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Research paper

Effect of bolt configurations on stiffness for steel-wood-steel connection loaded parallel to grain for softwoods in Malaysia

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Abstract: Steel-wood-steel connection is widely seen in many applications, such as timber structures. The stiffness of steel-wood-steel connection loaded parallel to grain for softwoods originated from Malaysia was investigated in this study. Numerical models have been developed in ABAQUS to study the stiffness connection. Softwoods of Damar Minyak and Podo have been selected in this analysis. The comprehensive study focused on the effect of bolt configurations on stiffness. Numerical analysis is carried out and the developed model has been validated with the previous study. Further investigations have been made by using the validated model. From this model, numerical analysis of the stiffness values have been made for various bolt configurations, including bolt diameter, end distance, bolt spacing, number of rows and bolts and edge distance. The result shows that the stiffness of bolted timber connections for softwood depends on the bolt diameter, number of rows and bolts, end distance and edge

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distance. Based on the result, stiffness increased as the diameter of the bolt, end distance, number of rows and bolts and edge distance increased. It is also discovered that the stiffness equation in Eurocode 5 (EC5) is inadequate as the equation only considered parameters which are wood density and bolt diameter. Other connection parameters such as geometry are not considered in the EC5 equation.

Keywords: stiffness, finite element analysis, bolt connection, steel-wood-steel, softwood, Eurocode 5

1. Introduction

The mechanical performances of timber connections are particularly crucial for timber engineers involved in the design of the wood structures. In general, joints are often one of the critical concerns when designing timber structures. The mechanism of the connection must be well understood to design a safe connection and avoid catastrophic failure. In Malaysia, a few types of softwoods have commercial significance in construction, such as Damar Minyak and Podo [1]. According to Malaysian Grading Rules [2], softwood can be referred to as coniferous timbers that lack fibres and vessels. Values of the properties vary for different species of trees, whether it is softwood or hardwood [3]. Properties of wood can be quantifiable, such as density, strength grouping, air-drying rates, shrinkage, durability rating, and kiln-drying schedules. Softwood is collected from gymnosperms and has a lower density than hardwood [4].

Bolted connections, in general, are made of two or more structural components connected with a specified number of bolts. The connectors transfer the loads from one part of the structure to another. In order to design the connection, many variables are involved, for example, the bolt diameter or number of the bolts. The majority of the research in the past has focused on the load carrying capacity of the connections. For example, Johansen (1949) did exceptional research, attempting to establish formulas to calculate the maximum load for one single bolt. His work was based on a double shear connection with different possible failure modes, including bearing failure, splitting failure, net tension failure, shear-out failure and block shear failure [5].

Various studies have been conducted numerically or experimentally to explore the characteristics of bolted timber connections when they are loaded perpendicularly or parallel to grain [6–9], but most of the research did not focus on the displacement-related properties such as stiffness. This information is critical for designers who are interested in designing for high wind loads and earthquakes, where stiffness and ductility, in addition to other serviceability issues, become a major issue. Furthermore, in Eurocode 5 (EC5) [10], it is stated that stiffness for bolt in timber depends on bolt diameter and wood density only. For each dowel with two shear planes, value for K_{ser} (in N/mm) in timber to timber and wood-based panel-to-timber connections for bolts with or without clearance is shown in Eq. (1.1).

$$K_{\text{ser}} = \rho^{1.5} \cdot \frac{d}{23} \tag{1.1}$$

where ρ is wood density and d is the bolt diameter.

No clear guidance is given in Eurocode 5 on the value to be used to determine the stiffness of a connection for single and double shear connections and the actual number of fasteners that should be used [11]. So, the aim of this research is to determine the effect of bolt configuration such as end distance, edge distance, bolt spacings, number of bolts and rows, bolt diameter on the stiffness of steel-wood-steel connection loaded parallel to grain for Damar Minyak and Podo.

2. Materials and method

In this research, numerical models have been developed in ABAQUS to study the stiffness of bolted timber connections loaded parallel-to-grain for softwood in Malaysia. Figure 1 shows a steel-wood-steel connection loaded parallel to the grain. Damar Minyak and Podo have been selected in this analysis since all the material properties can be found in [3]. Damar Minyak is a softwood timber with an air dry density of 360–660 kg/m^3, whereas for Podo, the air dry density ranges from 380 to 920 kg/m^3. Important information such as types of elastic properties, including modulus of elasticity and Poisson's ratio have been applied in the model.

