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EFFECTIVENESS VALIDATION ON EXISTING DESIGN EQUATIONS FOR THE SUSTAINABLE DESIGN OF MASONRY BUILDING RETROFITS

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Abstract: Due to the unsatisfactory performance of MS544-5 in estimating the design capacity of bolted timber connections, this present study was initiated to validate the existing predictive equations used by the Malaysian Standard (MS544-5). An evaluation of the European Yield Model (EYM) equation was also done to provide an optimal design equation for the bolted connection design in local hardwood. To verify these two sets of equations, a series of bolted timber connection tests was conducted on *Nyatoh* hardwood. *Nyatoh* was chosen as its strength makes it ideal for use as structural timbers, either as roof rafters or floor joists in masonry building constructions. The bolted timber connection tests conducted involved eight types of bolt configurations and the tests on each configuration was done in sets of 10 specimens. The experimental values obtained were then compared with the predictive equations of MS544-5 and EYM to examine their effectiveness. From the comparison, it was found that the prediction values given by MS544-5 were overly conservative with an average effective ratio of 0.34 while the EYM had an average effective ratio of 1.09. Thus, the use of EYM equations was recommended for the sustainable retrofit design development of Malaysian masonry buildings.

Keywords: Design equation, bolted connection, connection design, design standard, retrofit design.

Introduction

In relation to the design of a bolted timber connections loaded parallel to the timber grain, currently there are few design equations that can be used to predict the strength for both the ductile and brittle failure mechanisms of the wood connections. However, in this paper, the authors focus on the ductile failure that is related to the European Yield Model (EYM).

This was done intentionally to compare the effectiveness of the EYM models prediction as against the Malaysian Timber Standard (MS544) prediction efficiency. From the recent findings (Abdul Karim *et al.,* 2018; Abdul Karim *et al.,* 2021), it has been observed that the MS544 is unable to accurately estimate the capacity of bolted timber connections. If comparisons were made between the EYM and MS544, one can see that the former was developed using the mechanical models of possible failure modes of wood in bearing and fasteners in bending by considering the wood embedding strength and the fastener yield moment capacity, respectively.

This is clearly in agreement with the international timber engineering community as stated by Quenneville (2009). The latter was found to estimate the basic working load of bolted timber connections based on the selections of bolt diameter and effective thickness of timber cross-section. To review the details of design equations of both MS544 and EYM, the following paragraphs are referred.

In Section 11.2.3 of MS544-5 (Department of Standards Malaysia, 2001a), the following equations were referred to in order to determine the permissible loads (F_{adm}) of a bolt system loaded parallel to the timber grain.

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

where the *k* factors are defined as follows: k_1 is the duration factor of the load given in Table 4 of MS544-5; k_2 is taken as 1.0 for dry timber or 0.7 for wet timber; k_{16} is taken as 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 in which $b/d > 5$ for loads acting parallel to grain, *b* is the effective timber thickness and *d* is the bolt diameter or k_{16} is taken as 1.0 if otherwise; k_{17} is the factor for multiple bolted joint bolted given in Table 15 of MS544-5.

The basic working load value, *F* depending on the bolt diameter and effective timber thickness is obtained from Table 12 of MS544-5. The determination of basic working load considers a single shear of a bolt bearing parallel to the timber grain, which shows that this standard was developed based on the ductile failure mechanism.

However, this assumes that the brittle failure happens if the number of bolted connections is more than four, where k_{17} is considered as less than 1 as per given by Table 15 of MS544-5.

The predictive equations of EYM relate to 1949 Johansen's theory, that concerns possible ductile failure modes of a bolted connection. The theory assumes that both timbers and fasteners acted as plastic-rigid (Blass, 2003), this resulted in the fastener yield moment formula, M_y as shown in Table 1, note number 7, that states that the fastener is in plastic behaviour. In this study, the bolt yield strength, f_y was taken from the bolt grade. For instance, if the bolt grade is 4.6, the bolt's yield strength was taken as 240 MPa. Note that the first figure of the bolt grade specifies the tensile strength of the bolt, whereas the second figure indicates the percentage of the bolt's yield strength in proportion to its tensile strength given in the first figure.

