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VALIDATION OF SHEAR FAILURE ON BOLTED CONNECTION FOR NYATOH HARDWOOD

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Abstract

The lack of consideration of brittle failure by the Malaysian Timber Standard (MS544-5) in the design of bolted connections for local hardwood can be seen from the unacceptable under-design performance shown by the code. This makes the design output costly because of the increased use of steel materials due to either bigger bolt diameters or larger bolt quantities required. The current study was conducted to examine the effectiveness of the existing design equations for bolted connections in Nyatoh hardwood. This present study was to propose a set of optimised equations that can be used for the retrofit design of wall-diaphragm connections in unreinforced masonry buildings. The row shear failure observed in the tested bolted connections of Nyatoh hardwood was also reported. Ten different bolted connection configuration details in the manner of a steel-wood-steel arrangement were tested, which all had a single row bolted connection. By using the linear regression method in analysing the experimental data obtained, a calibration factor for optimising the Row Shear Model (RSM) equation was identified. From the comparisons made between the experimental results and the strength predictions given by both MS544-5 and RSM, it was found that the design strength calculated from MS544-5 was too conservative for predicting the bolted connection strength in Nyatoh hardwood, whereas the RSM predictions were acceptable and recommended.

Keywords: Bolted connection, Brittle failure, Nyatoh hardwood, Shear failure, Timber standard.

1. Introduction

Malaysian timber standard base its timber bolted connection strength capacity prediction on the basis of ductile failure behaviour only. Referring to MS544-5 [1], the permissible load, F_{adm}, of a bolted connection loaded laterally can be found in Section 11.2.3 of the standards and given as follows.

$$F_{adm} = k_1 k_2 k_{16} k_{17} F \tag{1}$$

where,

k_1 = duration of load, refer Table 4 of [1];

k_2 = (i) dry timber is equal to 1 or (ii) wet timber is equal to 0.7;

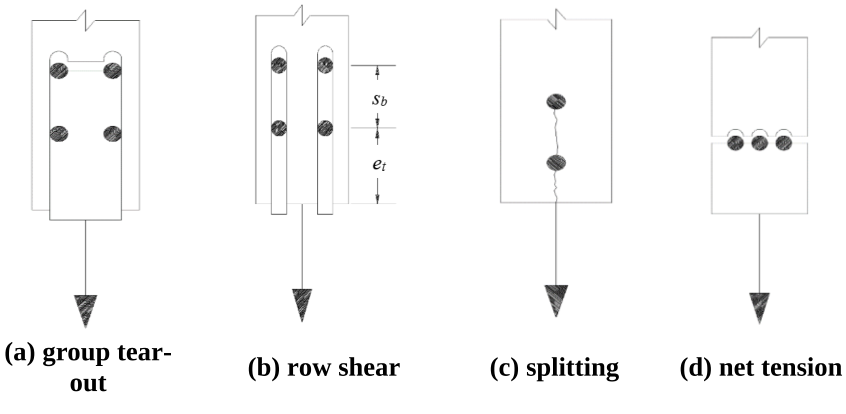
k_{16} = (i) 1.25 for bolts that transfer load through metal side plates of sufficient strength, and the bolts are a close fit to the holes in these plates provided that $b/d > 5$ for loads acting parallel to the grain and $b/d > 10$ for loads acting perpendicular to the grain (where b represents the effective thickness of timber and d indicates the bolt diameter) or (ii) 1.0 otherwise;

k_{17} = multiple bolted joint factor by referring to Table 15 of [1];

F = basic working load given in Section 11.2.2 of [1].

If one is to refer to Table 12 of [1], the basic working load, F, is estimated based on the selection of the bolt's diameter, d, and effective thickness of timber, b. Due to this, MS544-5 only considers ductile failure to predict the strength of bolted connections on timber. Brittle failure is only considered in the event the factor of multiple bolted joints is less than 1, where $k_{17} < 1$. Unless the bolted connection has more than or equal to five fasteners, the bolted connection is assumed to fail due to brittle behaviour.

By referring to many published research articles [2-12], bolted connection failures in brittle were also observed and not ductile only. The possible types of brittle failure modes in a bolted connection, loaded parallel to the timber grain, were reported by [2-5] as illustrated in Fig. 1. [6-10] underlined the significant influence of bolted geometrical configurations in the strength of multiple-fastener connections. [11, 12] mentioned that the equation of the Row Shear Model (RSM) was developed to predict the ultimate strength of the bolted connection based on the observed failure.



