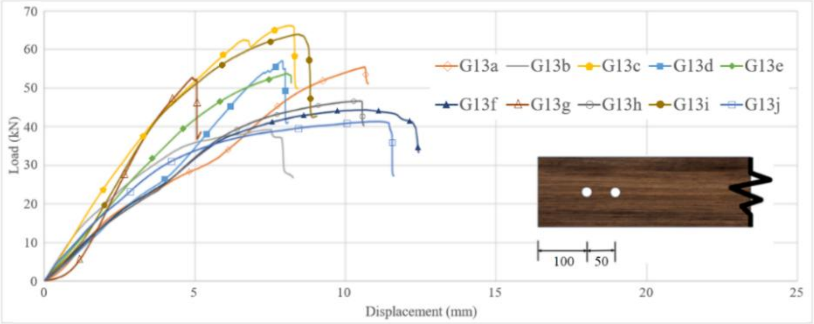
In groups 5 and 10-18, row shear failure was found in most specimens, while some failed in splitting. Figure 6 presents typical load-displacement curves for timber bolted connections that failed in brittle mode, showing a clear, sudden load drop at low displacement values. This abrupt load drop is associated with wood failure in row shear parallel to the grain, as evidenced by the wood-breaking sound heard upon failure and the noticeable load drop on the testing graph. As discussed, the failure mode in the bolted connections is primarily controlled by the minimum value of geometrical configurations between e_t and s_b. These geometrical configuration influences on the timber bolted connection failure were undoubtedly stated in other published research works [1-5, 8, 13-23].

The results and analyses of the bolted connections experimental data are summarized in Table 6. Since all samples were tested under local moisture content conditions, it is reasonable to compare the experimental results with the strength predictions from the Malaysian timber standard (MS544-5). To evaluate other equations for estimating strength, the RSM was also considered for comparison, as it was specifically derived to account for row shear failure. As this article focuses on bolted connections that failed in row shear, the results for groups 1-4 and 6-9 are not included in Table 6, as all specimens in these groups failed in wood bearing.

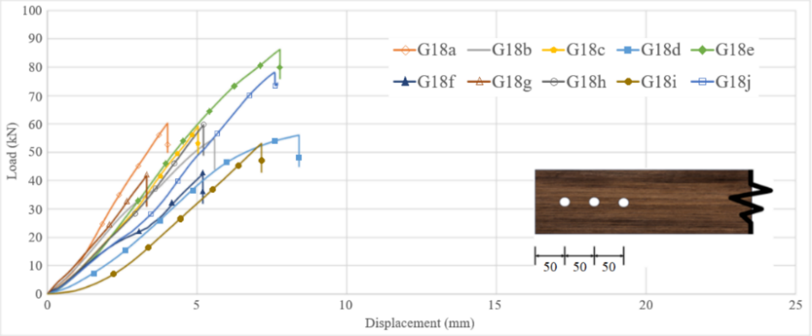
The experimental data presented are combined as Meraka+Alan Batu, and the average and 5th percentile strength values in Column 5 were calculated based on twenty specimens for each bolted connection group: 5, 10, 11, 12, 13, 14, 15, 16, 17, and 18. The CoV values in Column 6 show satisfactory data dispersion around the average. The experimental 5th percentile strength values in Column 7 allow for a comparison of predicted strength values from MS544-5 in Column 8 and RSM in Column 9. The MS544-5 predictions were calculated using the formula in Eq. (1), following the steps outlined in the second paragraph of the introduction. The RSM predictions were computed using Eq. (2), with shear strength correlated to the wood's dry density, as explained in the third paragraph of the introduction. The 5th percentile dry density value, $\rho_{5th\%}$, of the combined Meraka+Alan Batu data from Table 5 was used to calculate the 5th percentile strength predictions for RSM, as presented in Column 9 of Table 6.



(a) Group 5: et = 50 mm, nf = 1 bolt.



