MOMENT-ROTATION CURVE OF STEEL-TO-WOOD BOLTED CONNECTION WITH VARIOUS BOLT ARRANGEMENTS

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1. Introduction

Moment-resisting connections are mostly used to join members of arches and semi-rigid frames of timber structures. The bending moment is counter-balanced by the product of lateral load in each fasteners and the distance to the center of fastener group. Most fasteners in the group resist lateral load in inclined angles to wood grain. These inclined angles may vary from one fastener to another. Since wood response differs for different angle of load orientation to wood grain, the moment capacity of connection is greatly affected by the geometric of fastener arrangement. Analysis of moment resistance of multiple-bolt connection is complicated because of non-uniform load distribution among fasteners, and wood splitting due to stress-concentration. Wood-splitting failure is always found in multiple-bolt timber connection and govern the connection strength at very low capacity.

The aims of this study are to investigate the moment resistance and rotation curve of steel-to-wood bolted connection using different bolt arrangements. A tropical hardwood species (shorea obtusa) is considered in the experimental program. Theoretical prediction of moment resistance and moment-rotation curve are also carried out based on the test data of single bolted connection and the principle of energy conservation. Three kinds of bolt arrangements are examined.

2. Moment Resistance Analysis

For a moment-resisting connection subjected to an applied bending moment M as shown in Fig. 1(a), the applied bending moment will be counter-balanced by product of the lateral force in each fastener and its distance to the center of the group. Since side members and main member are much stiffer than fasteners, all fasteners will displace to their new positions by the same amount of rotation as shown in Fig. 1(b).

Moment resistance of connection can be derived from energy conservation principle[1)]. This principle simply stated that the external work done by applied bending is equal to internal work done by lateral load of fasteners. Since the relationship between applied moment and joint rotation is non-linear, moment resistance is expressed by Eq. (1) where θ is joint rotation, F and s are lateral load and slip of fastener, respectively.

$$M = \frac{d}{d\theta}\sum_{bolts}\left(\int_0^{s_{\max}} F ds\right) \tag{1}$$

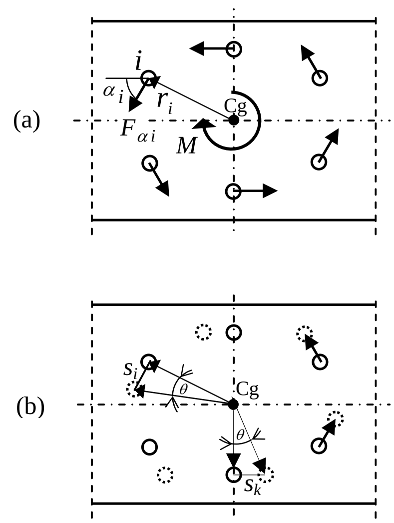


Fig 1 Moment-resisting connection, (a) acting forces, and (b) deformed configuration

The solution of Eq. (1) definitely depends on the relationship between the lateral load of fastener (F) and its fastener slip (s). Exponential model as in Eq. (2), known as Foschi's model[2)], will be discussed in this study. A, B, and C in Eq. (2) are material-dependency constants according to the experiment data. For small angle of rotation, fastener slip can be stated as in Eq. (3) where r is distance of fastener to the center of fastener arrangement and is assumed to be unchanged during rotation[1,3)]. By substituting Eq. (2) and Eq. (3) into Eq. (1), moment resistance of connection can be calculated from Eq. (4).

$$F = (A + Bs)\left(1 - e^{-\frac{C}{A}s}\right) \tag{2}$$

$$s = r\theta \tag{3}$$

$$M = \sum_{bolts} r_i\left(A + Br_i\theta\right)\left(1 - e^{-\frac{C}{A}r_i\theta}\right) = \sum_{bolts} r_i F_{\alpha i} \tag{4}$$