(a) group tear-out **(b) row shear** **(c) splitting** **(d) net tension**

Fig. 1. Brittle failure modes for timber bolted connection [2-5].

Due to the fact that this present study investigated a single row of bolted connections, only the row shear failure was considered the critical failure mode that governs the connection capacity in brittle. The RSM equation, which can be found in [12], to estimate the design capacity of a group dowel fastener per shear plane is given as follows.

$$R_{r\,rs} = RS_{i\,min}\, n_r \tag{2}$$

where,

n_r = number of rows in the joint as per load component;
$RS_{i\,min}$ = minimum (RS_1, RS_2, ..., RS_{nr});
RS_i = shear capacity along two shear planes of fastener row "*i*" in *N*;
= $\frac{2 f_v\, K_{ls}\, t\, n_{fi}\, a_{cri}}{CF}$;
f_v = member shear strength, in MPa; $17.8G^{1.24}$ as per Wood Handbook [13];
G = 5th percentile relative density of timber in the oven dry condition;
K_{1s} = factor for member loaded surfaces (0.65 - side, 1 - internal);
t = member in thickness, in mm;
n_{fi} = number of fasteners in a row "*i*";
a_{cri} = minimum of e_t and s_b for row "*i*", in mm;
CF = calibration factor.

As part of the improvement initiative for the wall-diaphragm connection design guideline to be used in retrofitting Malaysian unreinforced masonry buildings [2, 14, 15], it is essential to establish a database of bolted-connection experimental results on Malaysian local hardwoods in order to validate the existing design equations. The validation of the European Yield Model's (EYM) efficiency was reported in [16] to cover the ductile failure mode of bolted timber connections for the Nyatoh hardwood. To continue the verification of the brittle failure mode in bolted connections for Nyatoh hardwood, this present study reports herein the effectiveness of the RSM equation.

2. Experimental Materials and Approach

2.1. Materials used

Due to this present study was initiated to develop the wall-diaphragm connection design guideline for retrofitting the unreinforced masonry buildings in Malaysia, the selection of wood materials to be studied is very crucial. From [6], the wall-diaphragm connection is comprised of two major parts. The first part is the wall anchorage that can be in the form of either dowel or through-bolt types [17-19]. The second part is the diaphragm connection in the form of bolted connections that are commonly applied either to the joists or rafters of the timber floor or roof diaphragms, respectively [17-19].

Nyatoh is classified as a light hardwood and in class SG5 in terms of strength, accounting for a density of 750 kg/m^3 at 19% moisture content [20]. Despite being categorized as light hardwood, it can potentially be used as structural members such as joists and rafters [21]. As such, Nyatoh hardwood was chosen for this present study because of its potential use in the floor and roof diaphragms' construction of Malaysian unreinforced masonry buildings as structural joists and rafters that are commonly applied with bolted connections for retrofitting purposes.

Prior to conducting the bolted connection testing, the Nyatoh hardwood specimen went through a procedure of wood identification using a microscopic examination to determine the anatomical characteristics. The wood identification procedure is very important to ensure the reliability of the selection of the timber specimens to be further tested in determining their mechanical properties. Because this article was mainly written to discuss the possibility of the Nyatoh hardwood to fail in the brittle mode, specifically in the shear failure mode, all details on the wood identification, from the specimen preparation up to the wood genus verification, can be obtained from [16].

Because this present study investigates the steel-wood-steel (SWS) bolted connections, a pair of 15 mm thick side steel plates was used. The plates are mild steel with a 400 MPa ultimate tensile strength (f_{up}). A 13-mm-diameter (d) mild steel bolt of grade 4.6 was used as the fastener. To avoid the threaded bolt part touching the wood specimen, a shank length of 85 mm was used.

2.2. Bolted connection test

In the bolted connection test on Nyatoh hardwood, the cross-sectional size of 50 mm (width) by 100 mm (height) wood planks was cut into several specimen lengths in the range of 500 mm to 800 mm, depending on the bolt connection configurations. This cross-section dimension was chosen as this is one of the most common nominal sizes used for structural members, as per [20]. All specimens were then drilled following the bolted configurations as shown in Table 1. The pre-drilled holes of 14 mm in diameter were applied to all specimens as per the recommendation in [1] that they must be at least 10% bigger than the bolt diameter.