Because of the tested bolted connection specimens in this study were in steel-wood-steel configurations, only the resistances (R) per fastener per shear plane of four possible failures of the double shear connection type are shown in Table 1. The descriptions of the following failure modes from I to IV are based on the steel-wood-steel (SWS) bolted connection configuration of this experimental study, where member 1 is the steel side plates and member 2 is the wood specimen. Thus, the failure modes are hypothesised to be either:

(i) a failure only on both steel side plates,

(ii) a failure on the wood member only,

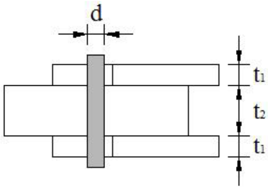
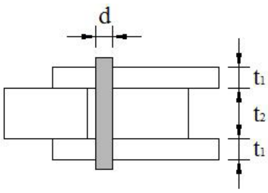
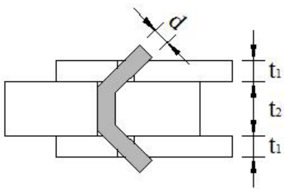
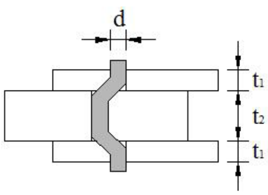
(iii) a failure on fastener and both steel side plates and

(iv) a failure on fastener, wood member and on both side plates.

To continue the efforts of Abdul Karim *et al*. (2018), Abdul Karim *et al.* (2021) and Abdul Karim *et al.* (2022) in establishing a comprehensive database of indigenous woods for the purpose of retrofitting the connection between the wall and the roof or floor diaphragms of masonry buildings, this present study was motivated to include the *Nyatoh* hardwood.

The *Nyatoh* hardwood was chosen as it was found to be one of the most typical hardwoods commonly used for the construction of roof and floor diaphragms of masonry buildings in Sarawak. The main objective of the current study was to provide an optimal set of design equations for strengthening the aforementioned connections between the brick wall and the timber roof or floor diaphragms, it is essential to confirm if the chosen hardwood specimen is commonly used for the construction of the timber roof diaphragms and floor diaphragms in masonry buildings. The Sarawak Forestry Department (1999) verified that the *Nyatoh* hardwood can be used as rafters and joists for the light constructions of roof and floor diaphragms. The wood identification, up to the genus level is also described this research paper. It is also very

Table 1: Possible failure modes for double shear connections as per EYM (Blass, 2003)

Failure Mode	Resistance, R per fastener per shear plane	
 I	$R = f_{h,1} t_1 d$	**(2)**
 II	$R = 0.5 f_{h,1} t_2 d \beta$	**(3)**
 III	$R = \frac{f_{h,1} t_1 d}{2+\beta}\left\{\sqrt{2\beta(1+\beta) + \frac{4\beta(2+\beta)M_y}{f_{h,1} {t_1}^2 d}} - \beta\right\}$	**(4)**
 IV	$R = \sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_y f_{h,1} d}$	**(5)**

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

important to undertake this research because it is not only providing an extensive experimental wood data for validating the effectiveness of the existing design equations, but it can be used to produce a sustainable wall-diaphragm connection design to retrofit heritage buildings in Malaysia.

Materials and Methods

Timber Material Used

Nyatoh hardwood chosen in this study is classified as light hardwood, its natural durability is categorised as somewhere between moderately durable and durable and its strength is listed as strong (i.e., green compressive strength between 27.6 MPa – 41.4 MPa) that falls under GROUP C (Forest Department Sarawak, 1999). Though not highly durable, its uses are suitable for light structural components such as rafters and joists. As such, *Nyatoh* hardwood was chosen for this study as it is having the potential to be used for the construction of the roof and floor diaphragms of light timber structures. Table 2 provides the descriptions of the *Nyatoh* physical properties as stated by the Department of Standards Malaysia (2001b) in the MS544-2 timber code and by the Forest Department Sarawak in the Handbook of Some Sarawak Timbers published in 1999.

Wood Identification

Prior to the preparation of specimens for the main bolted connection testing, a wood identification was first carried out on wood planks. A total of 50 planks with a cross-section of 50 mm × 100 mm supplied by the Forest Department Sarawak. From each plank, a specimen for wood identification was cut using a vertical band saw into a cube shape of 10 mm. The direction of the timber grain on the transverse plane of the specimen was taken as a reference to cut the cube shape specimen as shown in Figure 1.

