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Technical paper

Investigating the Meraka Hardwood Failure in Bolted Connections Parallel to the Timber Grain

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Abstract

The present study was performed to investigate the ductile failure mode of timber bolted connections, specifically in Meraka hardwood. This was done to initiate an effort in developing a comprehensive guideline in designing the timber bolted connections for the purpose of strengthening the wall-diaphragm connections of the Malaysia unreinforced masonry buildings. A series of experimental tests was conducted on the steel-wood-steel (SWS) with a single row connection type. A total of eight different bolted connection configurations or groups with ten replicates for each group was tested. The Meraka hardwood was selected in this study as it was found to be one of the most hardwood species that are commonly used in the construction of floor and roof diaphragms in the existing Malaysia unreinforced masonry buildings. From the experimental results obtained, the effectiveness of the Malaysian timber code of MS544 and European Yield Model (EYM) in predicting the bolted connection strength was verified. It was determined that the MS544 is too conservative in estimating the bolted connection strength with an average ratio of 0.38 compared to the test results. Thus, the use of the EYM is recommended to complement the timber code as the average ratio of 0.81 was identified in comparison to the test data.

Keywords: *Meraka wood, timber bolted, connections, strength prediction*

1. Introduction

In principle, there is an agreement within the international timber engineering community that the criteria in timber design standards for determining the capacity of bolted connections should be based on the recognized mechanical models that are capable of identifying each possible mode of failure [1]. The lowest capacity that governs performance of connection should be estimated from both failure modes of ductile/bearing and brittle/fracturing in wood. The following paragraphs describe the current design equations to predict the strength of bolted connections, parallel to the timber grain, for both Malaysian timber standard and European Yield Model.

Referring to the Malaysian timber standard of MS544: Part 5: 2001 in Section 11.2.3, the permissible load (Fadm) of a laterally loaded bolt system is given by:

$$F_{adm} = k_1 k_2 k_{16} k_{17} F \qquad \text{(Eq. 1)}$$

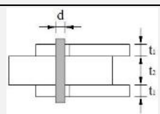
where

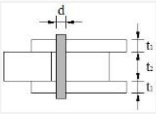
- k_1 = the factor for duration of load, refer to Table 4 of MS544: Part 5: 2001;
- k_2 = 1.0 for dry timber or 0.7 for wet timber;
- k_{16} = 1.25 for bolts that transfer load through metal side plates of adequate strength and the bolts are a close fit to the holes in these plates provided that b/d > 5 (where b denotes the effective timber thickness and d is the bolt diameter) or 1.0 otherwise;
- k_{17} = factor for multiple bolted joint, see Table 15 of MS544: Part 5: 2001;
- F = basic working load as derived in Section 11.2.2 of MS544: Part 5: 2001.

The values of the basic working load for a selection of bolt diameter and effective timber thickness can be taken from Table 12 of MS544: Part 5: 2001 considering for a single bolt bearing parallel to the timber grain acting in single shear. This shows that the timber code assumes the behaviour of connections to be ductile. A brittle failure is assumed to occur only in a connection that consisting of five or more fasteners, taken into account a value of $k_{17} < 1$.

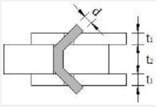
The European Yield Model (EYM), which considers ductile failure modes of bolted connections, is associated with the Johansen's theory. This theory is based on the assumption that both timbers and dowels behave as rigid-plastic [2]. In other words, the timber is under embedding stresses due to the bearing action as in contact with the fastener, whereas the fastener is under bending action when the embedding stresses exceeded the fastener bending capacity. For a double shear connection, the resistances (R) per fastener per shear plane are given by four possible failure modes as shown in Table 1, which the lowest value calculated will govern the capacity of the connection.