(b) Group 13: et = 100 mm, sb = 50 mm, nf = 2 bolts.



(c) Group 18: et = 50 mm, sb = 50 mm, nf = 3 bolts.

Fig. 6. Typical load versus displacement profiles for brittle failure.

The experimental 5th percentile strength values indicate that the connection capacity increases with the number of bolts. This is evident when comparing the strengths of 19 kN for Group 5, 39 kN for Group 15, and 45 kN for Group 18. To examine the effect of e_t on connection capacity, the three-bolt connections show a steady strength increase from 45 kN to 63 kN with rising e_t values (Groups 16, 17, and 18). However, since all specimens were fabricated with 50 mm for either e_t or s_b, the effect of geometrical configurations on strength for two-bolt connections is primarily controlled by the 50 mm parameter. For example, the strength of 32 kN in Group 10 was lower than 39 kN in Group 15, despite Group 10 having a higher s_b of 100 mm compared to the 50 mm s_b of Group 15. Regarding the effect of e_t, the strength values for Groups 11 to 15, all with two bolts and s_b = 50 mm, ranged from 32 kN to 43 kN. The highest strength of 43 kN occurred in Group 14 with e_t = 75 mm, while the lowest strength of 32 kN was found in Group 12 with e_t = 125 mm. These findings align with the RSM equation principle [8], which recommends using the minimum value between e_t and s_b as the input parameter for geometrical configurations in strength predictions for timber bolted connections.

Table 6. Predictions vs experimental results of Meraka+Alan Batu.

				Experimental			Predictions		Ratio	
	e_t	s_b		R_{avg}	*CoV*	$R_{5th\%}$	MS544-5	RSM	$\frac{\text{MS544-5}}{R_{5th\%}}$	$\frac{\text{RSM}}{R_{5th\%}}$
Group	**(*mm*)**	**(*mm*)**	n_f	**(*kN*)**	**(%)**	**(*kN*)**	**(*kN*)**	**(*kN*)**		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
5	50	-	1	25	14	19	8.20	14	0.43	0.75
10	50	100	2	49	22	32	16.40	29	0.52	0.91
11	150	50	2	53	17	38	16.40	29	0.43	0.75
12	125	50	2	50	21	32	16.40	29	0.51	0.89
13	100	50	2	51	14	39	16.40	29	0.42	0.73
14	75	50	2	55	13	43	16.40	29	0.38	0.68
15	50	50	2	50	13	39	16.40	29	0.42	0.75
16	100	50	3	79	12	63	24.60	43	0.39	0.68
17	75	50	3	74	19	51	24.60	43	0.48	0.85
18	50	50	3	62	17	45	24.60	43	0.55	0.96

Figure 7 plots the predicted vs. experimental strength to evaluate the accuracy of existing design equations. Predictions below the 45° line are considered safe but overly conservative if far below it. As shown in Fig. 7 and Table 6, MS544-5 [9] provides lower prediction values, with efficacy ratios between 38% and 55% (see Column 10), compared to the RSM, which has efficacy ratios between 68% and 96% (see Column 11). The over-conservative predictions require more steel materials, either through additional fasteners or larger bolt diameters, leading to uneconomical designs.

The RSM offers better accuracy, enabling more optimized and cost-effective connection designs. The RSM in Eq. (2) uses the shear parallel strength value related to specific gravity, equating to $17.8G^{1.24}$ [24]. While the Malaysian Timber Standard provides shear strength values parallel to the grain in Table 4 of MS544-2 [12], these values result in very low predictions of timber connection capacity, as highlighted by Abdul Karim et al. [5]. Therefore, this study does not adopt the shear strength value from MS544-2 in the RSM equation.