After all of 50 cube shape specimens were extracted, the cross-section surface of each specimen was then carefully sliced using a microtome. This is a mechanical device that is typically used to cut biological specimens into a very thin slices or segments for microscopic examination.

Table 2: Physical properties of *Nyatoh* hardwood

Physical Properties	Department of Standards Malaysia (2001b)	Forest Department Sarawak (1999)
Colour	Mainly pale red-brown of *Bitis*	Sapwood light pink-brown. Heartwood light pink-brown to light red-brown or deep red-brown, sometimes greyish red-brown.
Density	750 kg/m^3 (at 19% moisture content)	628 kg/m^3 (at 18% moisture content)
Class	Light hardwood	Light hardwood

Figure 1: Extracted specimens for wood identification

In this study, however, the specimens were sliced to remove the unwanted segments to obtain a clear-cut transverse surface. The clear-cut surface of the cube-shaped specimen was directly analysed under the microscope to identify the anatomy of the *Nyatoh* hardwood. Descriptions of some characteristics of hardwood anatomy are given in Table 3 to introduce the common features to be observed.

Table 3: Descriptions of hardwood anatomy (Meier, 2021)

Anatomy	**Descriptions**
Vessel elements	• Holes in the wood when viewed from the endgrain • Commonly refer to as pores
Pore size	• Small (< 50 µm) • Medium (50-100 µm) • Large (100-200 µm) • Very large (> 200 µm)
Pore frequency	• Very few (< 5 vessels/mm^2) • Few (5-20 vessels/mm^2) • Moderately numerous (20-40 vessels/mm^2) • Numerous (40-100 vessels/mm^2) • Very numerous > (100 vessels/mm^2)
Pore arrangement	• Solitary pores – single openings • Multiple pores – two or more adjacent pores that clearly shared the middle wall between them • Radial multiples – pore multiples that typically arranged vertically
Pore contents	• Deposits (coloured gums, resins or others) in the wood cells as sapwood becomes heartwood • Tyloses (singular, tylosis) – bubble-like structures that grow into open pores, it sometimes completely close-off the pores of the heartwood • Relative terms (sparse, common and abundant) are used to describe their presences
Wood Parenchyma	• Living tissue in the sapwood that serves as storage cells, commonly refer to axial or longitudinal parenchyma that oriented along the length of the stem of the tree • Apotracheal parenchyma – isolated parenchyma from the pores o diffuse parenchyma – single parenchyma but scattered o diffuse-in-aggregates parenchyma – joined parenchyma that forming thin tangential (horizontal) lines but noticeable • Paratracheal parenchyma – parenchyma associated with the pores o vasicentric parenchyma – ring or circular formed parenchyma that bordering the pore o aliform parenchyma – closely related to vasicentric with two main variants given below: ▪ winged – wing-shaped parenchyma either at one or both sides of the pore ▪ lozenge – diamond or elongated oval formed parenchyma that surrounding the pore o confluent parenchyma – an extensive aliform parenchyma that in contact with the parenchyma from adjacent pores o banded parenchyma – tangential (horizontal) parenchyma bands with variations as follows: ▪ marginal parenchyma – parenchyma bands along the borderline of the growth ring

	▪ reticulate parenchyma – both parenchyma (tangential/horizontal) and rays (radial/vertical) exist in thin and closely spaced bands, which appearing as a grid-like or net pattern ▪ scalariform parenchyma – combinations of wide rays and short-arched parenchyma between the rays, which creating a profile of rugs on a ladder
Rays	• Cells run in radial (vertical) direction when viewed from the endgrain, which forming a more-or-less straight lines that spaced evenly across the wood sample
Ray spacing	• Wide (< 5 rays/mm) • Normal (6-9 rays/mm) • Fairly close (10-13 rays/mm) • Close (14-20 rays/mm) • Extremely close (> 21 rays/mm)

Referring to the endgrain microscopic sections of *Nyatoh* hardwood shown in Figure 2, observed under 20 times magnification (20×), it can be seen that the size of the pores is small to medium. The pore frequency mostly very few to few and occasionally moderately numerous. Mostly pores are in radial multiples alignment with solitary pores are also present. No appearances of deposits but tyloses present can be seen.

