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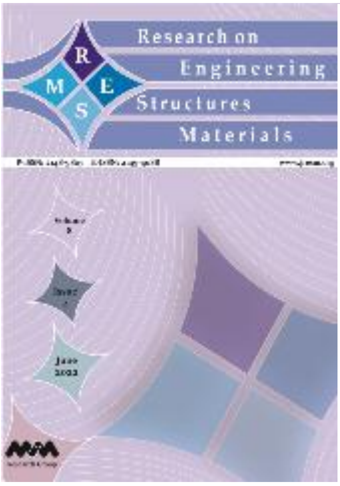

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Research Article

Evaluating the SWS bolted connection strength of Bitis wood

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Abstract

The current study was conducted to evaluate the strength of the steel-wood-steel (SWS) bolted connections of Bitis wood. The wood was chosen because it is commonly used as the structural elements of the as-built floor and roof diaphragms in Malaysian unreinforced masonry (URM) buildings. This present work was performed to continue the initiation of the wood database development for the purpose of retrofitting the wall-diaphragm connections of the URM building. The bolted connection testing was the main experimental investigation, where a total of eighteen groups of different connection configurations were tested, each consisting of ten specimens. The embedding strength tests, moisture content and density tests were also conducted to determine the wood's basic properties. The results obtained from this experimental study were utilized for verifying the prediction effectiveness of the existing design equations, namely the Malaysian Timber Standard (MS544-5), the European Yield Model (EYM), and the Row Shear Model (RSM). From the comparison made between the prediction values and the experimental results, the MS544-5 was found to be too conservative, whereas a combination of the EYM and RSM is recommended for predicting the bolted connection strength of the Bitis wood.

1. Introduction

It has long been recognized that the main issue with the as-built characteristic of an unreinforced masonry (URM) building is the discontinuity between its vertical and horizontal structural elements. An absence of the connection between the masonry walls and the timber floor diaphragms was found to be the main weakness causing the building to perform poorly in resisting the lateral load from earthquakes [1, 2, 3]. Thus, all countries over the world that still have this type of buildings must seriously confront retrofitting interventions due to the locality of these buildings that can be easily found in the main city areas, which typically use as commercial or residential purposes. Many reconnaissance reports [4, 5, 6] on damaging earthquakes show various catastrophic failures of masonry construction, supporting the claim that the unreinforced masonry buildings are not only dangerous to the occupants but also to the nearby pedestrians, including the neighboring public and private properties. All major collapses of masonry walls are mainly caused by the lack of wall-diaphragm connections. Therefore, this present study was carried out to continue the initiation of [7, 8, 9] in developing the wood database for the design of wall-

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diaphragm connections to retrofit the URM buildings. The wall-diaphragm connections are comprised of two major parts, which are the wall anchorages and the diaphragm connections [10, 11, 12, 13]. The former can be in the form of a through-bolt anchor connected with an external bearing plate or a dowel-type anchor drilled into the wall. The latter is typically a bolted steel cleat to the timber floor joists or to the timber roof rafters. Because the design details of the latter part are not provided by [12, 13], the next discussion focuses on the existing Malaysian timber code, in particular the bolted joint design procedures.

Referring to the Malaysian Timber Standard (MS544-5) [14] under clause 11.2.3, it outlines an equation to determine the permissible load, F_{adm}, of a bolt system loaded parallel to grain. The equation is given by:

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

where, k_1: Factor of duration of load given in Table 4 of [14], k_2: Factor of 1.0 for dry timber or 0.7 for wet timber, k_{16}: Factor of 1.25 for the 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 connections given in Table 15 of [14], F: Basic working load as derived in clause 11.2.2 of [14]. From clause 11.2.2 of [14], it can be seen that the design method considers only a ductile failure mode. The standard only reflects a brittle failure mode by applying the k_{17} value of less than one for connections with five bolts and more. This is not in agreement with the international timber engineering community because the criteria in the timber standards to determine the capacity of bolted joints shall be from an established mechanical model that is capable of identifying each conceivable failure mechanism [15]. Many published works [16, 17, 18, 19, 20] found that the geometric configurations of the bolted joints, such as the end distance, e_t, and spacing between bolts, s_b, can significantly control the mode of failure. From [7, 8, 9, 21, 22], the standard was identified as providing a very conservative design capacity for bolted joints in local hardwoods like Meraka and Nyatoh. Thus, this present experimental work continues the bolted connection study on the Bitis wood evaluation.

Besides utilizing the experimental data of the bolted connection on the Bitis wood for evaluating the effectiveness of the existing timber standard of the MS544-5 [14], this current study also examines the efficiency of the European Yield Model (EYM) and Row Shear Model (RSM). The EYM represents the mechanical models of the ductile failure mode developed by Johansen [23], whereas the RSM demonstrates the mechanical models of the brittle failure mode established by Quenneville [15]. Details of both design equations of the EYM and RSM can be found in [9], but herein the authors highlight and discuss the important parameters involved in both theories. In each possible failure mode as per EYM theory, the most important parameter in the design equation for determining the resistance of bolted timber joints, R, is the embedding strength of the wood, denoted as f_h. The absence of this parameter in the existing code of MS544-2 [24] makes the efficacy valuation of the EYM theory to estimate the bolted connection strength on local hardwood is impossible to be assessed. Besides providing the test data on bolted connection strength of local hardwood that was also found to be very limited, this present study conducted the embedding strength test on Bitis wood using the ISO/DIS 10984-2 [25] for the use of the EYM efficiency verification.

For the design equation in the RSM theory, the authors focus the discussion on the parameters of the wood shear strength parallel to the grain, f_v, and the calibration factor, CF. From [8], it was identified that the f_v value can be taken directly from Table 4 of [24]. However, it makes the prediction capacity of RSM became unacceptably under-designed. The use of the correlation of the f_v equivalent to $17.8G^{1.24}$, which can be obtained from Table

4-11a of the Wood Handbook [26], was recommended. Thus, this present study provides the density of Bitis in accordance with AS/NZS 1080.3 [27]. Note that G in the f_v correlation is the specific gravity of the wood. The calibration factor is another parameter to consider in the RSM design equations. From [9] and [22], it can be seen that different woods have a specific CF in order to optimize the design strength of timber bolted connections. Because of that, this present study also recommends a specific CF to be used for the bolted timber joints of Bitis wood.