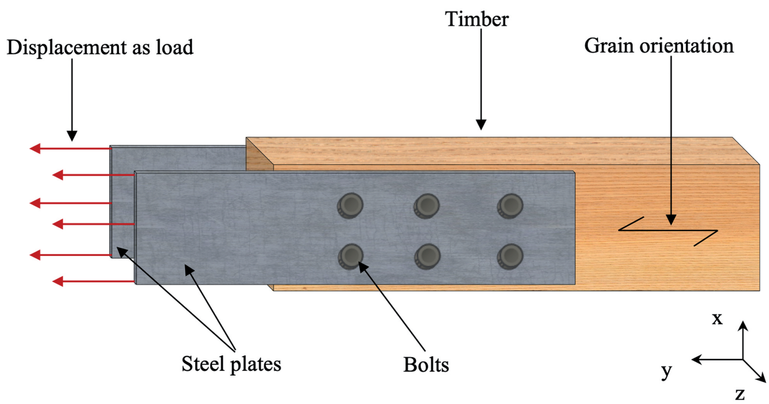

Fig. 1. Steel-wood-steel connection loaded parallel to grain [12]

2.1. Material model

Properties of the materials are described in this section. Table 1 shows material properties for the woods and steel used in this analysis. E is Young's modulus, N_u and v are Poisson's ratio, G is shear stress, while ρ is density. There are three directions of elasticity for wood, which are 1-longitudinal, 2-radial and 3-tangential whereas directions 1, 2, 3 are referred as x-axis, y-axis and z-axis in ABAQUS.

Table 1. Material properties [1, 3, 10]

Properties	Damar Minyak	Podo	Steel
E_1 (MPa)	12000	11000	E (MPa) = 210000
E_2 (MPa)	816	858	
E_3 (MPa)	600	473	
N_{u12}	0.292	0.372	$N_u/v = 0.30$
N_{u13}	0.449	0.467	
N_{u23}	0.390	0.435	
G_{12}	768	704	
G_{13}	936	671	
G_{23}	84	33	
ρ (tonne/mm^3)	3.6E–010	4E–010	7.85E–009

2.2. Modelling of bolted timber connection

This section presents 3D finite element modelling developed to simulate the structural behaviour with different configurations. Because connections modelled were geometrically symmetric, only half of the actual geometry was modelled in the ABAQUS. Figure 2 shows a flowchart for finite element analysis for bolted timber connection. First, preliminary models have been built as shown in Fig. 3, Fig. 4, Fig. 5. Then the models will be validated

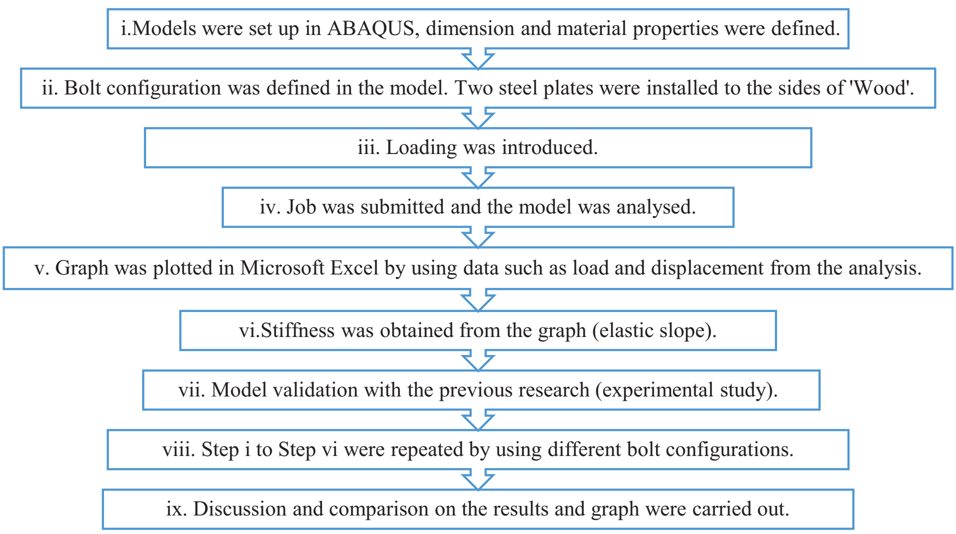

Fig. 2. Finite element analysis flowchart for bolted timber connection

by comparing initial connection stiffness with the experimental work done by [12]. The best model was chosen by accessing their speed and accuracy.

