Development of Limit State Design Method for Malaysian Bolted Timber Joints

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Summary

The existing procedure for designing bolted timber joints in Malaysia is still based on the working stress design method (WSDM), in accordance with the MS 544: Part 5:2001. Timber design standards in most developed countries presently have been revised to incorporate the limit state design method (LSDM). This paper outlines a study, which is being carried out to propose a procedure for adopting the LSDM in the next revision of the Malaysian Standard.

The embedment test parallel to the grain in accordance with the BS EN 383:1993 was carried out for three bolt sizes and five species of Malaysian timbers from various densities. The results were found to be similar to the values for hardwoods that are suggested in Eurocode 5.

Joint tests on double shear bolted joint parallel to the grain were also carried out to determine the ultimate capacities of the joints. The ultimate loads obtained from the experimental works were then compared to the European Yield Load (EYM).

Keywords: Limit State Design, bolted timber joints, European Yield Model.

1. Introduction

In recent years, the design method for structural members, in general, has evolved from the working stress design method (WSDM) to the limit state design method (LSDM). In Malaysia, however, works toward upgrading the timber design codes from those based on the WSDM to that of LSDM has just begun.

Among mechanical joints, bolts are very widely used due to their simplicity in production and their ability to carry reasonably high loads. However, the mechanical behaviour of a bolted joint is very complex and its general understanding and strength prediction varies significantly. To determine the strength of a bolt joint, LSDM’s based structural timber codes typically rely on the European Yield Model (EYM).

The objectives of this study include the establishment of the embedment strength properties of Malaysian timbers and to investigate the validity of using EYM’s approaches to Malaysian timbers.

2. Literature Review

2.1 Malaysian Standard MS 544

The Code of Practice for Structural Use of Timber, MS 544 was first published in 1978. It was based on the British Codes of Practice for the design of timber structures, CP112:1967 [1] [2]. The data used in the code were obtained from the laboratory works conducted at the Forest Research Institute of Malaysia (FRIM). The revision of the code started in 1997 and the new version was made available in 2001[3]. It was still based on the WSDM. Unlike the old code, the latter is separated into 12 parts, where the timber joints design is laid out in Part 5. This part gives guidance on designing joints in solid timber with mechanical fasteners such as nails, wood screws, bolts, coach screws, split-ring connectors, and shear plate connectors. The revised code was drafted taking into consideration various other standards such as AS 1720.1 and BS 5268: Part2 [4][5]. For bolted timber joint design, the data were also taken from [6].

2.2 European Yield Model

In the late 1940's, Johansen [7] proposed the yield theory to predict the ultimate capacities of joints with fasteners such as bolts. Over the years, this model has gone through several revisions but the basic concepts remain the same. The strength of the joint depends on the embedment strength of the timber and the bending strength of the fastener. He based his works on the assumption that the steel and timber load deformation curves behaved are the same to those of ideal rigid plastic materials. The yield and ultimate capacities of steel and timber can be used to predict the ultimate strength of dowel-type joints. The strength for various connection geometries and material combinations for two and three-member connections can therefore be predicted using EYM. A number of researchers [8][9][10] have reported good agreements between the EYM's prediction and actual experimental results. In EYM's approach, the maximum capacity of timber joints are taken to be the loads at which either the embedment strength or bearing failure or both occurred for the first time.

3. Test Programme

3.1 Embedment Test

The test was conducted using five species of Malaysian timbers from various densities and joint group in accordance with the MS 544: Part 5[11]. They are Balau *(Shorea spp.)* from joint group J1, Kempas (*Koompassia malaccensis)* from joint group J2, Mempening *(Quercus spp.)* from joint group J3, Mengkulang *(Heritiera spp.)* from joint group J4, and Pulai *(Alstonia spp.)* from joint group J. Three sizes of bolts (8mm, 10mm and 12mm) were also used in the study. For each species and bolt diameter 15 similar specimens were fabricated hence altogether 225 specimens fabricated and tested in this study. They were all were fabricated and tested in dry condition. The dimensions and test method followed the procedure laid out in BS EN383:1993[12]. Compressive load parallel to the grain at a constant rate of displacement 1.25mm/minute was applied to each of the specimens. The deformations of the specimens were measured using Linear Variable Displacement Transducers (LVDT). After the test, small clear specimens near the failure zones were cut for density and moisture content determination in accordance with the AS 1080.1-1998[13].