From the above discussion, this present study is not only providing the design parameters of Bitis Wood and adding its bolted connection results to the database as per the prior works of [7, 8, 9, 21, 22], but also recommending a set of enhanced design equations for the timber bolted connections of local hardwoods to assist the engineers in designing an optimized retrofit solution of wall-diaphragm connections for the URM buildings. The readers of this article should also be informed that this current study considers the critical part of the wall-diaphragm connections to be the diaphragm connection, which is the bolted joint on the timber floor and roof diaphragms. Therefore, it is assumed to fail before the masonry brick wall and the timber floor or roof diaphragms.

2. Selection of Wood Material and Wood Identification

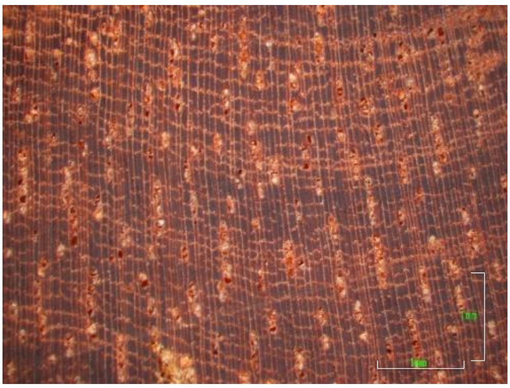
Since the focus of this current study is on the bolted joint design of the structural components of joists or rafters of floor and roof diaphragms in URM buildings, respectively, the selection of wood materials to be tested in the experimental works is crucial. From Table 3 of MS544-2 [24], it can be seen that Bitis is categorized under the strength group SG1, which is commonly used as structural components such as joists and rafters, as stated by the Malaysian Timber Industry Board [28]. From Table B1 of MS544-2 [24], there are common cross-sectional sizes of structural timbers in Malaysia. Also, to select the typical domestic rafters and joists sizing, a cross-checked was done by referring to [29] and [30], respectively. Based on the above findings, a Bitis wood measuring 50 mm in breadth, b, and 100 mm in depth, d, was chosen for this present study. Table 1 below provides an extract of the information on Bitis obtained from Table A1 of MS544-2 [24].

Table 1. Information on Bitis wood [24]

Class	Std. Name	Other Common Name	Species yielding the timber	Density at 19% Moisture Content (kg/m^3)	Specific Gravity	Color
Heavy Hardwood	Bitis	Nyatoh batu	Madhuca utilis, Palaquium ridleyi and P. stellatum	1100	0.98	Red-brown or purple brown

To ensure the right wood specimen was tested in this study, a wood genus verification was conducted using the end-grain microscopic examination technique. The similar steps of the specimen preparation outlined in [21] were adopted in this current study for obtaining the wood sample end-grain at a magnification of 20 times (20x), as shown in Fig. 1(a). From Fig. 1(a), the microscopic anatomical characteristics of the wood sample can be identified. It can be seen that the pore size is small (< 50 μm) with a pore frequency of very few (< 5 pores/mm^2) to few (5-20 pores/mm^2). The pore arrangement is in multiples of 2-6 pores and oriented in the vertical (radial) direction. A growth of tyloses, which sometimes closes off the pores completely, is common. The wood parenchyma is separated from the pores (apotracheal), which are identified as being in a joined parenchyma (diffuse-in-aggregates). This can be clearly seen by the formation of thin lines oriented in the horizontal (tangential) direction. The radial cells (rays), which are more-or-less straight lines, can be observed at a close (14-20 rays/mm) spacing. The presence of thin lines formed by both parenchyma and rays in a closely spaced pattern is also very apparent. This is known as a reticulate (net-like or grid-like) pattern. All readers are suggested to refer to [31] for definitions of some terms used in this article to describe the microscopic anatomical characteristics, as this article does not provide those definitions. A summary of the terms used can also be found in [21].

From the above descriptions of the microscopic anatomical characteristics of the wood sample, similar characteristic details can be found in [32] as shown in Fig. 1(b). The characteristic descriptions of the wood sample can also be similarly gathered from the genus of *Madhuca* outlined by [33]. From this comparison, the wood sample used in the present study was verified as Bitis wood from the genus of *Madhuca* spp. under the family of *Sapotaceae*. The reader of this article should be aware that the wood identification conducted herein was only confirmed to the genus level, which is specified by the spp. abbreviation that indicates species in plural form. In other words, more than one or some species falls under the same genus. The identification of the particular species is beyond the scope of this present research work.



(a) wood sample

(b) Bitis

Fig. 1. End-grain sections (20x) (a) from this present study, and (b) from [32]

3. Testing Program

This section describes the main bolted connection testing conducted to determine the strength of bolted connections in Bitis wood. The explanation includes specimen preparation and configuration details, as well as the experimental setup and procedures. The tests for determining the wood properties, such as embedding strength, f_h, and density, are also included as both are very important parameters for EYM and RSM predictions as per mentioned in Section 1 of this article, respectively. The wood density test was performed as per requirement of AS/NZS 1080.3 [27]. For the monitoring of water contents in all wood specimens, the moisture content test was also conducted in accordance with the procedures given in AS/NZS 1080.1 [34].

3.1. Bolted Connection Test

3.1.1 Specimen Preparation and Configuration Details

For the bolted connection testing, a total of eighteen groups of bolted connection specimens were prepared, with each group consisting of ten replicates. The supply of wood was in the form of rough-sawn timber planks with a cross-sectional area of 50 mm in width and 100 mm in height. All specimens in each group were ensured to be prepared from a different plank of timber supply so as to reduce the possibility of extracting the specimen from the same tree. Even a different timber plank can be from the same tree, but by applying this precautionary measure during the specimen preparation, it can at least increase the variations of the wood samples to be tested. Every specimen was fabricated with duplicated connection details at both extremities, with l_4 (refer to Fig. 2) not to be less than 30×d as per requirement stated in [25]. Because a 13-mm-diameter mild steel bolt was used in this present study, the distance to ensure two independent connections at both ends of each specimen, l_4, must not be less than 390 mm. However, the authors decided to round the l_4 into 400 mm for all specimens. Since the height of the timber plank used was 100 mm, a single row bolted connection was applied to all specimens because the a_1 must not be less than 3×d (39 mm) in accordance to [25]. Due to the focus of the study was on the one row bolted connection, only the row shear failure was considered to be the critical brittle failure mode in comparison to other failures such as group tear-out, splitting, and net tension specified in [15]. The specimen configuration details of each connection group tested can be obtained from Table 2. An illustration of the variables used in the specimen preparation of bolted connections is provided in Fig. 2.