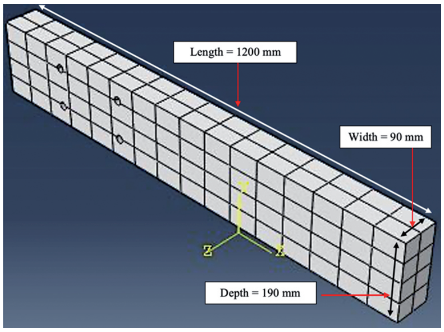

Fig. 3. Model for timber

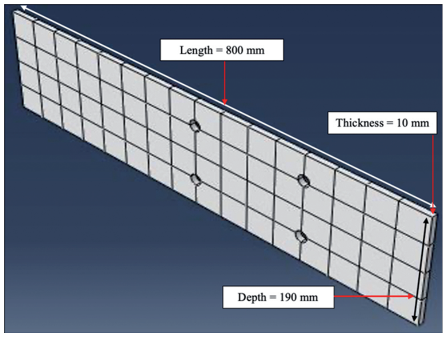

Fig. 4. Model for steel plate

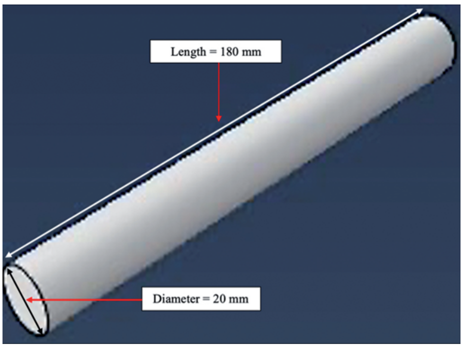

Fig. 5. Model for bolt

The dimension and configurations of the components have been referred to as the real experiment. Dimensions for the parts of the models are as follows:

i. Timber model: 1200 mm (length) ×190 mm (depth) ×90 mm (width) as shown in Fig. 3.
ii. Steel plates: 800 mm (length) ×190 mm (depth) ×10 mm (thickness) as shown in Fig. 4.
iii. The bolt model has a diameter of 20 mm and is 180 mm long, as shown in Fig. 5.

Figure 6 shows a definition of the variables used. Figure 7 shows the assembly of the model. After the parts were assembled, the boundary condition and loading of the assembly were defined. In this study, the loading was applied as an imposed displacement at a rate of 1 mm/min in the x-direction as shown in Fig. 8.

The interaction between the dowels and the surrounding timber is modelled by contact elements involving friction in the tangential direction of the dowels. Contact between the bolt and timber was modelled using contact pair surface with timber treated as slave surface and bolt surface treated as master surface since it is stiffer than wood. To evaluate the effect

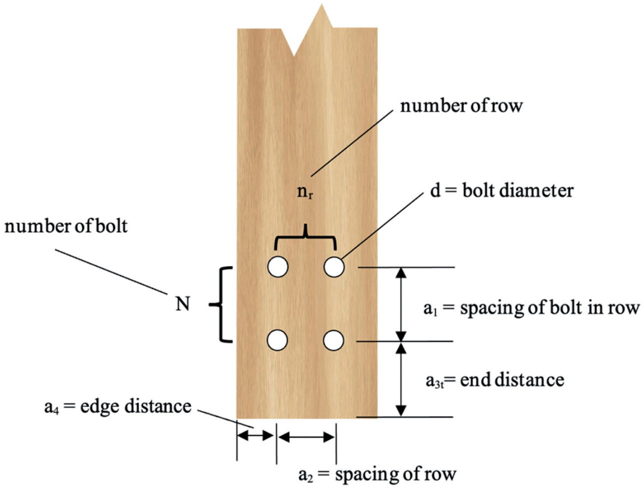

Fig. 6. Definitions of the variables used [12]