Table 1: Possible failure mode and resistance for double shear joint [2]

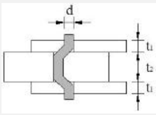
Failure mode	Resistance, R, per fastener per shear plane
	$R = f_{h,1}\, t_1\, d$ (Eq. 2)



$$R = 0.5\, f_{h,1}\, t_2\, d\, \beta \quad \text{(Eq. 3)}$$



$$R = \frac{f_{h,1}\, t_1\, d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_y}{f_{h,1}\, t_1^2\, d}}-\beta\right] \quad \text{(Eq. 4)}$$



$$R = \sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_y\, f_{h,1}\, d} \quad \text{(Eq. 5)}$$

Notes:
- β is the ratio of the embedding strengths, $\beta = f_{h,2} / f_{h,1}$.
- $f_{h,1}$ is the embedding strength corresponding to t_1, in MPa.
- $f_{h,2}$ is the embedding strength corresponding to t_2, in MPa
- t_1 and t_2 is the timber thickness or fastener penetration of member 1 and 2, in mm.
- d is the fastener diameter, in mm.
- M_y is the fastener yield moment, in Nmm, $M_y = (1/6)f_y d^3$.
- f_y is the fastener yield strength, in MPa.

In an effort to develop a comprehensive guideline for the purpose of designing the bolted connection in strengthening the wall-diaphragm connections of the existing Malaysia unreinforced masonry buildings, the above mentioned design equations were verified using the results obtained from the bolted testing conducted. The strength of the bolted connection was evaluated parallel to the timber grain using steel-wood-steel (SWS) type of connections. The use of these design equations is very important to be assessed, so that the effectiveness to predict the connection strength can be determined. Because of the objective is to strengthen the existing wall-diaphragm connection of the masonry buildings, the selection of hardwoods should be the species that are commonly used to construct the floor and roof diaphragm structural elements such as rafters and joists. Thus, from a review of [3], it was found that Meraka species is possible to be used for the applications as structural members of beams and joists.

2. Materials and Methods

The name of Meraka is referring to one of their common trade names in Sarawak, but also known as Red Balau in Peninsular Malaysia and Alan Batu in Brunei [3]. The Meraka hardwood was selected based on their strength group of SG3 that suitable for the applications as structural members of beams or joists [4], thus, can be typically used in the construction of the floor and roof diaphragms in Malaysia unreinforced masonry buildings. In the bolted connection tests, the cross section of each wood specimen used was 50 mm × 100 mm. The 13 mm diameter of bolts (d), which is 4.6 grade, was used with the shank length of 85 mm for avoiding the threaded part of the bolt in contact with the wood specimens. A total of four steel side plates with an ultimate tensile strength (f_{up}) of 400 MPa was used in these connection tests, where the plate thickness was 15 mm.

All test specimens consisted of three-member connections with two steel side plates at each end sandwiching a wood center piece (i.e. steel-wood-steel). This double shear connection was tested to remove the eccentricity of the connections during testing. Eight groups of different configurations of specimens were tested, where each group comprised of at least ten replicates. Each specimen consisted of an identical configuration of bolted connections at both ends. In order to ensure two independent connections achieved in all specimens, a minimum distance of 400 mm between connections was applied. The minimum distance chosen is in compliance with ISO/DIS 10984-2 [5]. All groups had one row of fasteners (n_r = 1), but the number of fasteners (n_f) and size of end distance (e_t) varied. The number of fasteners varied from one to two, whereas the group with two fasteners having 100 mm of bolt spacing (s_b). These connections were tested in order to maximize the number of observations on the bearing failure mechanisms for enabling the comparison of the connection strength between the experimental results and prediction values using MS544 and EYM. Refer to Figure 1 for the illustrations of the variables used in the preparation of the bolted connection specimens.

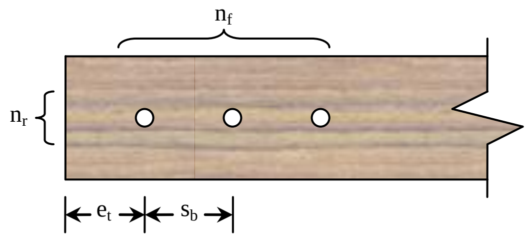


Fig. 1: Variables of timber bolted connections

All specimens were loaded in tension parallel to the timber grain up to the ultimate capacity of one of the two extremities of the connections using a 300kN SHIMADZU universal testing machine. Finger tight force was applied to all fasteners to permit self-alignment of the test specimens, and a monotonic tension load was applied through the steel side plates. Each specimen was tested at a displacement-control rate of 0.015 mm per second until failure, when the load dropped with no recovery. The ultimate load that was collected by a data acquisition system was recorded on a personal computer. The type of failure of each specimen was also recorded.