Table 2. Bolted connection specimen configuration details

Group	End distance, e_t (mm)	Spacing of bolts, s_b (mm)	Number of bolt, n_f
1	150	-	1
2	125	-	1
3	100	-	1
4	75	-	1
5	50	-	1
6	150	100	2
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

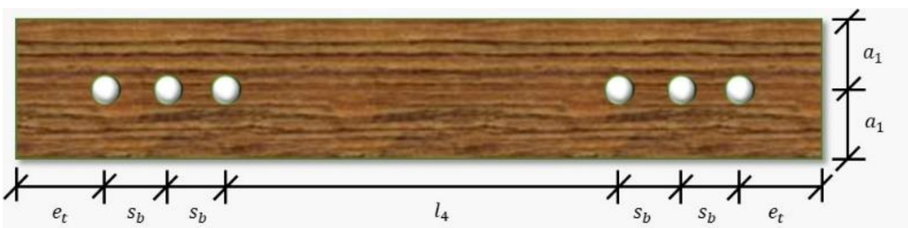


Fig. 2. Illustration of variables used

3.1.2 Experimental Setup and Procedures

Each bolted connection specimen was tested in the form of a steel-wood-steel (SWS) arrangement, in which this double shear connection sandwiched the timber specimen with two mild steel plates on both sides. The plates used were 16 mm thick and made from mild steel with a 400 MPa ultimate tensile strength in order to ensure a rigid test rig can be achieved. A mild steel bolt and nut graded 4.6, which varies in number for each connection group tested, was used to fasten the SWS specimen by applying only a finger-tight force to the nut. All specimens were loaded in tension parallel to the timber grain direction using a 300 kN universal testing machine. Through the side steel plate at both connection ends that were attached to the testing machine, a static force with a displacement rate of approximately 1 mm per minute was applied until any of the extremities reached their ultimate capacity as per the recommendation of ISO 6891 [35]. A force-displacement data set collected for each specimen was recorded to obtain the maximum strength of the tested bolted connection specimen. A failure mode observed on every tested specimen of bolted connections was also identified. The failure pattern on the tested specimen was clearly marked and photographed.

3.2. Tests of Wood Properties

3.2.1 Embedding Strength Test

The test specimens for the embedding strength determination were extracted from the timber bolted connection strength tested specimens. In ISO/DIS 10984-2 [25], the minimum height of the embedding test specimen must not less than 7×d (91 mm). Thus, all specimens were prepared with 100 mm height as shown in Fig. 3. In order to ensure the test piece was uniformly loaded, a 13-mm-diameter bar with 70 mm length made from stainless steel was used.

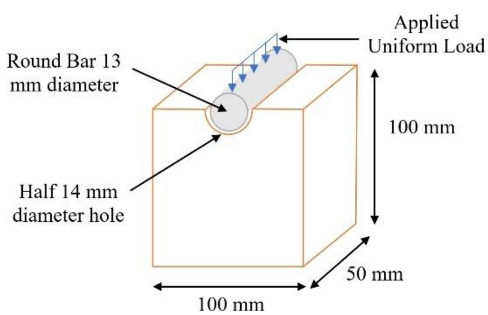


Fig. 3 Illustration of the test piece

Fig. 4 Embedding strength test setup

A static compression load with a rate of 1 mm per minute was applied in this test until the wood specimen fails. If the bar is fully compressed into the half 14-mm-diameter hole of the test piece, the load was observed to keep on continue to increase. This occurrence was due to the surface of the loading plate was in contact with the surface of the wood test piece. The loading of the universal testing machine was stopped for some specimens that exhibited this behavior. For this condition, one should note that the maximum force should only be taken up to the bearing failure of the wood that in contact with the bar. A typical setup for the embedding strength test can be seen in Fig. 4. All load-displacement data were collected and the embedding strength of Bitis wood was calculated by using the following equation:

$$f_h = F_{max}/A_b \quad (2)$$

where, F: Maximum force, A_b: Bearing area of contact between bolt diameter (d) and wood test piece thickness (t).

3.2.2 Moisture Content and Density Tests

As per recommended by [27] and [34], the specimens for both wood density and moisture content tests were extracted from the bolted connection test piece. All extracted specimens were cut into 20 mm (width) x 50 mm (length) x 10 mm (thick) size. An initial mass of each specimen was measured to an accuracy of 0.01 g before placing all of the wood samples in an oven for a drying process with 103°C ± 2°C of temperature. After 24 hours of the oven-dry process, all specimens were taken out from the oven and each wood sample was weighed to determine the oven-dry mass of the first day. The 24-hour oven-dry step was repeated until a constant mass on each wood specimen was achieved. From this present study, it was found out that the constant mass of each wood sample was achieved in three days, which was then taken as the final mass. The difference between the initial mass and the final mass of each specimen was used to calculate the moisture content of Bitis wood. The oven-dry density value was also computed using the mass difference dividing by the volume of the wood test piece.

4. Results and Discussion

This section describes the test results of Bitis wood properties such as embedding strength, f_h, density, ρ, and moisture content, MC, as well as the strength of the bolted connection. An average value, designated as an abbreviation of avg in a subscript form, was calculated based on the total number of specimens tested. Due to the specimen preparation of the wood properties testing was done by extracting from the main bolted connection test piece, both embedding strength and density tests should have the same total of 180 specimens. However, it should be noted that due to some of the tested specimens of the bolted connection were failed in splitting for its entire length, the total specimens that can be prepared for the embedding strength test was only 137 pieces. A 5th percentile value, designated as an acronym of 5th% in a subscript form, was also computed for all results obtained, including the bolted connection strength results. The 5th percentile value was calculated based on an assumption that the results obtained is in the variation of the normal data distribution curve. The 5th percentile embedding strength, $f_{h,5th\%}$, was used in EYM and the 5th percentile density, $\rho_{5th\%}$, was used in RSM to estimate the bolted connection strength in ductile and brittle failure modes, respectively. These were then enabling a comparison to be made between the bolted connection characteristic strength estimation given by the Malaysian timber code of MS544-5, which typically provides the bolted connection capacity in the 5th percentile value [9]. One should note that the present study was carried out to investigate the Malaysian local timber, namely the Bitis wood. Thus, in order to ensure a realistic comparison of results was made in this article, the specific former studies of Meraka wood [7, 8, 9] and Nyatoh wood [21, 22] were selected. This is due to the comparable geometrical configuration details of bolted connections and the moisture content of wood specimens during the execution of the testing. Both factors are very important to be considered because of the significant influences in the timber bolted connection failure modes as well as its strength.