A total of ten groups of bolted connections with one to three bolts were tested. The end distances, e_t, of 50 mm to 125 mm were used. Most of the specimens are fabricated with a spacing of 50 mm between bolts (s_b) in order to maximise the observation of shear failure in the wood specimen. Each group has 10 replications, which in turn gives a total of 100 specimens involved in the bolted connection testing programme. Each specimen has a similar bolted configuration at both extremities. To ensure two independent bolted connections are assessed in each specimen during testing, a minimum distance of l_4 was set at 400 mm to comply with [22].

All bolted configuration details are defined in the illustration given in Fig. 2. Once all specimen preparation works were completed, all specimens were stored in a staggered pile at room temperature for an air-drying period of at least two weeks. This was done to ensure a dry state specimens were achieved before tested. According to [20], a wood specimen with a moisture content of 19% or less is considered to be in a dry condition.

Because this present study is the continuation of [16], in further investigating the shear failure of Nyatoh hardwood, similar experimental setup and procedures outlined in [16] were conducted. All bolted connection specimens were loaded in tension parallel to the timber grain using the 300 kN universal testing machine. The loading rate of 1 mm per minute [23] was applied to the wood specimen through the two side steel plates with bolted connection up to three fasteners.

All bolts were applied with a finger tight force to allow self-alignment of specimens during testing. The ultimate load of any extremity that failed was taken as the capacity of the connection. Also recorded was the failure mode observed on each wood specimen after testing.

Table 1. Groups of bolted connection configurations.

Group	End distance, e_t (mm)	Spacing between bolts, s_b (mm)	Number of bolts, n_f	Total specimen length (mm)
1	50	-	1	500
2	50	100	2	700
3	150	50	2	800
4	125	50	2	750
5	100	50	2	700
6	75	50	2	650
7	50	50	2	600
8	100	50	3	800
9	75	50	3	750
10	50	50	3	700

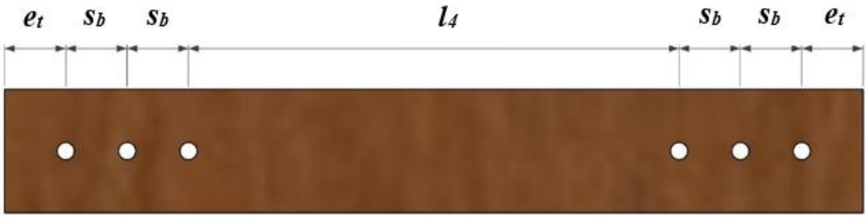


Fig. 2. Bolted configuration details.

2.3. Embedding strength test

All tested specimens of bolted connections in this study were extracted for the embedding strength tests, even though the embedding strength, f_h, value is only the important parameter for the EYM equation, which this article did not discuss on the effectiveness of the EYM strength prediction. This is because the f_h values reported by [16] were analysed based on 78 specimens as shown in Table 2.

Thus, this article includes the analysis of 183 specimens for the determination of the embedding strength of the Nyatoh hardwood. Both the specimen preparation and testing method were performed in accordance with the [22] recommendations.

One should note that, the updated data on the embedding strength of Nyatoh hardwood reported herein supersedes the previous data provided by [16]. Thus, the value of $f_{h,5th\%}$ of 23.22 MPa shall be used by the designer for the EYM equations.

Table 2. Embedding strength of Nyatoh hardwood.

Reported by	No. of Specimens	$f_{h,avg}$ (MPa)	CoV (%)	$f_{h,5th\%}$ (MPa)
[16]	78	37.25	16.62	27.07
Present study	183	34.69	20.09	23.22

Notes:
$f_{h,avg}$ = Average embedding strength
CoV = Coefficient of variations
$f_{h,5th\%}$ = 5th percentile embedding strength

2.4. Moisture content and density test

Since the effect of moisture content in the wood specimen is significantly reducing the strength of bolted connections, monitoring of the moisture content for each specimen was performed. Adopting the procedure from [24], all moisture content specimens that were extracted from the tested bolted connection specimens were oven dried until a constant mass was achieved. From the results of the moisture content test, each specimen can be identified as being in a dry condition or not. This was performed to ensure the strength of the tested bolted connections was not influenced by the wet conditions.