To provide the basic parameters of Meraka that are required for predicting the bolted connection strength values, the moisture content and embedding strength tests were conducted. To predict the connection strength using the European Yield Model, the value of the timber embedding strength is required. The monitoring of the timber moisture was also done as it will affect the connection capacities. The moisture content tests were executed in accordance with the procedures outlined in both AS/NZ 1080.1: 1997 [6], whereas the embedding strength tests were performed by complying with the ISO/DIS 10984-2 [5]. All specimens for both tests were extracted from the bolted connection test specimens as recommended by the standards.

3. Results and Discussion

From the moisture content tests conducted, it was determined that the average moisture content was 18% (≤ 19%), which considered as dry condition specimens in accordance to MS544. The embedding strength test results are tabulated in Table 2, whereas the 5th percentile values of the embedding strength ($f_{h,5th\%}$) of Meraka were calculated assuming a normal distribution.

Table 2: Embedding strength of Meraka.

Species	$f_{h,avg}$ (MPa)	CoV	$f_{h,5th\%}$ (MPa)
Meraka	45.3	24.2	27.3

Notes: $f_{h,avg}$ = average embedding strength;
CoV = coefficient of variations;
$f_{h,5th\%}$ = 5th percentile embedding strength.

In bolted connection tests, as expected, a dominant ductile failure mode was observed (i.e. wood in bearing due to in contact with the steel bolts). This can be clearly seen from the occurrence of the enlargement of the hole diameter in wood. All groups of connections fabricated with a range of end distances from 75 mm to 150 mm were determined to behave primarily in this mode. This finding is in agreement with other experimental data available in published literature [7-9]. A bending failure can also be recognised on the fasteners. Following the ductile failure, a secondary brittle failure was identified in those specimens, but it does not control the resistance of the connection. Such brittle failure modes observed were either splitting or row shear. The typical load versus displacement curves exhibiting the ductile behaviour is shown in Figure 2. From this figure, one can see that the secondary brittle failure mode was clearly evident by a sudden drop of load.

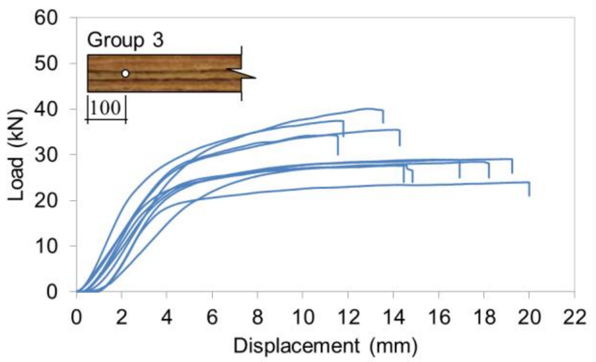


Fig. 2: Typical load versus displacement profiles of ductile behaviour

A comparison between prediction strength values and experimental results is tabulated in Table 3. The 5th percentile strength values estimated using EYM were calculated using equations 2 to 5 presented in Table 1, which the strength values given in column 7 are the lowest predicted strength from the EYM equations for double shear joint. In column 8, the strength values presented are the 5th percentile strength of three-member type bolted connections parallel to the timber grain predicted using MS544: Part 5: 2001 [10]. The test results of the eight groups tested are given in columns 9 to 11, whereas the average experimental values, R_{avg}, were determined and the lower 5th percentile strength of the test results, $R_{5th\%}$, was calculated assuming a normal distribution. Referring columns 12 and 13, the effectiveness of both EYM and MS544 in predicting the strength of bolted connections in Meraka hardwood is demonstrated, respectively. This was done by comparing the 5th percentile prediction values with the 5th percentile test results obtained. A graph showing the effectiveness of the strength prediction equations versus the test results is also plotted in Figure 3. Any prediction values plotted below the 45° line are considered to be conservative or safe.