3. Grain Orientation Effect

Load-slip response of bolted timber connection differs according to direction of load to wood grain. When the direction of applied load is parallel to wood grain, the maximum load that can be sustained is significantly higher than that of loading perpendiculars to grain. This phenomenon is also true for maximum fastener slip[4]. The grain orientation effect on lateral load can be expressed by Hankinson formula as stated in Eq. (5) where *m* is material-dependency constant, and α is the direction of load to wood grain in unit of degree. *m* equals to two is used in this study. To evaluate the lateral load for any direction of grain orientation as stated in Eq. (5), the ratio between lateral load for parallel and for perpendicular to wood grains ($F_{//}/F_{\perp}$) is necessarily required. Empirical model of this ratio is given by Li and Chui[4] as shown in Eq. (6) in which a_1, a_2, and a_3 are constants obtained from test data. By substituting Eq. (1) and Eq. (6) into Eq. (5), finally the lateral load as a function of fastener slip and grain orientation can be expressed by Eq. (7).

$$F_\alpha = \frac{F_{//}}{\left(\frac{F_{//}}{F\perp}\sin^m\alpha + \cos^m\alpha\right)} \tag{5}$$

$$\frac{F_{//}}{F_{\perp}} = a_1 - a_2 e^{-\frac{a_3}{a_2}s} \tag{6}$$

$$F_\alpha = \frac{(A+Bs)\left(1 - e^{-\frac{C}{A}s}\right)}{\left(\left(a_1 - a_2 e^{-\frac{a_3}{a_2}s}\right)\sin^2\alpha + \cos^2\alpha\right)} \tag{7}$$

4. Experimental Program

Shorea obtusa of thickness 34 mm and two steel plates of 4 mm thickness are used in this test. The diameter of bolt and lead-hole are 12.4 mm and 13 mm respectively. Moisture content and specific gravity measurement is conducted. Specimen assembly and test are carried out when the wood lumber is in equilibrium moisture condition. Specimen is tested using four-point bending test as shown in Fig. 2. Clear-span length and the height of tested specimen are 2750 mm and 200 mm, respectively. There are two symmetrical joints in each specimen which are expected to perform in the similar manner during test.

Three multiple-bolt arrangements of connection that are shown in Fig. 3 were applied because they are used commonly in practice. These bolt arrangements have similar characteristics: the number of bolts, and the area of connection. Geometric requirement of connection was designed with EUROCODE 5 (1995)[5]. Each load and displacement data points is measured continuously by a data acquisition system and saved on a personal computer.

Single bolted connection test for direction parallel and perpendicular to wood grain are also conducted besides the multiple-bolt connection test. Wood lumber used in single bolted connection test are taken from the same wood pieces that has been used in moment-resisting connection test. This single bolted connection test is carried-out in order to define the parameters constants for analysis. All single bolted connections are loaded in compression with constant displacement rate of 1.2 mm/min. The diameter of lead-hole and the diameter of bolt are the same with those used in multiple-bolt connection tests.

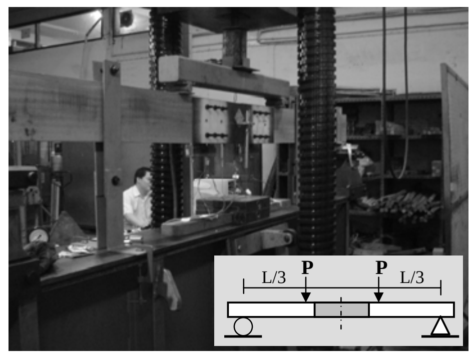


Fig 2 Multiple-bolt connection under investigation

5. Test Results and Discussion

Average moisture content and specific gravity of wood specimens are found as 14.17% and 0.86, respectively. Load-slip response of single bolted connections for direction parallel to wood grain obtained from experiment is replaced with exponential model (Eq. 2). It is found that the values of *A*, *B*, and *C* as listed in Table 1 are successfully fitted the test data.