Because this article was intended to validate the RSM's efficiency in predicting bolted connection strength, the density of all tested bolted connection specimens was also identified. The same specimens prepared for the moisture content test were used in the density test. The density test was conducted in accordance with the method outlined in [25].

3. Results and Discussion

3.1. Moisture content and density results

From the results shown in Table 3, the calculations to determine both the average and 5th percentile values were based on 200 specimens. The 5th percentile value was calculated by considering a normal data distribution of the results obtained. The average moisture content was found at 16%, which is less than 19% as per requirement of [20]. Thus, all bolted connection specimens were confirmed to be in dry condition during testing.

The average density at 16% average moisture content was 651 kg/m^3 with a standard deviation of 81. This is found to be comparable to the values of (i) 628 kg/m^3 at 18% moisture content with a standard deviation of 101 given by [21] and (ii) 750 kg/m^3 at 19% moisture content stated by [20].

One must note that the density values given in Table 3 are the dry densities of Nyatoh hardwood that were used in the prediction of the bolted connection capacity using the RSM equation.

Table 3. Moisture content and density results of Nyatoh hardwood.

Hardwood	No. of specimens tested	ρ_{avg} (kg/m^3)	CoV (%)	$\rho_{5th\%}$ (kg/m^3)	MC_{avg} (%)
Nyatoh	200	574.33	12.39	457.25	16

Notes:
ρ_{avg} = Average dry density
CoV = Coefficient of variations
$\rho_{5th\%}$ = 5th percentile dry density

3.2. Bolted connection test results

In general, most of the tested specimens in all groups (G1-G10) were observed to fail in row shear, hence, the dominant brittle failure mode out of ten specimens in each group of the tested bolted connection samples. Figure 3 shows the occurrence of the row shear failure that can be observed in the G5 specimen, where the s_b was

50 mm. Another specimen from G2, shown in Fig. 4, with an e_t of 50 mm instead, was also found to fail in the row shear mode.

From the observations made on all tested specimens, the row shear failure was observed when the bolt configurations of either e_t or s_b equalled 50 mm. This is in line with findings in many published literatures [2, 6], where the row shear failure can be potentially observed in the timber bolted connection with 50 mm or less for e_t or s_b.

In this present study, all specimens were not found to have any enlargement of bolt holes or wood in bearing. There were also no bending failures on the fasteners that were significantly visible. Thus, any bolt configurations for Nyatoh hardwood with either e_t or s_b 50 mm or less are most likely to fail in row shear.

Fig. 3. Bolted connection specimen with s_b = 50 mm and e_t = 100 mm.

Fig. 4. Bolted connection specimens with s_b = 100 mm and e_t = 50 mm.

Experimental data from each group of bolted connections was plotted in a graph as shown in Fig. 5. The ultimate capacities of each group calculated as average and 5th percentile are tabulated in columns 5 and 7 of Table 4, respectively. The experimental 5th percentile strength values were calculated following the variation of the normal distribution curve. The RSM 5th percentile strength prediction was also calculated using the same variation curve that are tabulated in column 8.

These were done to enable a comparison with the characteristic strength provided by the MS544-5 [20] because the timber bolted connection capacity given by the design code is calculated based on the lower 5th percentile value [15]. In other words, at least 95% of the timber bolted connection samples should have capacity that is higher than that value.

Before comparisons between the RSM predictions and experimental results were made herein, the geometrical influence of s_b and e_t and the effect of bolt numbers on the ultimate strength capacity of bolted connections were discussed in the next paragraphs.