The calibration factor (*CF*) for the Meraka+Alan Batu combined data was validated by comparing the RSM's average strength predictions with the experimental average strengths. This was done iteratively with different *CF* values until the RSM's best-fit regression line aligned optimally with the 45° (1:1) reference line, as shown in Fig. 8. In statistics, the coefficient of determination (R^2) measures how well data fits the regression model. It quantifies the proportion of variance in the dependent variable (predictions) that is explained by the independent variables (experimental), expressed on a 0-100% scale. Higher R^2 values indicate stronger correlations between model predictions and experimental results. Referring to published work by Abdul Karim et al. [4], a *CF* of 2.5 for Meraka wood resulted in 99% R^2. However, this *CF* over-predicted the 5th percentile strength of Group 12 for Meraka (2-bolt connection with e_t = 125 mm and s_b = 50 mm) with a ratio of 1.10 compared to the experimental result. Therefore, this study proposes a *CF* of 2.7 for the Meraka+Alan Batu combined data, with 99% R^2 as shown in Fig. 8. A higher *CF* value was chosen to avoid unsafe or over-predicted 5th percentile strengths. Although a higher *CF* may lead to a conservative design, the proposed *CF* in the RSM shows an 80% average accuracy, compared to 45% for MS544-5.

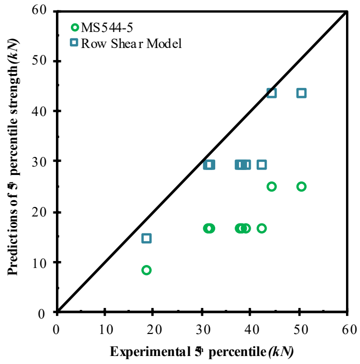


Fig. 7. Effectiveness of MS544-5 and RSM in strength prediction.

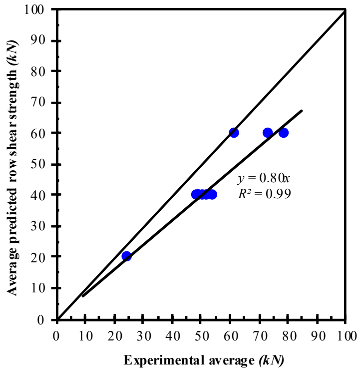


Fig. 8. Meraka+Alan Batu wood RSM calibration factor.

4. Conclusions

The strength of bolted connections in Alan Batu wood was investigated, with findings comparable to Meraka wood. This present study combines experimental data from both species to confirm the bolted connection design parameters. The key conclusions and recommendations are as follows:

- The brittle row shear failure mode and the strength of timber bolted joints are controlled by the minimum of e_t and s_b.
- The MS544-5 underestimates the strength of timber bolted joints by 45%, leading to over-designed connections with oversized bolts.

- The RSM optimises timber bolted connection strength with 80% efficacy, using the $\rho_{5th\%}$ of Meraka+Alan Batu, $f_v = 17.8\ G^{1.24}$, and $CF = 2.7$, leading to cost-effective and sustainable retrofit designs of wall-diaphragm connections in masonry buildings by using less steel materials.
- Due to the focus of the present study only on Alan Batu and Meraka woods, further research on other wood species is needed for broader applicability and the generalisation of design parameters for Malaysian woods.

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Nomenclatures

a_{cr}	Minimum of e_t and s_b, in mm
b	Effective timber thickness, in mm
CoV	Coefficient of variation
CF	Calibration factor
d	Diameter of bolt, in mm
e_t	End distance, in mm
F	Basic working load, in kN
F_{adm}	Permissible load, in kN
f_v	Member shear strength, in N/mm^2
G	Wood specific gravity
k_1	Load duration factor
k_2	Timber condition factor
k_{16}	Load transfer factor
k_{17}	Multiple bolted joint factor
K_{ls}	Member load surface factor
MC_{avg}	Average moisture content
n_f	Number of fasteners
n_r	Number of rows
s_b	Bolt spacing, in mm
t	Member thickness, in mm

Greek Symbols

$\rho_{5th\%}$	5th percentile dry density
ρ_{avg}	Average dry density

Abbreviations

RSM	Row Shear Model
URM	Unreinforced Masonry

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