Both parenchyma and rays are abundant and thin, which occur in closely spaced reticulate bands. These anatomy findings of *Nyatoh* hardwood were then compared with some endgrain microscopic sections (20×) of hardwoods that are available at the Wood Library, Development and Innovation Division, Forest Department Sarawak.

From the microscopic analysis, the comparative anatomy can be seen in Figures 3 (a) to (d). Thus, the *Nyatoh* hardwood specimen used in this current study was identified from the genus of *Palaquim spp* or *Payena spp.* under the *Sapotaceae* family. The reader should be noted that the wood identification was only established up to genus level whereas the *spp.* stands for several species under one genus, as the species level could not be ascertained by only conducting the procedure provided herein.

Specimen Preparations and Experimental Setup for Bolted Connections Testing

After the genus of the hardwood was identified, the 50 mm × 100 mm (H × W) cross section wood planks supplied were then cut into length from 600 mm to 900 mm depending on the configurations of the bolted connection groups. This cross-section dimension was chosen as it is the most common size of structural components, either as rafters or joists in the construction

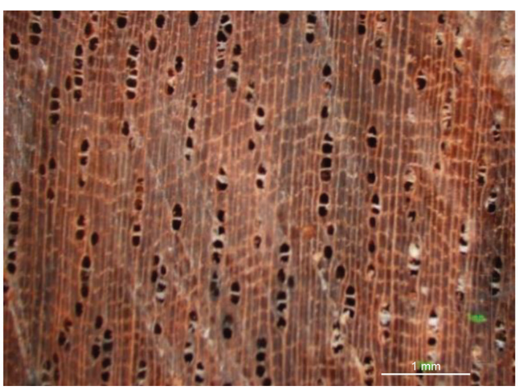


Figure 2: Endgrain microscopic sections (20×) of the *Nyatoh* specimen

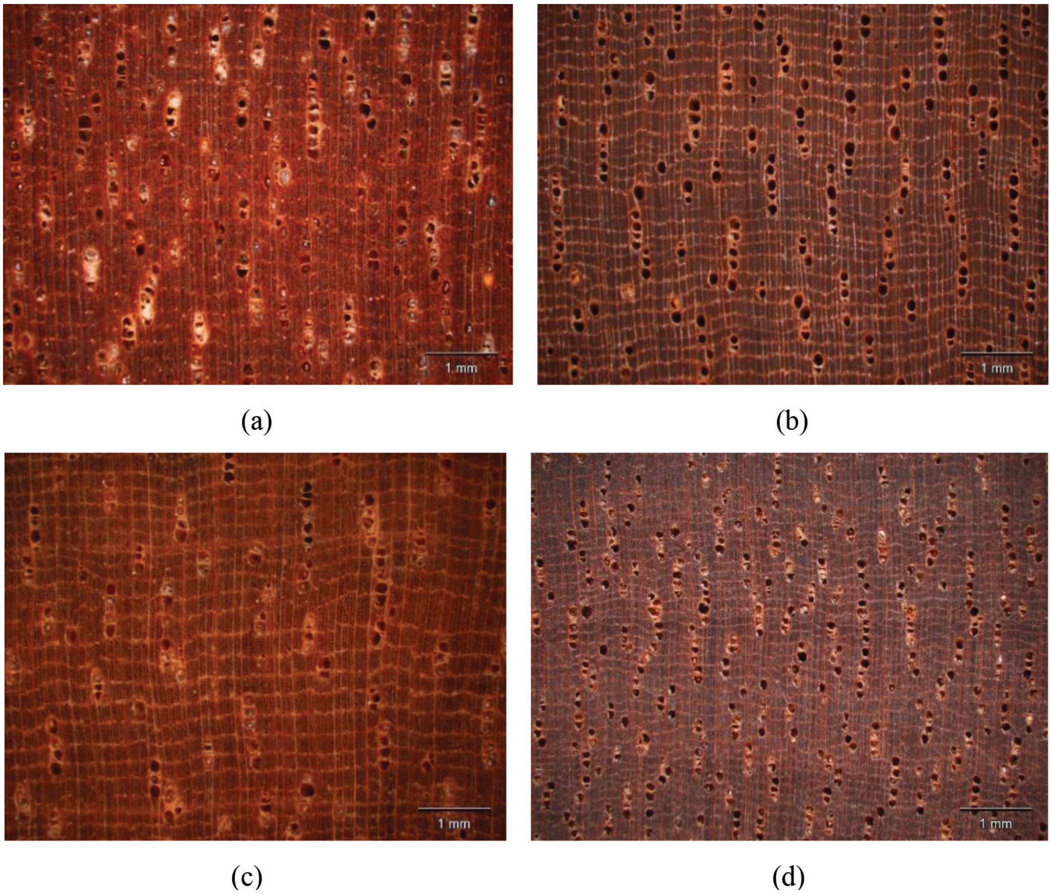


Figure 3: Endgrain microscopic sections (20×) (a) *Palaquim beccarianum*, (b) *Palaquim ridleyi*, (c) *Palaquim rivulare* and (d) *Payena endertii* (Source from Wood Library, Development and Innovation Division, Forest Department Sarawak)

of the roof and floor diaphragms, respectively (Department of Standards Malaysia, 2001c & 2001d).

There were eight groups of bolted connections involved in this study as listed in Table 4. Each group consists of 10 replicates, which gives 80 specimens in total. The illustrations of bolted connection configurations are also given in Figure 4. From Figure 4, a minimum 400 mm was fabricated to each tested specimen to ensure two independent bolted connections were assessed during testing. A 4.6 grade of 13 mm diameter (d) mild-steel bolts with a shank length of 85 mm was used.