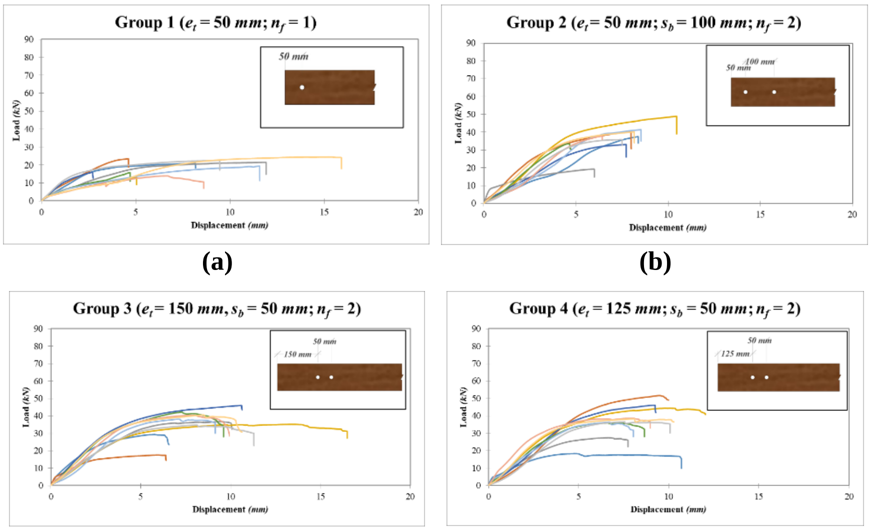
Comparing the 5th percentile strength between G7 and G2, the strength value increases as s_b increases from 50 mm in G2 to 100 mm in G7. The increase in e_t, from 50 mm in G10 to 75 mm in G9 and 100 mm in G8 was found to increase the 5th percentile strength. This can also be seen in a comparison between G7, G6, and G5.

In general, the increments of e_t and s_b cause the increment of the bolted connection capacity. However, when further comparison is made between G5, G4, and G3, one can see that the 5th percentile strength was reduced even with the e_t increases from 100 mm in G5 to 125 mm in G4 and to 150 mm in G3.

This shows that for connections with two bolts and more, a minimum value between e_t and s_b must be taken as the critical distance that governs the bolted connection capacity. Therefore, the principle of a_{cri} used in the RSM equation is valid.

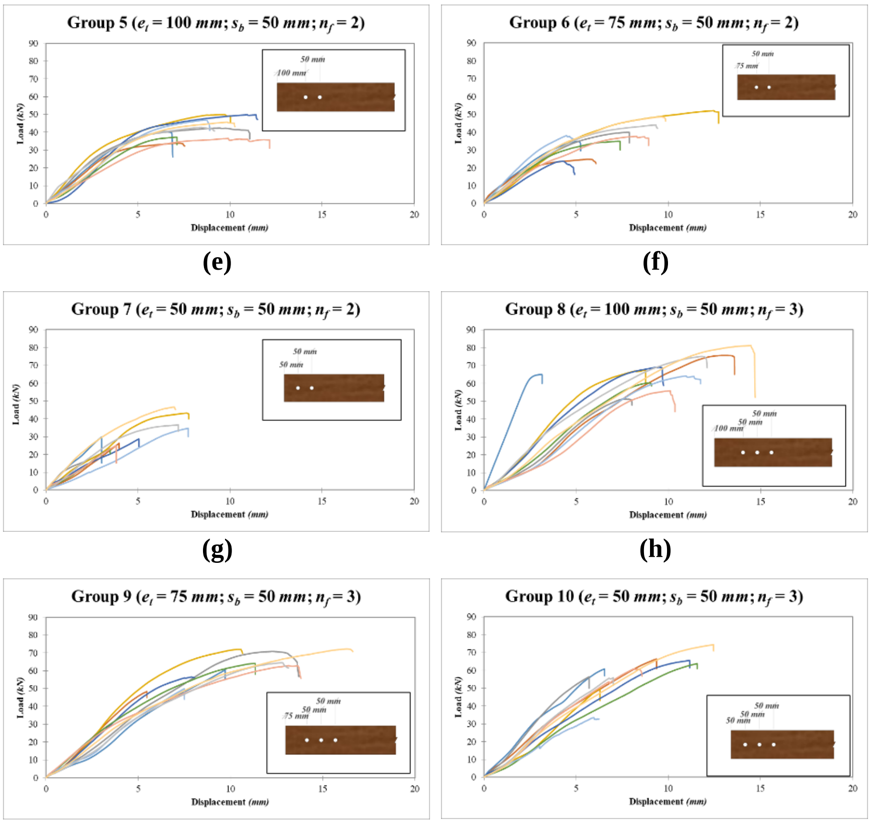
From the perspective of ultimate strength being affected by the number of bolts, in general, the increment in strength can be seen when the number of bolts increases. By comparing the 5th percentile strengths of one-bolt (G1), two-bolt (G2-G7), and three-bolt (G8-G10) connections, the normalised strength ratio can be seen as follows: G1 (1.00), G2 (2.00), G3 (1.92), G4 (1.75), G5 (2.75), G6 (1.92), G7 (1.42), G8 (4.25), G9 (4.00), and G10 (3.42). These showed that, on average, the two-bolt connections can almost double the strength, whereas the three-bolt connections can triple or nearly quadruple the strength.