4.1 Wood Properties

The results of embedding strength of Bitis wood are tabulated in Table 3. Both average embedding strength, $f_{h,avg}$, and 5th percentile embedding strength, $f_{h,5th\%}$, values are determined from a total of 137 wood samples. From the statistical analysis of the embedding strength data, the coefficient of variation, CoV, shows an acceptable dispersion of data obtained in relation to the mean. Due to the lack of this embedding strength of Bitis wood in the existing MS544-5 [14], this present study initiates this important parameter determination for the use of an efficiency evaluation of the EYM equation in predicting the bolted connection capacities. The results of density of Bitis wood are presented in Table 4. The value of the average oven-dry density, ρ_{avg}, was computed using a total of 180 wood samples. The 5th percentile oven-dry density value, $\rho_{5th\%}$, was also obtained from the similar total of wood samples. In the statistical analysis of the density results, he coefficient of variation, CoV, shows the experimental results obtained are acceptably clustered around the average value. As per discussion made in the fourth paragraph of Section 1 in this article, the oven-dry density obtained was use to find the wood shear strength parallel to the grain using the correlation given by $17.8G^{1.24}$ [26]. This allows an assessment of RSM equation effectiveness in estimating the bolted connection strength of Bitis wood to be performed. Because of the wood moisture content can significantly affects the bolted connection capacity, it is essential to monitor the condition of the wood samples either in green or dry. From the average moisture content calculated from 180 wood samples, it can be seen that the wood samples were tested in dry condition, which in compliance with the MS544-2 [24]. Thus, the effect of moisture content to the bolted connection strength of Bitis wood was not a concern in this present study.

Table 3. Embedding strength of Bitis wood

Hardwood	No. of Specimens	$f_{h,avg}$ (MPa)	CoV (%)	$f_{h,5th\%}$ (MPa)
Bitis	137	42.21	25.23	24.69

Table 4. Moisture content and density of Bitis wood

Hardwood	No. of specimens	ρ_{avg} (kg/m^3)	CoV (%)	$\rho_{5th\%}$ (kg/m^3)	MC_{avg} (%)
Bitis	180	800	14.95	603	19

4.2. Bolted Connection

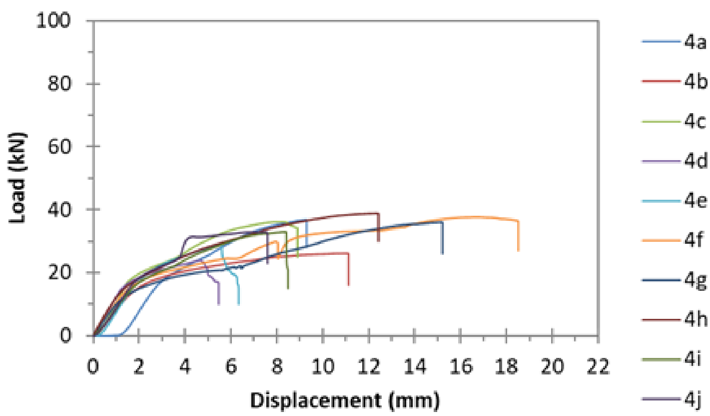
4.2.1 Observation on Ductile Failure Mode

Referring to the bolted connections of Groups 1-4 and Groups 6-9, with end distance, e_t, and bolt spacing, s_b, equal and more than 75 mm, it can be seen that the failure of the tested specimens was predominantly exhibited in ductile mode. This can be identified from the initial bearing failure observed in the wood part that directly in contact with the steel bolt, which caused the diameter of the pre-drilled hole to enlarge (see Fig. 5). At this stage, the embedding strength of the wood was mainly utilized. The bending of steel fasteners can be observed, which the bending strength of the steel bolts was triggered when the wood embedding strength exceeds the fastener bending resistance. The brittle failure, either row shear (Fig. 5a) or splitting (Fig. 5b), can be finally observed in the wood test piece of the bolted connection when the bending capacity of the bolt surpasses either the wood shear strength parallel to the grain or the wood embedding strength, respectively. However, this brittle failure, which can be seen from Fig. 6 as a sudden drop in loading, was identified as a secondary failure mode that did not control the bolted connection capacity. From Fig. 6, it can be seen that the load-displacement curves of the bolted connection that failed in this ductile mode show an occurrence of a strain hardening. This can be spotted from the development of a plateau of the load-displacement curves of the bolted connection system. One should note that an alphabetical tagging system from a to j was implemented to represent the running number of the ten replicate specimens in each group of the bolted connection tested, as shown in the legend of Fig. 6.

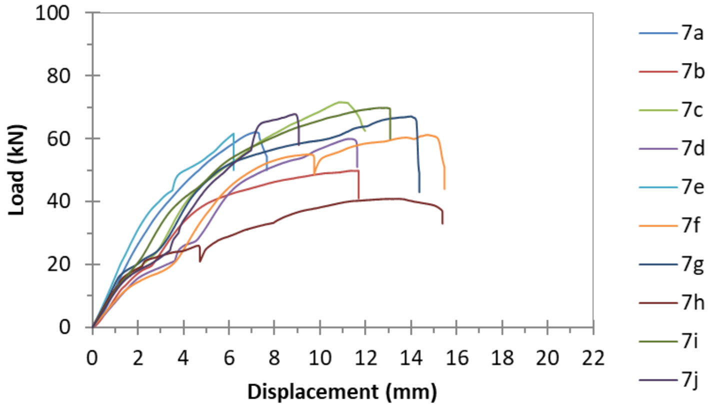
(a) Group 4 with e_t = 75 mm

(b) Group 7 with e_t = 125 mm and s_b = 100 mm

Fig. 5 Tested bolted connection specimen that showing initial wood bearing failure with secondary brittle failure



(a) Group 4 with e_t = 75 mm

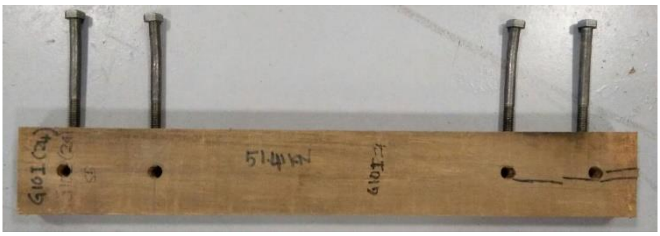


(b) Group 7 with e_t = 125 mm and s_b = 100 mm

Fig. 6 Typical load-displacement curves of bolted connections that exhibit the ductile failure mode

4.2.2 Observation on Brittle Failure Mode

In the bolted connection of Group 5 and Groups 10-18, with a minimum of 50 mm either e_t or s_b, majority of the specimens were primarily failed in brittle mode. No visible expansion of pre-drilled hole diameter was found, whereas the row shear failure parallel to the grain of the wood test piece was evident (see Fig. 7). At this point, only the shear strength parallel to the wood grain was fully utilized as the embedding strength of the wood is prominently greater than the wood shear parallel capacity.