3.2 Joint Test

Double shear bolted joint parallel to the grain test was carried out for three of the five species of timber used in the embedment strength tests. These are Kempas, Mengkulang and Pulai. Each specimen was fabricated using three timber members jointed with one mild steel bolt. The nominal diameters of the bolts were the same as those use in the embedment strength tests, which are 8mm, 10mm and 12 mm. Thicknesses of the side members, were half of that of the centre member. Length of the members was cut in such a way that they were sufficient for loading and attachment of the LVDT during the test. Before testing, the samples were stored under controlled temperature 20±2°C (68±6°F) and 63±2% relative humidity for 14 days ensure joint relaxation could take place as recommended in AS 1649-1998[14]. The testing was carried out in accordance with the AS 1649-1998. After the test, small clear specimens were taken in line with the bolt hole to determine the moisture content and density of the test specimens.

The tensile test was also carried out to determine the tensile strength values for the bolts. Bolts were necked down to assure that failure occurs in a controlled manner away from the threaded portion of the shank.

4. Results and Discussion

4.1 Embedment Test Result

Embedment strength was calculated using the following equation taken from [12],

$$f_h = \frac{F_{\max}}{td} \quad (1)$$

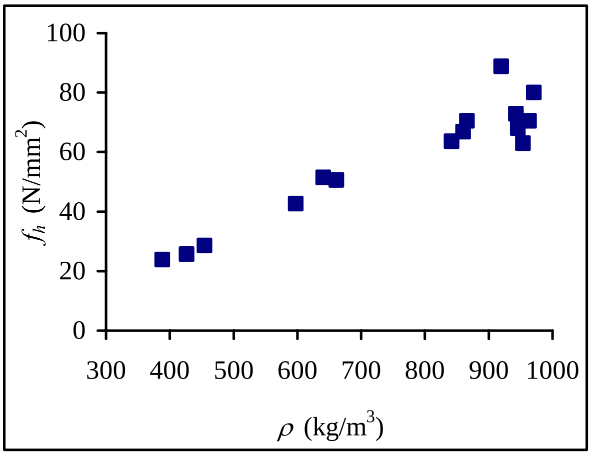
where f_h is the embedment strength, F_{max} is the maximum load, t is the thickness of the specimen, and d is the bolt diameter.

Table 1 shows the average embedment test results from 15 specimens.

Table 1 Embedment test results

Timber species	Code	Actual diameter, d (mm)	Actual Thickness, t (mm)	Maximum Load, F_{max} (kN)	Embedment strength, f_h(N/mm^2)	Moisture content, mc (%)	Density, ρ (kg/m^3)
Balau	J1D8	7.72	15.61	10.70	88.79	11.01	919.69
	J1D10	9.39	20.09	15.10	80.04	11.84	971.04
	J1D12	12.54	24.07	21.26	70.44	12.49	963.21
Kempas	J2D8	7.73	16.03	8.28	66.82	10.47	859.86
	J2D10	9.38	19.97	11.91	63.58	10.79	841.80
	J2D12	12.52	24.46	21.57	70.44	10.45	865.81
Mempening	J3D8	7.69	15.53	8.70	72.85	12.23	942.87
	J3D10	9.38	19.78	12.63	68.07	13.14	945.64
	J3D12	12.55	23.60	18.65	62.97	13.45	953.95
Mengkulang	J4D8	7.71	16.27	5.35	42.65	9.92	597.42
	J4D10	9.40	19.89	9.45	50.54	11.20	661.52
	J4D12	12.54	24.32	15.68	51.41	10.68	640.95
Pulai	J5D8	7.72	16.09	3.19	25.68	9.67	426.51
	J5D10	9.40	20.02	5.37	28.54	10.98	454.44
	J5D12	12.55	24.22	7.26	23.88	10.21	388.11

Previous studies reported that there was a correlation between density and embedment strength [15] [16] [17]. As the densities get higher, the embedment strengths were found to increase accordingly. This relationship can also be seen in Table 1 and Fig 1. It can therefore be concluded that density is a significant factor in determining embedment strength characteristic. Fig 2 presents the embedment strength as a function of bolt diameter. In this study, the results generally show that the embedment strength was almost constant regardless of bolt diameter except for timbers with densities greater