As the calculated RSM strength predictions in column 8 of Table 4 depend on the calibration factor, the determination of the calibration factor for RSM optimisation is described in the next paragraph.



(a) (b)

(c) (d)



(e) (f)

(g) (h)

(i) (j)

Fig. 5. Experimental data plotted into load versus displacement graphs (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4, (e) Group 5, (f) Group 6, (g) Group 7, (h) Group 8, (i) Group 9, and (j) Group 10.

Table 4. Bolted connection strength - experimental versus predictions.

				Experimental			Predictions		Ratio	
Group (1)	e_t (mm) (2)	s_b (mm) (3)	n_f (4)	R_{avg} (kN) (5)	CoV (%) (6)	$R_{5th\%}$ (kN) (7)	RSM (kN) (8)	MS544-5 (kN) (9)	$\frac{RSM}{R_{5th\%}}$ (10)	$\frac{MS544\text{-}5}{R_{5th\%}}$ (11)
1	50	-	1	19	21.44	12	8	5.48	0.68	0.44
2	50	100	2	37	20.81	24	17	10.96	0.70	0.45
3	150	50	2	36	22.08	23	17	10.96	0.74	0.48
4	125	50	2	37	26.34	21	17	10.96	0.82	0.53
5	100	50	2	43	13.07	33	17	10.96	0.51	0.33
6	75	50	2	38	24.13	23	17	10.96	0.74	0.48
7	50	50	2	32	27.34	17	17	10.96	0.98	0.63
8	100	50	3	67	13.94	51	25	16.44	0.50	0.32
9	75	50	3	62	13.74	48	25	16.44	0.53	0.34
10	50	50	3	59	18.92	41	25	16.44	0.63	0.41

Referring to the RSM equation, one can see that the standard calibration factor of two (2) is commonly used [12]. However, from [15], it shows that a different wood has a specific calibration factor. By analysing the experimental data in this present study, the calibration factor can be identified for the strength optimisation of bolted connections specifically for Nyatoh hardwood.

A linear regression method as stipulated in [15] was implemented, whereas a calibration of 4 was identified. In the analysis, 55% similarities between the average RSM predictions and the average experimental data were recommended, as shown in Fig. 6. This was done to avoid an over-prediction of characteristic strength by the RSM equation. A good value of the coefficient of determination (R^2) 0.99 was obtained.

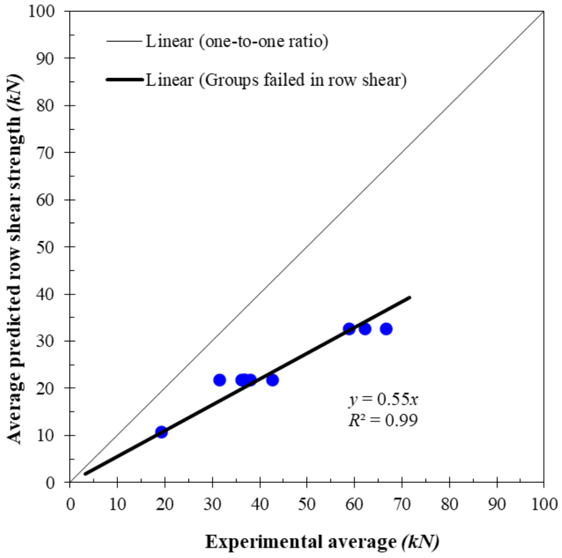


Fig. 6. Linear regression method for calibration factor determination.

For the comparisons between the 5th percentile experimental results and prediction values given by both RSM and MS544-5, columns 8 and 9 of Table 4 are referred to, respectively. In order to measure the effectiveness of the prediction values, the ratios of both RSM and MS544-5 over the 5th percentile experimental data in column 7 were calculated and tabulated in the final two columns (10 and 11) of Table 4. From column 10, it can be seen that the efficiency of RSM predictions ranged from 50% to 98%, or 68% on average. A low efficacy was seen in MS544-5 with a range from 32% to 63% as per column 11, which is only 44% on average.