This shank length was chosen to stop the threaded part from coming in contact with the pre-drilled wood specimens. The pre-drilled holes for all specimens were prepared to approximately 10% greater than the bolt diameter as per Department of Standards Malaysia (2001a) recommendations. Prior to the bolted connection testing, after the specimens were cut into the desirable length and the holes were pre-drilled accordingly, the specimens were left to air-dry for two weeks at room temperature to ensure the moisture content in the wood was less than or equal to 19% in compliance with Department of Standards Malaysia (2001b) requirements.

Table 4: List of bolted connection groups tested

Group	End Distance, e (mm)	Spacing of Bolts, s_b (mm)	Number of Bolts (n_f)	Total Length (mm)
1	150	-	1	700
2	125	-	1	650
3	100	-	1	600
4	75	-	1	550
5	150	100	2	900
6	125	100	2	850
7	100	100	2	800
8	75	100	2	750

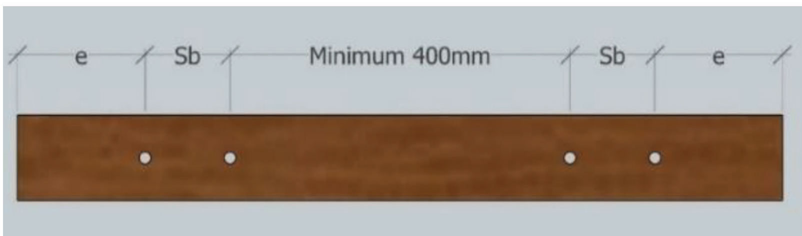


Figure 4: Illustration of bolted-connection configurations

Two mild steel plates of 400 MPa ultimate tensile strength (f_{up}) with a 15 mm thickness were used to sandwich each end of the specimen and fitted with single or double bolts. The other ends of the steel plates were fabricated to fasten onto the 300 kN SHIMADZU Universal Testing Machine using stainless steel rods fitted to the plates. The loading was applied with a rate of 1 mm per minute as per recommended in ISO 6891 (International Organization for Standardization, 1983).

Loads applied by the machine was stopped when one of the connection ends failed, whereas the load falls drastically and can be seen in the load-displacement graph plotted. The failure mode observed in each tested specimen was also examined to determine the type of failure it has undergone.