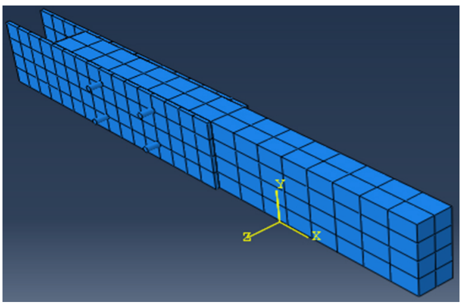

Fig. 7. Assembled model

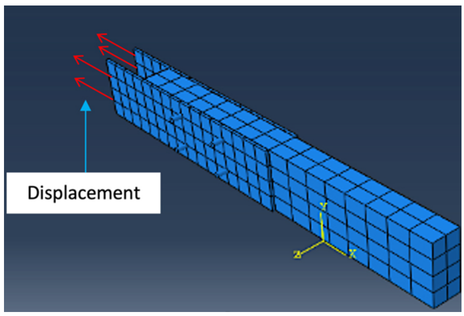

Fig. 8. Displacement control as load

of the friction coefficient, many simulations with friction constants varying from 0.1 to 0.4 between fasteners and timber were performed. The predicted results showed that the influence of the friction coefficients on the ultimate loads can be neglected as no significant difference was noticed. This is the reason why simulations with friction coefficient = 0.2 between each material composing the assembly were carried out.

"Wood", "steel bolt" and "steel plate" are meshed with the same approximate global size. The parts are partitioned before meshing to improve meshing quality. Wood, steel plate and steel bolt have 12672, 2048 and 60 linear hexahedral elements of type C3D8R, respectively. At first, simulation analysis was performed using the total mesh of 7545, 9840, 14780 and 18522 elements for discretizing the multiple-dowel steel-to timber joints. The mesh refinement had little effect on the results for the two last simulations, so that the results with 14780 and 18522 elements were indistinguishable on the load–displacement response. A value close to the experimental one was obtained using 14780 elements type

C3D8R. This is the reason why the mesh with 14780 elements was used for the rest of the study as shown in Fig. 9.

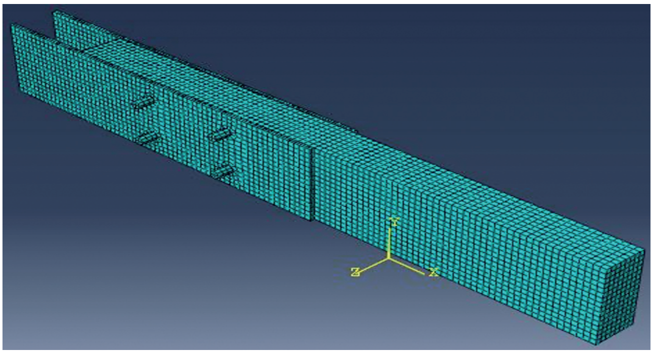

Fig. 9. Meshed model

After a job had been completed, the result (load and displacement data) were exported to Microsoft Excel and stiffness was developed from the line of best fit from the elastic part of the graph. Then, after the models have been validated with the experimental result from [12], various bolt configurations and properties are then modified for the purpose of this study as shown in Table 2.

Table 2. Various model configurations

Model number	Bolt diameter (mm)	End distance (mm)	Bolt spacing (mm)	Number of bolts	Number of rows	Edge distance (mm)
M1	20	200	200	4	2	45
M2	25	200	200	4	2	45
M3	30	200	200	4	2	45
M4	20	250	200	4	2	45
M5	20	200	250	4	2	45
M6	20	200	150	4	2	45
M7	20	200	200	2	1	45
M8	20	200	200	3	2	45
M9	20	200	200	4	2	35
M10	20	200	200	4	2	55
M11	20	150	200	4	2	45
M12	20	200	200	2	2	45

3. Result and discussion

3.1. Model visualization

All models have been developed successfully. Figure 10 shows a visualisation of the model after the simulation. As can be seen, the model has a critical deformation at the connection (bolt) area. A contour plot (U1) displays the values of displacement at a specified step and frame of the analysis. Figure 10 shows the simulation results in terms of deformation in the x-direction at the last increment. As the specimen displaced considerably in the x-direction, additional boundary conditions to restrain the movement at the bottom were applied and no displacement occurred at the bottom. As can be seen, the timber is subject to displacement up to 1.5 mm.