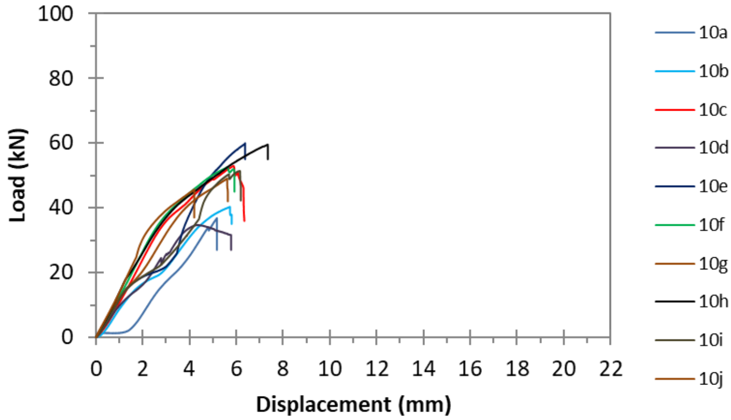


(a) Group 10 with e_t = 50 mm and s_b = 100 mm

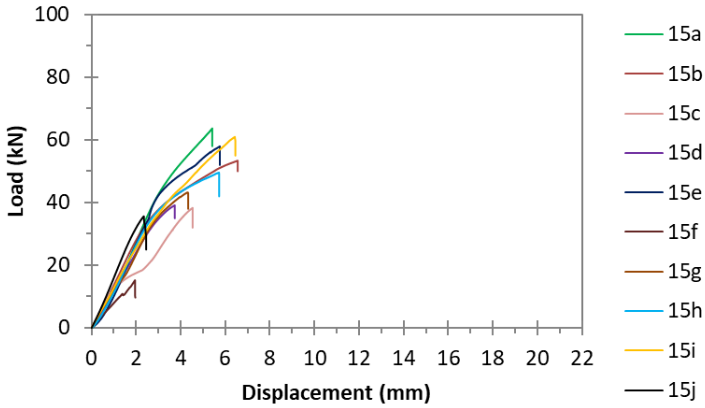
(b) Group 15 with e_t = 50 mm and s_b = 50 mm

Fig. 7 Tested bolted connection specimen that showing row shear parallel to the wood grain failure

No significant bending can be observed on the steel bolts used translates that the steel fastener bending resistance is also very high in comparison to both embedding and shear strengths of the wood. From these observations, the bolted connection specimens of the above-mentioned groups can be concluded to fail mainly in row shear parallel to the wood grain due to no utilization of the wood embedding strength and the steel bolt bending capacity. The row shear failure was the brittle mode that governs the capacity of the bolted connection system. Also, it should be noted that the geometrical configuration of the e_t and s_b are extremely important parameters in the design considerations. The failure of this brittle mode can be obviously spotted from the sudden drop of loading at a low displacement value with no establishment of plateau in the load-displacement curves shown in Fig. 8. A similar alphabetical labelling mentioned in the previous section was also used as per shown in the legend of Fig. 8.



(a) Group 10 with e_t = 50 mm and s_b = 100 mm



(b) Group 15 with e_t = 50 mm and s_b = 50 mm

Fig. 8 Typical load-displacement curves of bolted connections that exhibit the brittle failure mode

4.2.3 Strength Prediction Effectiveness of Ductile Failure Mode - EYM versus MS544-5

The test results of this present study, specifically for the bolted connections that failed in wood bearing (i.e. Groups 1-4 and Groups 6-9) are summarized in the Table 5. It should be noted that the experimental results were analyzed using the ultimate capacity of each bolted connection specimen. The CoV values show a satisfactorily dispersion of data obtained that were calculated based on ten specimens in each bolted connection group. The bolted connection strength estimation of EYM was calculated using equations of the four possible failure modes for a double shear joint type that can be found in [7, 9, 21]. It should be noted that the EYM estimation for each bolted connection group tabulated in Table 5 was taken from the minimum strength value out of the four possible failure mode capacities. The MS544-5 prediction on bolted connection capacity was computed using

Table 12 of [14] by taking the effective timber thickness, b, equal to 50 mm, and the bolt diameter, d, equal to 13 mm. In bolted joint design using MS544-5, it is required to perform a joint group classification for a specific timber species. From Table 1 of [14], one can see that there are five joint groups from J1 to J5 where the particular wood species are clustered to the specific joint group. For the prediction of bolted connection capacity using MS544-5, the Bitis wood used in this present study can be classified as J1 in accordance with Table 1 of [14]. Thus, from Table 12 of [14], the dry basic load for one bolt in a single shear can be obtained. It should be noted that for this present study, the double shear connection was tested, therefore, the capacity value gathered from Table 12 of [14] was multiplied by two. Also, for connections more than one fastener, a multiplication is required depending on the number of bolts used. From the comparison made between the predicted values and the experimental results, a ratio of EYM/$R_{5th\%}$ and MS544-5/$R_{5th\%}$ for each bolted connection group was calculated to show their effectiveness. It was found that, for the bolted connections of the Bitis wood that failed in ductile mode, the EYM strength predictions better than the MS544-5 with an average efficacy of 70%, whereas the code provides an average efficiency of 43%.