Wood Embedding Strength Testing

Apart from the main bolted connection testing, a series of embedding strength tests was also conducted to determine the wood embedding strength value for *Nyatoh*. It is an important parameter needed to be used in Equations 2 to 5 given in Table 1. The testing performed was in line with the ISO/DIS 10984-2 (International Organization for Standardisation, 2008). The wood samples for this testing were prepared by extracting the specimens that had undergone the bolted connection testing as recommended by the ISO/DIS 10984-2 (International Organization for Standardisation, 2008).

Moisture Content Test

It is very essential to ensure the moisture content of each specimen was monitored as it can significantly affect both the wood embedding strength and the bolted connection strength values. Therefore, in this study, a procedure outlined in AS/NZ 1080.1 by the Australian/New Zealand Standard (1997) was strictly followed. As recommended in the procedure by the standard, the preparation of samples for the moisture content test were extracted from the bolted connection specimens.

Results and Discussion

Moisture Content and Embedding Strength Results

After the experimentation of bolted connection testing of *Nyatoh* hardwood, the embedding strength tests were carried out and the results obtained were then computed in both average and 5th percentile as shown in Table 5. The 5th percentile value was analysed based on the assumption of a normal distribution data of results. Note that, only 78 samples were tested for embedding strength because the other two samples were unable to be extracted from the bolted connection specimens of G6h(29) and G8a(2) following a splitting failure of the entire specimen length. It was also determined that, from the results of the moisture content tests conducted, the average moisture content is equal to 17%. This shows that the wood specimens tested in this study can be considered to be dry per MS544-2 standards (Department of Standards Malaysia, 2001b).

Bolted Connection Test Results

From the observations on the failure mode of the tested bolted connection specimens, it was found that a ductile failure was observed in all the specimens. The initial wood bearing failure can be clearly seen as due to the enlargement of the bolt hole as seen in Figure 5. The following bending failure of the bolt was also visible showing the wood bearing stresses has exceeded the bolt bending capacity.

Apart from the ductile failure, a final brittle failure was also observed in all specimens. The brittle failure observed was mainly splitting or row shear, which can be seen when the specimens fail abruptly after reaching its breaking point. Thus, from this finding, all timber bolted connections with 75 mm or more of an end-spacing and of a bolt spacing exhibited ductile failures. These findings match the research results of Quenneville and Mohammad (2000), Abdul Karim *et al.* (2013) and Abdul Karim *et al.* (2018).

Figures 6 (a) to (h) show the trend of load versus displacement graph for all tested groups of bolted connections conducted in this study. The readers should be noted that the maximum loads of each specimen were used in the analysis of the experimental results.

Table 5: Embedding strength of *Nyatoh* hardwood

Hardwood	No. of Specimens	$f_{h,avg}$ (MPa)	CoV (%)	$f_{h,5th\%}$ (kg/m^3)
Nyatoh	78	37.25	16.62	27.07