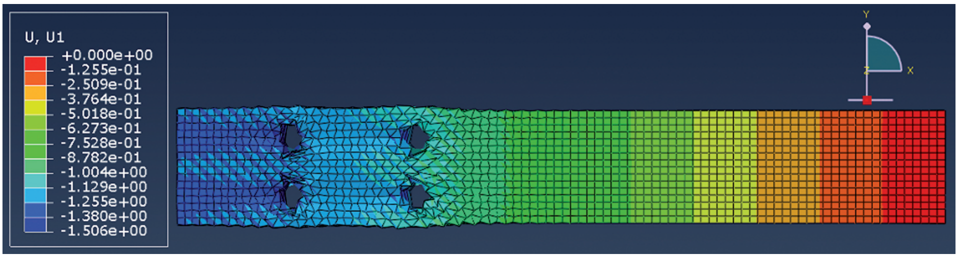

Fig. 10. Displacement in x-direction

3.2. Validation with the experimental result

In order to validate the simulation model, the stiffness result has been compared with the experimental data. In the laboratory tests of bolted connections done by [12], the cross-section of each wood specimen used was 90 mm (thickness) ×190 mm (width). The diameter of the bolt used (d) was 20 mm with shank lengths of 180 mm. A total of four steel side plates were used in these connection tests, where the thickness of the plates was 10 mm. All test specimens consisted of three-member connections with two steel side plates at each end sandwiching a wood centrepiece, as shown in Fig. 11. Each specimen consisted of an identical configuration of bolted connections at both ends. All specimens were loaded in tension parallel to the timber grain using a 500 kN MTS loading system. The laboratory test result for V1 and V2 is shown in Table 3.

Figure 12 shows a comparison of the experimental and simulation models. The result shows good agreement with the experimental result where Validation 1 has 95.2% accuracy while Validation 2 has 92.6% accuracy which means that the finite element model correctly predicts the linear part of the load-displacement response. By using this validated model, further investigation has been done to analyse the effect of bolt configurations on stiffness.

Fig. 11. Specimen configuration in bolted connection test done by [12]

Table 3. Bolted connection experimental test result

Group (10 replicates)	d (mm)	a_{3t}	a_1	a_2	n_r	N	Cross-section (mm)	Young's modulus, E (MPa)	Stiffness from the experimental study (kN/mm)
V1	20	$10d$	$10d$	$5d$	2	2	90×190	8000	75.3
V2	20	$10d$	$10d$	$5d$	2	2	90×190	11000	92.0

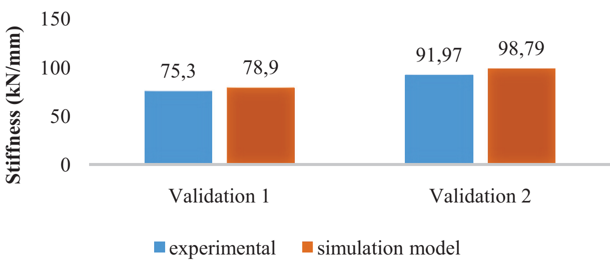

Fig. 12. Comparison of experimental and simulation model

3.3. Load-displacement responses

Load slip curves have been analysed for all simulations in order to get the values of stiffness for each configuration. Only the linear region of the graph is being examined in this research. Elastic stiffness is determined as the slope of the initial straight line fitted to the linear portion of the load–displacement curve. Figure 13 shows an example of a load versus displacement graph that is generated from Microsoft Excel. The load, 275 kN is the maximum load among all the graphs generated for the analysis of Damar Minyak. The graph is generated for the bolt configuration of Damar Minyak in which its edge distance is 55 mm, 45 and 35 mm. Referring to Fig. 13, the initial stiffness for each curve has been calculated from the slope of the best fit line to the elastic part of the graph.

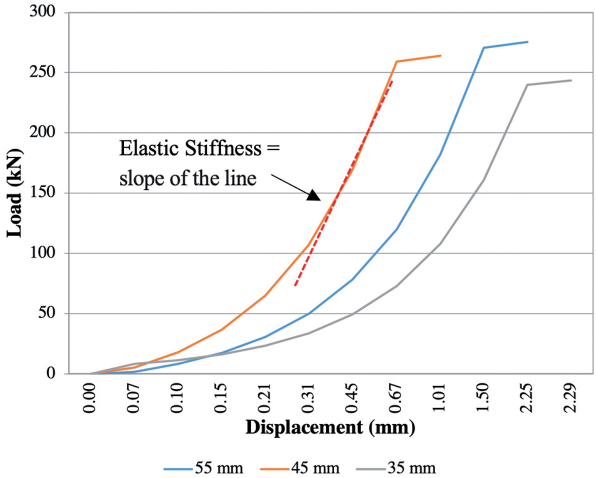

Fig. 13. Load versus displacement graph for Damar Minyak with various edge distance