Table 5. EYM predictions vs experimental results of connection groups that failed in ductile

Group	Experimental			Predictions		Ratio	
	R_{avg} (kN)	CoV (%)	$R_{5th\%}$ (kN)	EYM (kN)	MS544-5 (kN)	EYM / $R_{5th\%}$	MS544-5 / $R_{5th\%}$
1	34.37	13	26.78	16.05	9.88	0.60	0.37
2	33.21	14	25.62	16.05	9.88	0.63	0.39
3	34.50	11	28.34	16.05	9.88	0.57	0.35
4	33.12	15	24.74	16.05	9.88	0.65	0.40
6	63.81	22	40.70	32.10	19.76	0.79	0.49
7	59.78	22	37.75	32.10	19.76	0.85	0.52
8	63.80	14	49.44	32.10	19.76	0.65	0.40
9	61.86	23	38.37	32.10	19.76	0.84	0.52

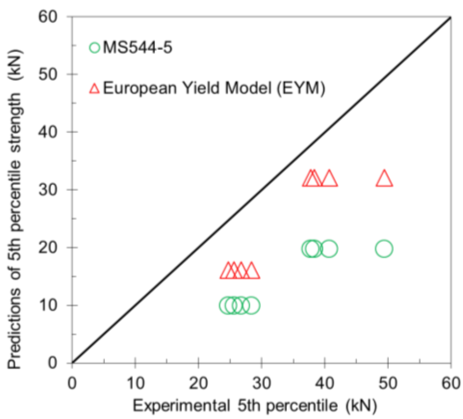


Fig. 9 Effectiveness of MS544-5 and EYM in predicting the strength of bolted connections that failed in ductile

The efficiency of both EYM and MS544-5 can be obviously seen in the plotting of predictions versus the experimental results (see Fig. 9). A one-to-one ratio line was drawn to show the efficacy of both predictions of EYM and MS544-5. The farther below the plotting from the one-to-one ratio line indicate that the estimation of the strength provided is too conservative. This finding is in agreement with the previous published articles that investigating the bolted connection for Meraka wood [7] and Nyatoh wood [21].

4.2.4 Strength Prediction Effectiveness of Brittle Failure Mode - RSM versus MS544-5

Referring to the bolted connections that failed in row shear, Group 5 and Groups 10-18, the connection strength results obtained from the experiment are tabulated in Table 6. The average and 5th percentile strength values shown in Table 6 were analyzed using the maximum resistance of ten specimens for each group of connections. From the calculated CoV, one can see that the test data obtained show an acceptable data distribution. To get the RSM equation to predict the strength of the bolted connections, which is not included in this article, one can obtain from [8, 9, 15, 16, 22]. As per discussion in Section 1 of this article, the shear strength parallel to the wood grain was calculated using the correlation with the wood density which is equal to $17.8G^{1.24}$ as per recommendation of [8]. It should be noted that the factor of 0.6 to convert the average to 5th percentile, as per mentioned in [15] and [16], was not applied in the connection resistance calculation. This is because the 5^{th} percentile of oven-dry wood density was used when performing the capacity estimations of the bolted connections for Bitis wood. Also, due to the average moisture content of Bitis wood obtained was 19%, the $17.8G^{1.24}$ was used instead of $21.9G^{1.13}$ because the former correlation is suitable to the local dry timber condition compared to the latter correlation that based on wood condition at 12% moisture content [26]. Another important item to highlight in the bolted connection capacity prediction using RSM equation is the calibration factor as discussed in Section 1 of this paper. The details of the calibration factor identification are described in the next section, whereas the analysis was performed in considerations of the failure mode of the connection groups to be selected in the calibration factor determination. For the MS544-5 strength predictions in the bolted connection of Bitis wood, a similar approach was implemented as per explained in the previous Section 4.2.3. In evaluating the effectiveness of both strength predictions of RSM and MS544-5 against the experimental data obtained, the calculated ratios of RSM/$R_{5th\%}$ and MS544-5/$R_{5th\%}$ show that the RSM provides better efficacy to predict the connection capacity of Bitis wood with an average of 82% efficiency.

Table 6. RSM predictions vs experimental results of connection groups that failed in brittle

Group	Experimental			Predictions		Ratio	
	R_{avg} (kN)	CoV (%)	$R_{5th\%}$ (kN)	EYM (kN)	MS544-5 (kN)	RSM / $R_{5th\%}$	MS544-5 / $R_{5th\%}$
5	26.02	23	16.14	11.88	9.88	0.74 (0.67)	0.61
10	48.60	18	33.83	23.77	19.76	0.70 (0.64)	0.58
11	55.19	21	36.23	23.77	19.76	0.66 (0.60)	0.55
12	52.93	26	30.45	23.77	19.76	0.78 (0.71)	0.65
13	59.38	27	33.31	23.77	19.76	0.71 (0.65)	0.59
14	55.72	29	29.14	23.77	19.76	0.82 (0.74)	0.68
15	45.74	32	21.73	23.77	19.76	1.09 (0.99)	0.91
16	84.97	30	43.67	35.65	29.64	0.82 (0.74)	0.68
17	72.37	31	35.75	35.65	29.64	1.00 (0.91)	0.83
18	59.84	19	41.38	35.65	29.64	0.86 (0.78)	0.72

The MS544-5 was found to only provide 68% of prediction effectiveness. From Fig. 10, one can see clearly the effectiveness comparisons between the timber code of MS544-5 and the RSM. It should be noted that the RSM shows 9% of over-predicted strength in Group 15. This is mainly due to the variation of the experimental data obtained because the failure of all specimens in Group 15 was thoroughly inspected to confirm that the strength was not influenced by any of the strength affecting factors like the slope of grain and moisture content. Also, the wood defects such as pre-cracked or knot occurrence on the specimens of Group 15 were not visibly evident. The designers should take note that this over-prediction issue can be resolved by applying a higher calibration factor value, which is further discussed in the next Section 4.2.5.

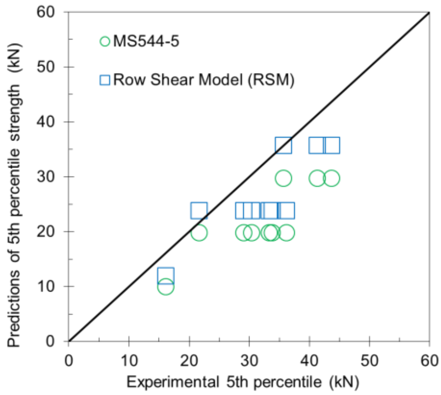


Fig. 10 Effectiveness of MS544-5 and RSM in predicting the strength of bolted connections that failed in brittle