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

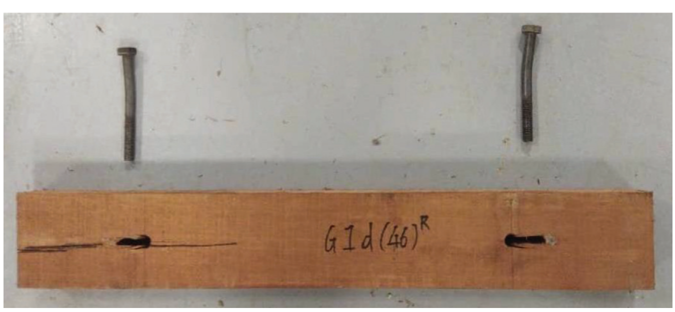


Figure 5: Illustration of bolted-connection configurations

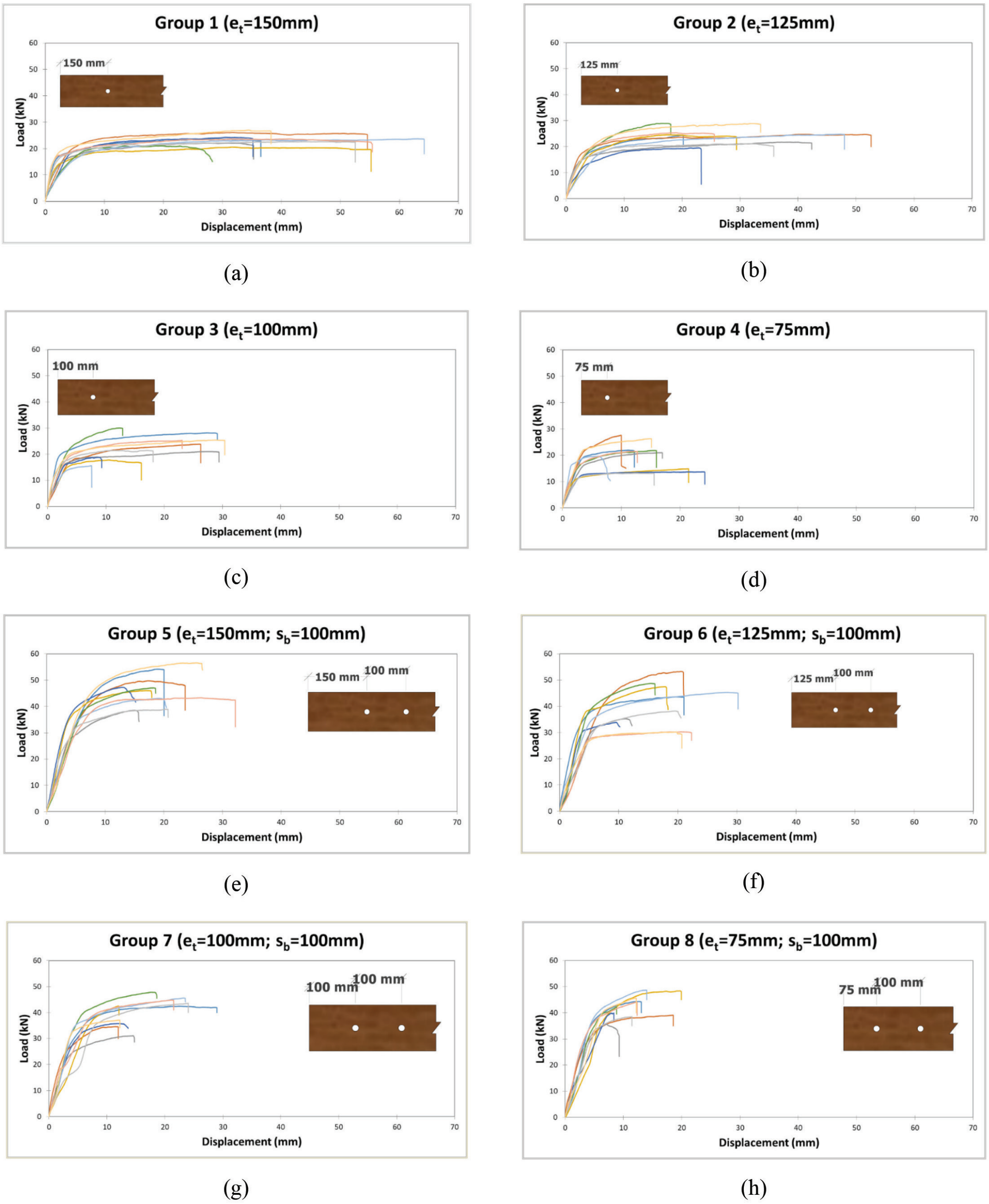


Figure 6: Load versus displacement graphs (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4, (e) Group 5, (f) Group 6, (g) Group 7 and (h) Group 8

A comparison between the experimental values and the predictive strength values of EYM and MS544-5 is tabulated in Table 6. The $R_{D,min}$ values were calculated using Equations 2 to 5, refer to Table 1. The minimum strength values calculated come from the Equation 3, which give the lowest capacities that govern the performance of bolted connections in ductile failure.

Note that the $R_{D,min}$ values represent the 5th percentile connection resistance as the 5th percentile embedding strength value was used in the calculation. Meanwhile, the $Q_{n,min}$ values represent the characteristic 5th percentile strength predicted using MS544-5. The R_{avg} values were determined as the average experimental values from ten specimens for each group, whereas the $R_{5th\%}$ values were calculated by using a normal distribution data analysis. For a graphical presentation, Figure 7 shows the efficiency tabulation of the EYM and MS544-5 prediction values against the experimental values.