Figure 14 shows an example of a load versus displacement graph for Podo. From the graph, it shows that 273 kN is the maximum load generated among all the graphs from the

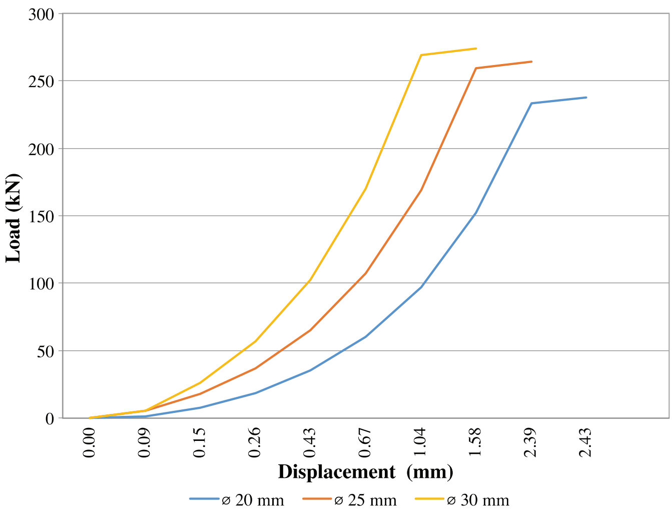

Fig. 14. Load versus displacement graph for Podo with various bolt diameters

analysis of Podo. The graph is generated for bolt configuration of Podo with bolt diameter of 20 mm, 25 mm and 30 mm. All graphs have been plotted from the simulation and all stiffness values have been calculated for every configuration as shown in Section 3.4.

3.4. Effect of bolt configurations on stiffness

Stiffness values for both types of wood were tabulated as shown in Table 4. It was found that the initial stiffness of connection increased as bolt diameter, edge distance, number of rows and bolts were greater for Damar Minyak and Podo. The effect of each configuration is simplified in Sections 3.4.1 until 3.4.5.

Table 4. Stiffness value for Damar Minyak and Podo

							Damar Minyak		Podo	
Model number	Bolt diameter (mm)	End distance (mm)	Bolt spacing (mm)	Number of bolts	Number of rows	Edge distance (mm)	Model stiffness (kN/mm)	Stiffness from Eq. (1.1) (EC5) (kN/mm)	Model stiffness (kN/mm)	Stiffness from Eq. (1.1) (EC5) (kN/mm)
M1	20	200	200	4	2	45	110.86	190.07	103.26	222.61
M2	25	200	200	4	2	45	123.22	237.58	114.12	278.26
M3	30	200	200	4	2	45	133.43	285.10	124.30	333.91
M4	20	250	200	4	2	45	110.73	190.07	110.78	222.61
M5	20	200	250	4	2	45	108.07	190.07	99.44	222.61
M6	20	200	150	4	2	45	109.16	190.07	100.28	222.61
M7	20	200	200	2	1	45	59.01	47.52	54.69	55.65
M8	20	200	200	3	2	45	98.84	142.55	90.90	166.96
M9	20	200	200	4	2	35	106.11	190.07	97.72	222.61
M10	20	200	200	4	2	55	112.94	190.07	103.67	222.61
M11	20	150	200	4	2	45	108.40	190.07	99.78	222.61
M12	20	200	200	2	2	45	78.90	95.03	92.41	111.30

3.4.1. Diameter

Stiffness for both types of woods increased as the diameter of a bolt used is larger as shown in Fig. 15. A larger force is required as the resistance of the connection to load increases. In the case of a 30 mm bolt diameter, wood is subjected to a higher force with a lower displacement. The stiffness value for Damar Minyak increased by 11.15% when a larger bolt is used (25 mm) and further increased by 10.2 kN/mm when a bolt diameter of 30 mm is used.