4.2.5 Calibration Factor Determination for Bitis Wood

In the calibration factor identification, only groups of bolted connections that failed in the row shear mode were included in the analysis, they are Group 5 and Groups 10-18. These groups were fabricated with 50 mm, either the end distance or bolt spacing. In general, a linear regression technique was used to obtain the calibration factor for Bitis wood. To start the analysis, a graph of the average predicted strength by RSM versus the experimental average plotting was developed with a trial-and-error calibration factor value. The graph is also equipped with a reference one-to-one ratio line shown in Fig. 11. A linear regression line was then drawn for the plotting as shown in Fig.11 as the thick line. The calibration factor can be determined by repeating the trial-and-error process with a different calibration factor value until the regression line is comparably matched the reference line. For Bitis wood, a calibration factor of 4 with 66% similarities of regression model was suggested to achieve an acceptable prediction of the 5th percentile strength by the RSM equation. One can see that the coefficient of determination, R^2, of 0.98 obtained from the analysis shows a good data fit was achieved with respect to the proposed regression model. To provide a remedial solution of the over-predicted value by RSM in Group 15 as per mentioned in the previous section, a higher calibration factor of 4.4 is recommended with 60% regression model relationships can be achieved as shown in Fig.12. This application of 4.4 calibration factor makes the preceding over-predicted ratio of 1.09 to drop to 0.99 (see figures in parentheses) as given in Table 6. By using the new 4.4 calibration factor for Bitis wood, the effectiveness of RSM predictions was still identified to be better than the timber code of MS544-5 estimations as per calculated ratios of RSM/$R_{5th\%}$ shown in parentheses of Table 6. In average, the RSM was found to give 74% efficacy for the recommended calibration factor of 4.4. From this finding, one can see even the selection of the calibration factor for the particular wood species is based on the decision of designers to obtain their intended optimized strength prediction. However, it is strongly recommended the designers to establish the regression model of the 5th percentile strength predictions as shown in Fig.13. This was to cross-check that the plotting data of the 5th percentile strength estimations to be below the one-to one ratio line for ensuring a safe strength prediction can be obtained from the RSM.

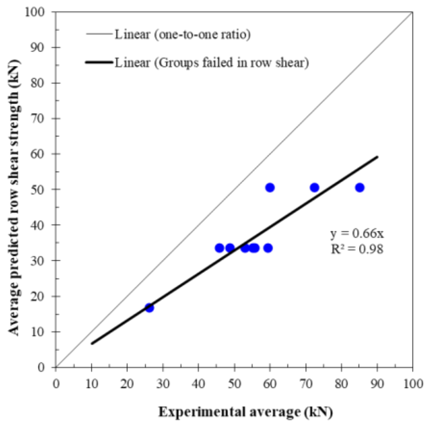


Fig. 11 Calibration factor of 4

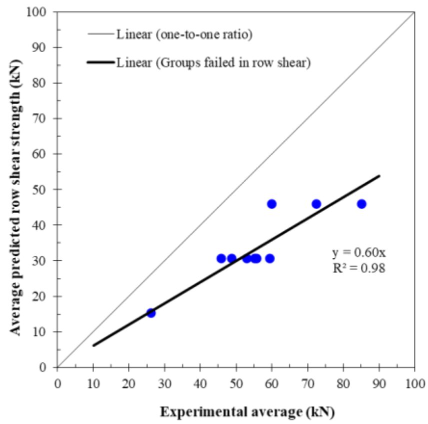


Fig. 12 Calibration factor of 4.4

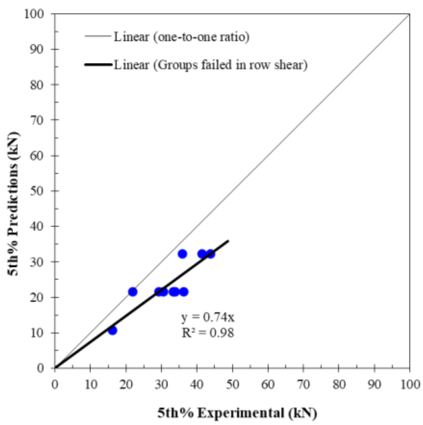


Fig. 13 Regression model of 5th pecentile strength

5. Conclusions

The addition of the bolted connection findings on the Bitis wood obtained from this present experimental work was not only to enrich the wood database of the preceding works done by Abdul Karim et al. [9] on the Meraka wood and Ujan et al. [22] on the Nyatoh wood, but the design parameters for optimizing the strength are proposed. The geometrical parameters of both the end distance, e_t, and bolt spacing, s_b, were identified to affect significantly the strength of the connections as they are the main cause to govern the failure mode of the bolted connection parallel to the wood grain. For the Bitis wood, it was recognized that either end distance or bolt spacing that equal or than 50 mm can cause the bolted connection to behave in the brittle failure of the row shear. This is very crucial to be avoided in the fabrication of the connection configuration unless a significant number of fasteners are required to be used due to the strength demand, which consequently a small distance of the geometrical parameters could not be avoided. The embedding strength of the Bitis wood, which is not provided by the timber code of MS544-2 [24], was determined in this present study. The proposed embedding strength value was validated to offer 70% efficiency (in average) of the European Yield Model (EYM) in estimating the bolted connection capacity for the ductile failure mode, whereas the timber standard of MS544-5 [14] only 43% of efficacy. On the use of the calibration factor, CF, for predicting the strength of bolted connections using the Row Shear Model (RSM), a value of 4.4 for the Bitis wood is proposed due to neither to provide an over-predicted strength nor a too conservative strength. The calibration factor recommended herein offers 74% of average effectiveness, whereas the MS544-5 provides 38% of efficiency.

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References

[1] Griffith MC. Performance of Unreinforced Masonry Buildings during the Newcastle Earthquake, Australia. Research Report No. R86, The University of Adelaide, Adelaide, Australia, 1991.

[2] Blaikie EL, Spurr DD. Earthquake vulnerability of existing unreinforced masonry buildings. Works Consultancy Services, Wellington, New Zealand, 1992.

[3] Bruneau M. State-of-the-art report on seismic performance of unreinforced masonry buildings. Journal of Structural Engineering 1994;120(1):230-251. https://doi.org/10.1061/(ASCE)0733-9445(1994)120:1(230)

[4] Evans N. The earthquake's impacts on buildings and infrastructure. In: Shaken Up, proceedings of a workshop on Recovery following the Gisborne Earthquake (Vol. 7), 2009.