A 45° line is used to differentiate the upper and lower parts of the graph, represent over-designed and under-designed approach, respectively. One should be noted that the $R_{5th\%}$ values were used to verify the effectiveness of EYM and MS544-5 because the strength values provided by the design equations were based on an estimation of the characteristic strength that is liable to come on bolted joints during its lifetime.

In other words, the variation in the strength is assumed to follow a normal distribution curve, which is typically known as the 5th percentile strength value.

Referring to Figure 7, it can be ascertained that the predicted value of MS544-5 is way too conservative as the tabulation is far below the 45° line. Referring to Table 6, the ratio of predicted value of MS544-5 in comparison to the lower 5th percentile experimental value was in the range of 0.27 to 0.45 with an average of 0.34. This is in a contrary to that of the predicted values given by the EYM, where its ratio to lower 5th percentile experimental value ranges from 0.87 to 1.46, with an average of 1.09.

Although some strength values given by the EYM were found to be over-designed for G3, G4, G6 and G7, it is mainly due to the experimental data divergence attained whereby the strength affecting factors such as moisture content, slope of grain or specimen defects were thoroughly checked. From the comparisons made above, the use of EYM for the purpose of designing a bolted connection of local Malaysian hardwoods is recommended rather than the MS544-5 that found to be too conservative.

Table 6: Predicted values vs experimental values

						EYM	**MS544-5**	**Experimental**			**Ratio**	
Group	**d (mm)**	**e (mm)**	**Sb (mm)**	**n_r**	**N**	**$R_{D,min}$ (kN)**	**$Q_{n,min}$ (kN)**	**R_{avg} (kN)**	**CoV (%)**	**$R_{5th\%}$ (kN)**	**$R_{D,min}$ /$R_{5th\%}$**	**$Q_{n,min}$ /$R_{5th\%}$**
1	13	150	-	1	1	17.60	5.48	23.51	8.63	20.17	0.87	0.27
2	13	125	-	1	1	17.60	5.48	24.45	12.45	19.44	0.90	0.28
3	13	100	-	1	1	17.60	5.48	22.65	20.25	15.10	1.17	0.36
4	13	75	-	1	1	17.60	5.48	20.20	24.41	12.09	1.46	0.45
5	13	150	100	1	2	35.19	10.96	46.51	12.72	36.78	0.96	0.30
6	13	125	100	1	2	35.19	10.96	39.76	17.64	28.22	1.25	0.39
7	13	100	100	1	2	35.19	10.96	40.55	13.56	31.51	1.12	0.35
8	13	75	100	1	2	35.19	10.96	42.74	10.04	35.69	0.99	0.31

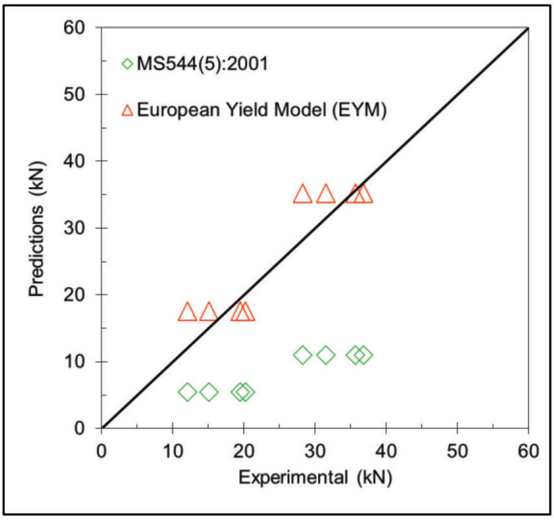


Figure 7: Effectiveness of MS544-5 and EYM in predicting the bolted connection strength

Conclusion

From the outcomes of this study, it was found that a failure in bearing is most likely to occur for connections with the end distance ranges from 75 mm to 150 mm as well as the spacing between bolts of 100 mm. It also can be concluded that the use of EYM equations for the purpose of designing a bolted connection on *Nyatoh* is recommended rather than MS544-5. This is due to the very conservative design of MS544-5 when compared to the experimental data.

Thus, the expansion of this present work on a brittle failure mode is crucial to validate the effectiveness of the existing design equations.

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