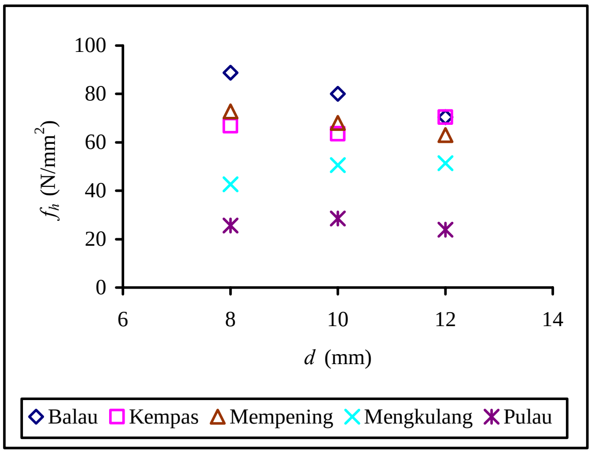


Fig 1 Embedment strength and density relationship

Fig 2 Embedment strength vs. bolt diameter

than 900kg/m^3 which agreed well with the study from Rammer [16] and Sawata and Yasumura [17]. Hilson et al. however, found that the embedment strengths decreased slightly as the dowel diameter increased [15]. Balau and Mempening, which had density more than 900kg/m^3 tend to agree with Hilson's finding.

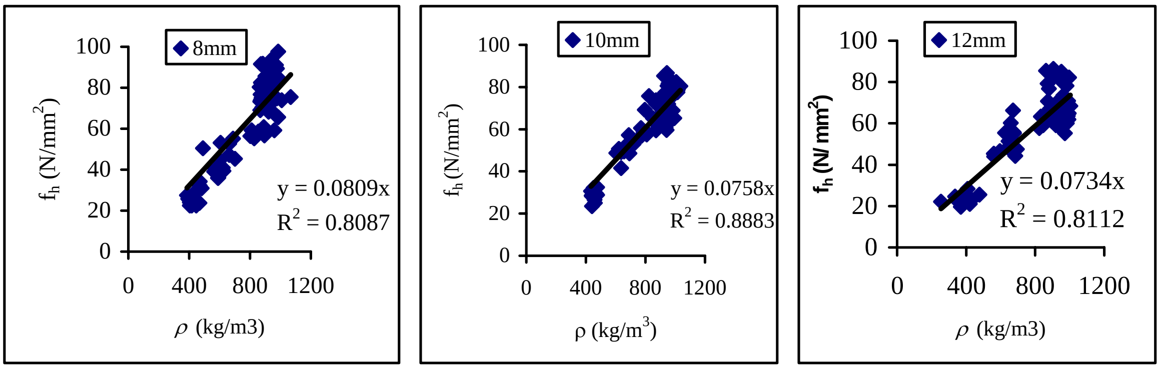


Fig 3 Correlation between embedment strength and density (each bolt diameter)

The regression lines between embedment strength and density for each diameter bolts are shown in Fig 3. The correlation equations from this study were used in deriving equations that best describe the embedment strength of Malaysian timbers. In the Eurocode 5[18], the embedment strength parallel to the grain is given as follows,

$$f_h = 0.082(1 - 0.01d)\rho \qquad (2)$$

where f_h is the embedment strength (N/mm^2), d is the dowel diameter (mm) and ρ is the density (kg/m^3).

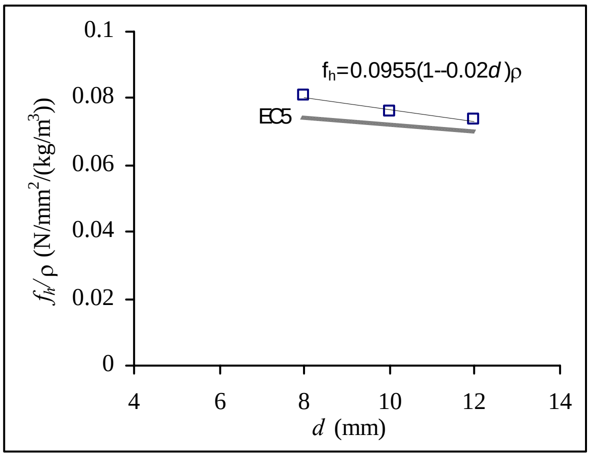


Fig 4 Comparison between test and Eurocode 5

Fig. 4 shows the equation which best fit the regression lines from the experimental work the equation from Eurocode 5. From the graph, it shows that the gradient of the equation from the test result is slightly steeper than the Eurocode 5. This might be due to the higher densities of the timbers used in the test compared to the timbers used in obtaining the Eurocode 5 equation. The equation that best suited the relationship from Fig 4 is as follows,

$$f_h = 0.0955(1-0.02d)\rho \qquad (3)$$

When the embedment strengths parallel to the grain was calculated using Equation (3), the values were found to be 0.5% to 7% larger than those that were derived from Equation (2).

4.2 Joint Test Result

Table 2 illustrates the average results from the double shear joint test. P_{ult} is taken as the ultimate or maximum load achieved by the specimen or when the deformation exceeded 12.5 mm. The failure modes for each specimen were also observed. It was found that most of the joints failed in either mode III, mixed mode III/IV, or mode IV.