[5] Dizhur D, Lumantarna R, Ismail N, Ingham JM, Knox C. Performance of unreinforced and retrofitted masonry buildings during the 2010 Darfield earthquake. Bulletin of the New Zealand Society for Earthquake Engineering 2010;43(4):321. https://doi.org/10.5459/bnzsee.43.4.321-339

[6] Dizhur D, Ingham J, Moon L, Griffith M, Schultz A, Senaldi I, Magenes G, Dickie J, Lissel S, Centeno J, Ventura C, Leite J, Lourenco P. Performance of masonry buildings and churches in the 22 February 2011 Christchurch earthquake. Bulletin of the New Zealand Society for Earthquake Engineering 2011;44(4):279-296. https://doi.org/10.5459/bnzsee.44.4.279-296

[7] Abdul Karim AR, Quenneville P, MSa'don N, Yusof M. Investigating the Meraka Hardwood Failure in Bolted Connections Parallel to the Timber Grain. International Journal of Engineering & Technology 2018;7(3.18):62-65. https://doi.org/10.14419/ijet.v7i3.18.16675

[8] Abdul Karim AR, Quenneville P, Sa'don N M. Shear failure of the Meraka hardwood in bolted connections loaded parallel to the timber grain. In: IOP Conference Series: Materials Science and Engineering 2021;1101(1):012005. https://doi.org/10.1088/1757-899X/1101/1/012005

[9] Abdul Karim AR, Quenneville P, Sa'don N M. Design Optimization of the Bolted Connection Loaded Parallel to the Timber Grain for Masonry Building Retrofits.

International Journal of Mechanics 2022;16:6-14. https://doi.org/10.46300/9104.2022.16.2
[10] Abdul Karim AR, Quenneville P, MSa'don N, Ingham J. Assessment Guidelines of Wall-Diaphragm Connections for Masonry Buildings. In: Yazdani S, Singh A, eds. New Developments in Structural Engineering & Construction. Research Publishing, Singapore, 2013. https://doi.org/10.3850/978-981-07-5354-2_St-136-427
[11] Abdul Karim AR. Seismic Assessment of Wall-Diaphragm Connections in New Zealand Unreinforced Masonry Buildings. PhD thesis The University of Auckland, New Zealand, 2012.
[12] New Zealand National Society for Earthquake Engineering. Draft Guidelines for Assessing and Strengthening Earthquake Risk Buildings, New Zealand National Society for Earthquake Engineering, Wellington, New Zealand, 1995.
[13] Federal Emergency Management Agency. Techniques for the Seismic Rehabilitation of Existing Buildings. FEMA 547, Federal Emergency Management Agency, Washington, D.C., 2006.
[14] Department of Standards Malaysia. Code of Practice for Structural Use of Timber: Part 5: Timber Joints. MS544-5, Department of Standards Malaysia, 2001.
[15] Quenneville P. Design of Bolted Connections: A Comparison of a Proposal and Various Existing Standards. Journal of the Structural Engineering Society (SESOC) New Zealand Inc. 2009;22(2):57-62.
[16] Quenneville JHP, Jensen J. Validation of the Canadian Bolted Connection Design Proposal. CIB-W18 meeting Proceedings 2008.
[17] Jockwer R, Fink G, Köhler J. Assessment of the failure behaviour and reliability of timber connections with multiple dowel-type fasteners. Engineering Structures 2018;172:76-84. https://doi.org/10.1016/j.engstruct.2018.05.081
[18] Yurrita M, Cabrero JM. New design model for brittle failure in the parallel-to-grain direction of timber connections with large diameter fasteners. Engineering Structures 2020;217:110557. https://doi.org/10.1016/j.engstruct.2020.110557
[19] Lokaj A, Dobes P, Sucharda O. Effects of loaded end distance and moisture content on the behavior of bolted connections in squared and round timber subjected to tension parallel to the grain. Materials 2020;13(23):5525. https://doi.org/10.3390/ma13235525
[20] Cao J, Xiong H, Liu Y. Experimental study and analytical model of bolted connections under monotonic loading. Construction and Building Materials 2021;270:121380. https://doi.org/10.1016/j.conbuildmat.2020.121380
[21] Ujan XL, Karim ARA, Sa'don NM, Teng XY, Quenneville P, Rahim NL. Effectiveness Validation on Existing Design Equations for the Sustainable Design of Masonry Building Retrofits. Journal of Sustainability Science and Management 2022;17(6):79-91. https://doi.org/10.46754/jssm.2022.06.007
[22] Ujan XL, Karim ARA, Sa'don NM, Sahari SH, Rahim NL, Quenneville P. Validation of Shear Failure on Bolted Connection for Nyatoh Hardwood. Journal of Engineering Science and Technology 2023;18(5):2398-2410.
[23] Johansen KW. Theory of timber connections. Publications of International Association for Bridge and Structural Engineering 1949;9:249-262.
[24] Department of Standards Malaysia. Code of Practice for Structural Use of Timber: Part 2: Permissible Stress Design of Solid Timber (First Revision). MS544-2, Department of Standards Malaysia, 2001.
[25] International Organization for Standardization. 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, 2008.
[26] Forest Products Laboratory. Wood Handbook: Wood as an Engineering Material. Forest Service U.S. Department of Agricultural, Washington, D.C, 1987.

[27] Australian/New Zealand Standard. Timber - Methods of Test - Method 3: Density. AS/NZS 1080.3, Standards New Zealand (electronic copy), 2000.
[28] Malaysian Timber Industry Board. Strength Groups of Timber and Their Applications. [Date of update: 28/09/2020] https://www.mtib.gov.my/en/wisdec?view=article&id=64:specifying-timber-for-building-construction&catid=2
[29] Malaysian Standard. MS 544: Part 11: 2001 Code of Practice for Structural Use of Timber: Part 11: Recommendations for the Calculation Basis for Span Tables - Section 4: Domestic Rafters. Department of Standards Malaysia, 2001.
[30] Malaysian Standard. MS 544: Part 11: 2001 Code of Practice for Structural Use of Timber: Part 11: Recommended Span Tables and Their Calculations: Section 1: Domestic Floor Joists. Department of Standards Malaysia.
[31] Meier E. The Wood Database: Hardwood Anatomy. [Date of access: 06/04/2023] https://www.wood-database.com/wood-articles/hardwood-anatomy/
[32] Universiti Putra Malaysia. Laboratory Report of Wood Properties: Wood Anatomy (Bitis) by Universiti Putra Malaysia Kampus Bintulu Sarawak. [Date of report: 14/09/2021] http://histaf.upm.edu.my/upload/inovasi/2021/20211130163926LAB_2_WOOD_ANATOMY_compressed-2.pdf
[33] PlantUse English contibutors. Madhuca (PROSEA Timbers). [Date of update: 05/08/2017] https://uses.plantnet-project.org/e/index.php?title=Madhuca_(PROSEA_Timbers)&oldid=326801
[34] Australian/New Zealand Standard. Timber - Methods of Test - Method 1: Moisture content. AS/NZS 1080.1, Standards New Zealand (electronic copy), 1997.
[35] International Organization for Standardization. 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, 1983.