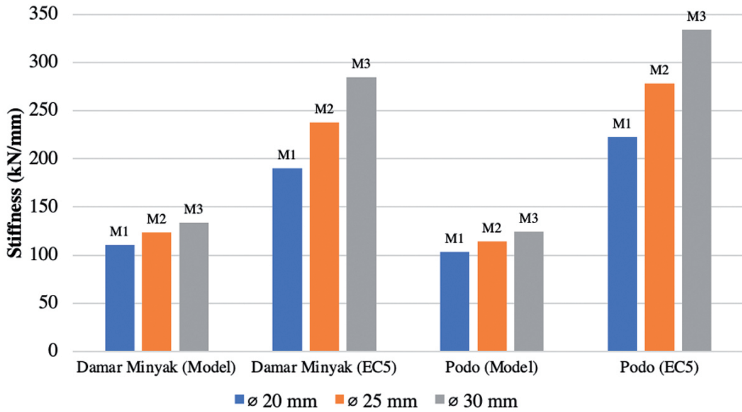

Fig. 15. Stiffness versus bolt diameter

For Podo, its initial connection stiffness is 103.26 kN/mm and was increased by 10.9 kN/mm when a larger bolt diameter is used (25 mm) and reached 124.30 kN/mm when a bolt diameter of 30 mm is used. This result agrees with the experiments and analyses done by [13] showed that the initial stiffness and ultimate load decreased when the bolt diameter is smaller than the diameter of the lead hole, provided that the ultimate slip increased with an increase in the clearance. As can be seen in Fig. 15, stiffness values calculated from EC5 are very far from the model's stiffness values.

3.4.2. End distance

There is a consistent trend (value of the stiffness model) for both types of wood as can be seen in Fig. 16. Stiffness value rose when the end distance increased. This study gives a good agreement with [14]. He conducted a research on the slip characteristics of

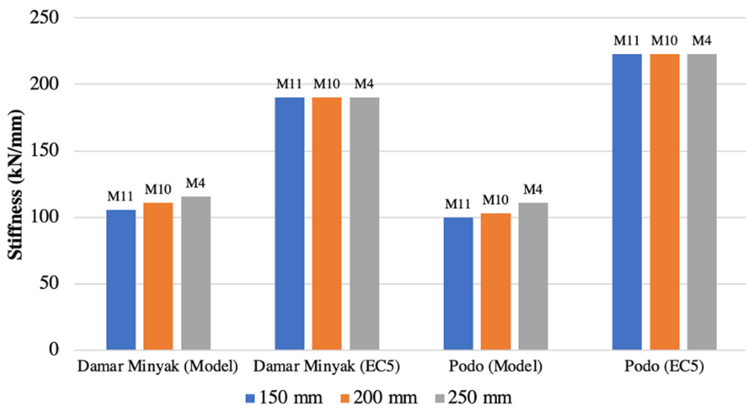

Fig. 16. Stiffness versus end distance

multiple bolted wood to wood connections, which consisted of 850 short-term tests on full-scale connections, loaded parallel to the grain. The slip characteristics of multiple bolted connections were analysed experimentally and theoretically. According to the research, it was found that the stiffness values obtained by tests were considerably lower than those suggested in EC5. This can be explained by some influence of the loaded end distance on the stiffness parameter k_s, where k_s increase if the loaded end distance increases. Figure 16 also shows the stiffness values calculated from EC5 are very far from the model's stiffness values and EC5 shows the same value for all configurations.

3.4.3. Bolt spacing

As can be seen in Fig. 17, for the same dimension of bolt spacing, Damar Minyak has a higher stiffness than Podo. Stiffness value fluctuated for both types of softwood. The trend's occurrence might be due to the quality of mesh and partition. Then, an insufficient amount of data may be contributing to the trend. By observing the graph shown in Fig. 17, it can be noticed that the bolt spacing doesn't have much effect to the connection stiffness while predicted stiffness from EC5 are overpredicted the value of the stiffness connection. In many cases, Eurocode 5 was found to overestimate the deformation resisting capability of dowelled connections [15–18] making it difficult to predict the deformation of connections with satisfactory precision.