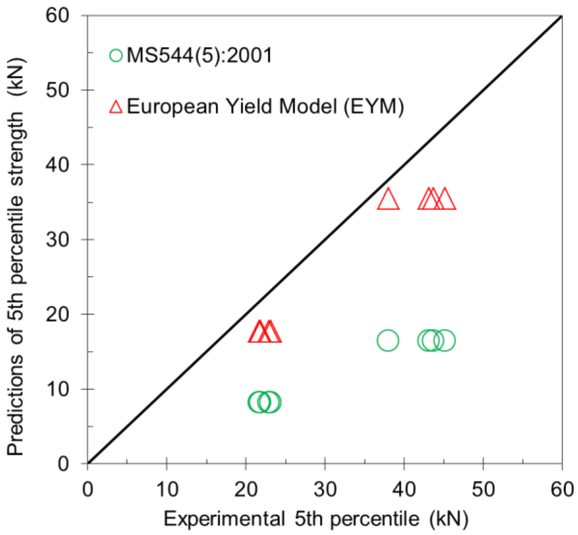


Fig. 3: Effectiveness of MS544 and EYM in predicting the strength value of bolted connections

By referring to both Table 3 (i.e. columns 12 and 13) and Figure 3, strength predictions using the current MS544(5): 2001 [10] were found to be too conservative compared to the lower 5th percentile of the experimental results. The ratio of the timber standard values to the test results varies between 0.35 and 0.43, with an average of 0.38. This obviously would make the strengthening design for wall-diaphragm connections in Malaysia unreinforced masonry to be uneconomical as more fabrication of steel bolts is needed due to a bigger size of bolt diameter will be designed. Better prediction values were obtained using the EYM equations with the same ratio ranges from 0.77 to 0.93 and an average of 0.81. From the comparisons made above, the use of the current Malaysian timber standard and EYM to estimate the bolted connection strength in Meraka hardwood was verified. It was found that the use of the EYM equations provides a better prediction of the bolted connection capacity in comparison to the MS544.

Table 3: Predictions versus experimental results

Group	d (mm)	e (mm)	s_b (mm)	n_r	N	EYM $R_{D,min}$ (kN)	MS544 $Q_{n,min}$ (kN)	Experimental R_{avg} (kN)	Experimental COV (%)	Experimental $R_{5th\%}$ (kN)	Ratio $R_{D,min}/R_{5th\%}$	Ratio $Q_{n,min}/R_{5th\%}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	13	150	-	1	1	18	8.20	32	20	22	0.82	0.38
2	13	125	-	1	1	18	8.20	30	16	22	0.81	0.37
3	13	100	-	1	1	18	8.20	31	16	23	0.77	0.35
4	13	75	-	1	1	18	8.20	30	14	23	0.77	0.36
5	13	150	100	1	2	35	16.40	46	10	38	0.93	0.43
6	13	125	100	1	2	35	16.40	53	12	43	0.82	0.38
7	13	100	100	1	2	35	16.40	57	13	45	0.79	0.36
8	13	75	100	1	2	35	16.40	56	13	44	0.81	0.38

4. Conclusions

By conducting the bolted connection tests, the ductile failure mode was identified for connections with the end distance from 75 mm to 150 mm with bolt spacing of 100 mm. The use of the current Malaysian timber code and European Yield Model in predicting the strength of bolted connections in Meraka hardwood was also evaluated. It can be seen that the MS 544 is too conservative in designing the strength in comparison to the actual 5th percentile strength with an average of 38% of effectiveness. This can obviously cause a bigger diameter of steel bolts being used in the design, consequently more steel fabrication cost is required. The European Yield Model is found to be better in predicting the bolted connection strength for the ductile failure mode compared to the actual 5th percentile strength with an average effectiveness of 81%. Therefore, the use of the European Yield Model to complement the current Malaysian timber standard is recommended to design the bolted connections in Meraka hardwoods.

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