Table 2 Double shear bolted joint test result

Timber species	Code	Actual bolt diameter, d (mm)	Ultimate Load, P_{ult} (kN)	Density, ρ (kg/m³)	Failure Mode
Kempas	K8	7.50	18.77	853.55	III
	K10	9.50	22.47	854.63	III&IV
	K12	12.50	39.56	850.23	IV
Mengkulang	M8	7.50	12.34	628.74	III
	M10	9.50	18.53	643.58	III
	M12	12.50	30.77	661.63	IV
Pulai	P8	7.50	8.47	430.89	III
	P10	9.50	12.95	415.62	III
	P12	12.50	19.25	441.80	III& IV

4.3 Calculated shear strength using EYM Equations

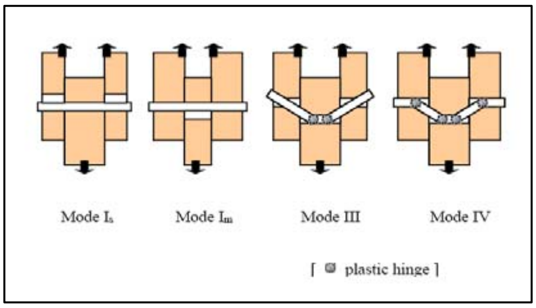


Fig 5 Failure mode for double shear joints (After Smith and Foliente) [19]

With the EYM, the double shear bolted timber joints have four failure modes as shown in Fig 5. Equation (4) was used for calculating the shear strength of bolted joint and was adopted from Eurocode 5 where;

$$P_y = \min \begin{cases} f_{h,1} t_1 d & \text{Mode I}_s \\ 0.5 f_{h,2} t_2 d & \text{Mode I}_m \\ 1.05 \dfrac{f_{h,1} t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta) + \dfrac{4\beta(2+\beta)M_y}{f_{h,1} d t_1^2}} - \beta\right] & \text{Mode III} \\ 1.15\sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2 M_y f_{h,1} d} & \text{Mode IV} \end{cases} \quad (4)$$

P_y is the load carrying capacity per shear plane per bolt
t_i is the timber penetration depth with i either 1 or 2 ; 1=side member, 2 = main member
f_h is the embedment strength in timber member i
d is the bolt diameter
M_y is the bolt yield moment
β is the ratio between the embedment strength of the members; in this case, is equal to 1

Equation (3) was used for determining the embedment strength and the bolt yield moment was calculated using the following equation taken from [18],

$$M_y = 0.3 f_u d^{2.6} \quad (5)$$

where:

M_y is the bolt yield moment in Nmm
f_u is the tensile strength in N/mm^2
d is the bolt diameter in mm

Table 3 Strength of bolted joint by EYM equations

Timber Code	d (mm)	t_1 (mm)	t_2 (mm)	f_h (N/mm^2)	M_y (Nmm)	P_y Equation (4), (kN)	Failure Mode	P_{ult} from the test, (kN)	Failure Mode test
K8	7.5	14	28	69.29	31091.61	4.50	III	18.77	III
K10	9.50	23	46	66.11	38672.69	6.69	III	22.47	III & IV
K12	12.50	24	48	60.90	105606.9	10.39	III	39.56	IV
M8	7.50	14	28	51.04	31091.61	3.74	III	12.34	III
M10	9.50	23	46	49.78	38672.69	5.40	III	18.53	III
M12	12.50	24	48	47.39	105606.9	8.84	III	30.77	IV
P8	7.50	14	28	34.98	31091.61	3.03	III	8.47	III
P10	9.50	23	46	32.15	38672.69	3.99	III	12.95	III
P12	12.50	24	48	31.64	105606.9	6.95	III	19.25	III & IV

The ultimate strength of bolted joints obtained from the experiments was compared with those calculated from the Equation (4), as shown Table 3. These results were similar to that reported by Sawata [20] where the percentage differences between P_y and higher P_{ult} were in the range 0%-74%. This indicated that the EYM underestimates the experimental ultimate strength for bolted joints.

5. Conclusions

The conclusions that can be drawn from this study are:

1. The embedment strength of Malaysian timber is significantly affected by the density.
2. The equation that can be used to determine the embedment strengths of Malaysian timbers is $f_h = 0.0955(1 - 0.02d)\rho$
3. The ultimate strength calculated using EYM equations tend to grossly underestimate the ultimate strength of bolted joints for Malaysian timbers.

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