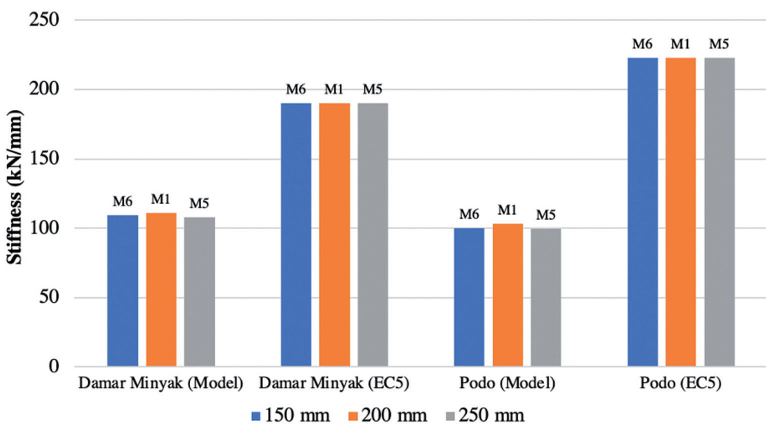

Fig. 17. Stiffness versus bolt spacing

3.4.4. Number of rows and bolts

From Fig. 18, it is clear that the stiffness value is higher when there are more bolts installed in the connection. Stiffness values were increasing for both parameters for Damar Minyak and Podo. Stiffness prediction for one row gives good agreement between the stiffness model and EC5.

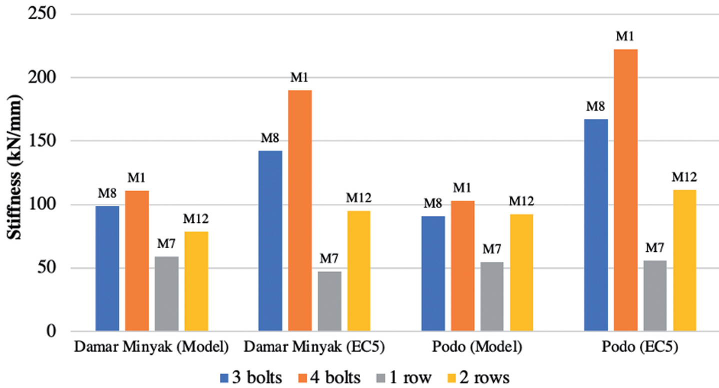

Fig. 18. Stiffness versus number of bolts and rows

3.4.5. Edge distance

Figure 19 shows that stiffness increased as edge distance rose. The trends strongly indicated that this parameter affects the initial stiffness of a steel-wood-steel connection. Steel bolt is a material that is high in tensile strength and yield strength, indicating that a larger force is required for dragging a larger bolt, resulting in a higher stiffness. It is clear that the stiffness values are different based on the arrangements of bolts being used, but EC5 gives the same values of stiffness for all connections.

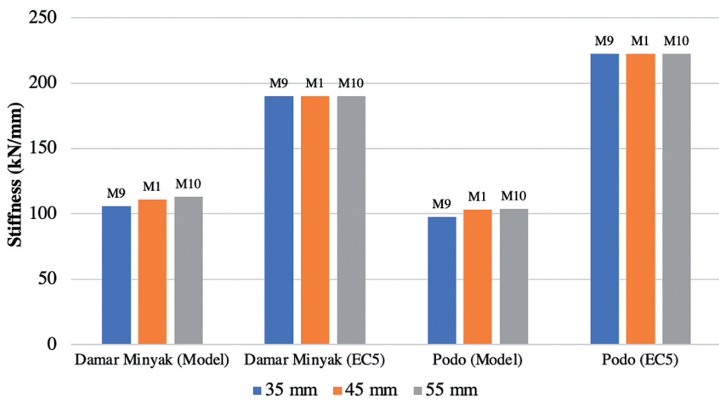

Fig. 19. Stiffness versus edge distance

4. Conclusions

The main aim of the study was to determine the important geometric parameters that influence the stiffness connection for softwood in Malaysia. In timber structures, wood members are usually manufactured in a factory and assembled via connections on site.

The load-carrying capability and stiffness of connections are usually weaker than the corresponding wood members, hence the importance and the necessity of investigating the performance of the connections [19]. Based on the result:

i. 11% stiffness increased as the diameter of the bolt increased.
ii. 4% stiffness increased as the end distance increased.
iii. 12% stiffness increased as the number of bolts increased.
iv. 46% stiffness increased as the number of rows increased.
v. 4% stiffness increased as the edge distance increased.

The stiffness equation given in EC5 for bolted connections is expressed as a function of fastener diameter and wood density only. Other connection parameters such as geometry need to be included in the equation.

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