For a better comparison on effectiveness in predicting the bolted connection strength between RSM and MS544-5, a graph of predictions against experimental results with a 45° reference line was plotted as shown in Fig. 7. The strength predictions plotted under the reference line are considered safe, while those plotted above the reference line are over-predicted or unsafe. However, the reader must take note that any plotted strength predictions that are deemed too low from the reference line should be classified as too conservative.

As seen in Fig. 7, the MS544-5 predictions are far too low compared to the reference line, whereas the RSM predictions are better. This causes the MS544-5 outputs of the bolted connection design for Nyatoh hardwood to be over-designed, which can cause the designer to increase either the diameter or number of fasteners. Therefore, the use of the RSM equation for the bolted connection design to retrofit the wall-diaphragm connection in unreinforced masonry buildings is found to be more practical and recommended.

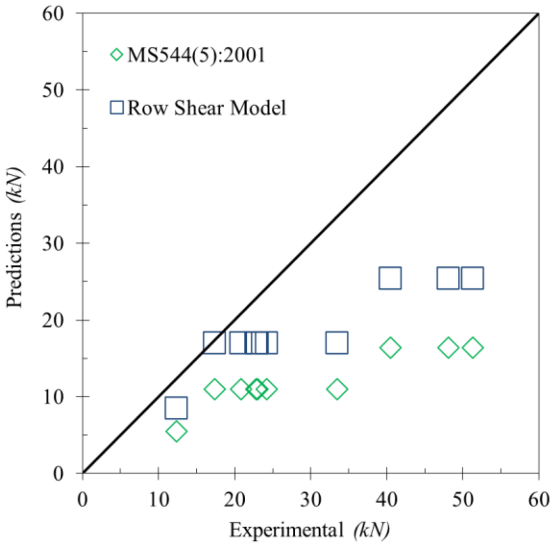


Fig. 7. Effectiveness of MS544 and Row Shear Model in predicting ultimate strength of bolted connections.

4. Conclusions

From the findings of this present work, it can be seen that the observed failure mode in most tested specimens with 50 mm, either the end distance (e_t) or bolt spacing (s_b) was primarily in the form of a row shear failure. It validates this brittle failure mode on bolted connection for Nyatoh hardwood, which controls by the geometrical parameters of e_t and s_b. Besides, these e_t and s_b parameters significantly affect the ultimate strength of the timber bolted connections, not only the number of bolts (n_f).

The calibration factor of 4 was identified for the Row Shear Model (RSM) equation, to be used by the designer for the strength optimisation of bolted connection for Nyatoh hardwood.

From the effectiveness evaluation made, this present study verifies that the MS544-5 was too conservative in providing the design strength of bolted connections for Nyatoh hardwood with an average effectiveness of 44% when compared to the actual experimental results. A more satisfactory average efficiency of 68% can be obtained using the RSM equation. Therefore, the use of RSM equation is recommended in the bolted connection design for the purpose of retrofitting the wall-diaphragm connections of unreinforced masonry buildings.

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References

1. Department of Standards Malaysia (2001). MS 544: Part 5: 2001 Code of practice for structural use of timber: Part 5: Timber joints. Department of Standards Malaysia.
2. Abdul Karim, A.R.; Quenneville, P.; and Sa'don, N.M. (2021). Shear failure of the Meraka hardwood in bolted connections loaded parallel to the timber grain. *IOP Conference Series: Materials Science and Engineering*, 1101, 012005.
3. Yurrita, M.; and Cabrero, J.M. (2021). On the need of distinguishing ductile and brittle failure modes in timber connections with dowel-type fasteners. *Engineering Structures*, 242, 112496.
4. Yurrita, M.; Cabrero, J.M.; and Quenneville, P. (2019). Brittle failure in the parallel-to-grain direction of multiple shear softwood timber connections with slotted-in steel plates and dowel-type fasteners. *Construction and Building Materials*, 216, 296-313.
5. Quenneville, P. (2018). Brittle failures of connections loaded parallel-to-grain. *Proceedings of the COST Action FP1402, International Conference on Connections in Timber Engineering-From Research to Standards*, Graz, Austria, 154-165.
6. Abdul Karim, A.R.; Quenneville, P.; Sa'don, N.M.; and Ingham, J. (2013). Assessment guidelines of wall-diaphragm connections for masonry buildings. *New Developments in Structural Engineering and Construction*, Volume II, 1-6.
7. Quenneville, P. (2009). Design of bolted connections: A comparison of a proposal and various existing standards. *Journal of Structural Engineering Society*, 22(2), 57-62.
8. Quenneville, J.H.P.; and Jensen, J. (2008). Validation of the Canadian bolted connection design proposal. *Proceedings of the CIB-W18 meeting*, paper CIB-W18/41-7-2, St. Andrews, Canada.
9. Quenneville, J.H.P.; Smith, I.; Aziz, A.; Snow, M.; and Ing, H.C. (2006). Generalised Canadian approach for design of connections with dowel fasteners. *Proceedings of the CIB-W18 meeting Proceedings*, paper CIB-W18/39-7-6, Florence, Italy.
10. Quenneville, P.; and Bickerdike, M. (2006). Effective in-row capacity of multiple-fastener connections. *Proceedings of the CIB-W18 meeting*, paper CIB-W18/39-7-1, Florence, Italy.
11. Mohammad, M.; and Quenneville, J.H.P. (2001). Bolted wood-steel and wood-steel-wood connections: Verification of a new design approach. *Canadian Journal of Civil Engineering*, 28(2), 254-63.

12. Quenneville, J.H.P.; and Mohammad, M. (2000). On the failure modes and strength of steel-wood-steel bolted timber connections loaded parallel-to-grain. *Canadian Journal of Civil Engineering*, 27, 761-73.
13. Forest Products Laboratory (1987). *Wood Handbook: Wood as an engineering material*. Forest Service U.S. Department of Agricultural, Washington, D.C.
14. Abdul Karim, A.R.; Quenneville, P.; Sa'don, N.M.; and Yusof, M. (2018). Investigating the Meraka hardwood failure in bolted connections parallel to the timber grain. *International Journal of Engineering & Technology*, 7(3.18), 62-65.
15. Abdul Karim, A.R.; Quenneville, P.; and Sa'don, N.M. (2022). Design optimization of the bolted connection loaded parallel to the timber grain for masonry building retrofits. *International Journal of Mechanics*, 16, 6-14.
16. Ujan, X.L.; Karim, A.R.A.; Sa'don, N.M.; Yao, T.X.; Quenneville, P.; and Rahim, N. L. (2022). Effectiveness validation on existing design equations for the sustainable design of masonry building retrofits. *Journal of Sustainability Science and Management*, 17(6), 79-91.
17. Abdul Karim, A.R. (2012). *Seismic assessment of wall-diaphragm connections in New Zealand unreinforced masonry buildings*. PhD thesis. The University of Auckland, New Zealand.
18. Federal Emergency Management Agency (2006). Techniques for the seismic rehabilitation of existing buildings. FEMA 547. Federal Emergency Management Agency, Washington, D.C.
19. New Zealand National Society for Earthquake Engineering (1995). Draf guidelines for assessing and strengthening earthquake risk buildings. New Zealand National Society for Earthquake Engineering, Wellington, New Zealand.
20. Department of Standards Malaysia (2001). MS 544: Part 2: 2001 Code of practice for structural use of timber: Part 2: Permissible stress design of solid timber (First Revision). Department of Standards Malaysia.
21. Forest Department Sarawak (1999). *Handbook of some Sarawak timbers*. Forest Department Sarawak, Kuching, Sarawak, Malaysia.
22. International Organization for Standardization (2008). Draft international standard ISO/DIS 10984- 2 timber structures - dowel-type fasteners - Part 2: Determination of embedding strength and foundation values. International Organization for Standardization, Geneva, Switzerland.
23. International Organization for Standardization (1983). International standard ISO 6891 timber structures - joints made with mechanical fasteners - general principles for the determination of strength and deformation characteristics. International Organization for Standardization, Geneva, Switzerland.
24. Australian/New Zealand Standard (1997). AS/NZS 1080.1: 1997 Timber - Methods of test - Method 1: Moisture content. Standards New Zealand (electronic copy).
25. Australian/New Zealand Standard (2000). AS/NZS 1080.3: 2000 Timber - Methods of test - Method 3: Density. Standards New Zealand (electronic copy).