Table 1 Constant parameters of analysis

A N/mm	*B* N/mm^2	*C* N/mm^2	a_1	a_2	a_3
546	42	891	1.368	-1.380	-1.063

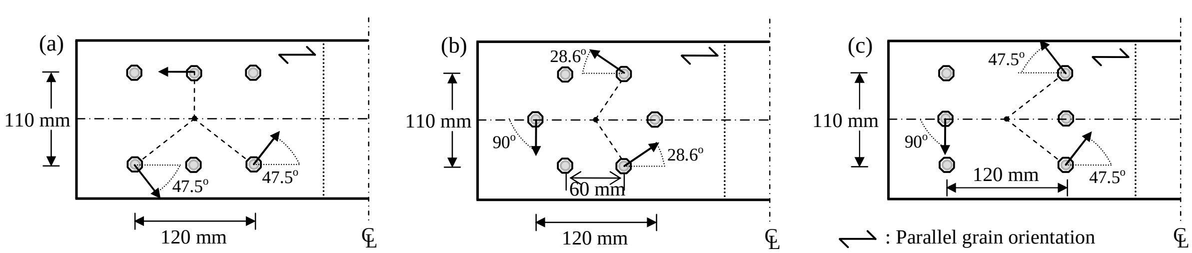


Fig 3 Different bolt arrangement: (a) 6H arrangement, 6C arrangement, and (c) 6V arrangement

Comparison between test results of single bolted connection for parallel and perpendicular to grain is presented in Fig. 4. The ratio between lateral load parallel and perpendicular to wood grain is well presented by Eq. (6) with the constant parameters (a_1, a_2, and a_3) shown in Table 1. By using the values listed in Table 1, a load-slip response of any load orientation to wood grain can be generated by Eq. (7). For this case, load-slip responses for load direction parallel, 28.6°, 47.5° and perpendicular to wood grain are analyzed and presented in Fig. 5.

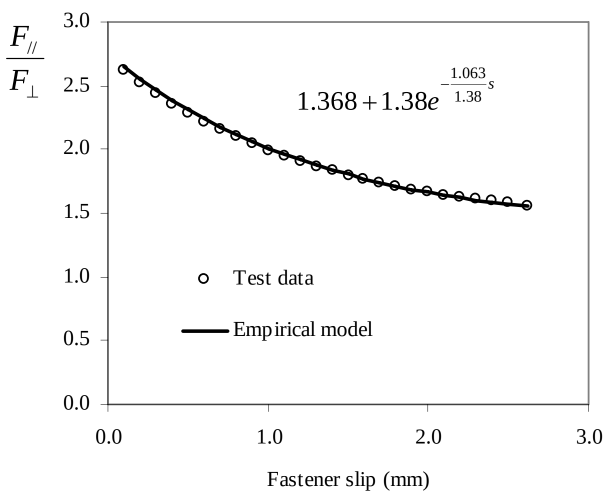


Fig 4 Ratio of lateral load between parallel and perpendicular to grain

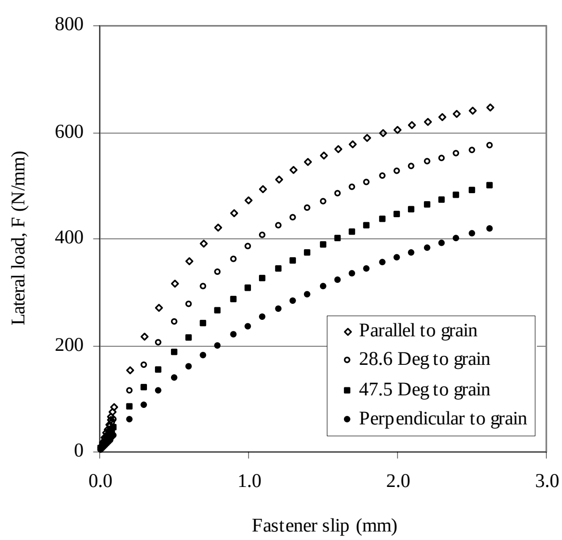


Fig 5 Simulated load-slip response of exponential model

Maximum moment resistance of connection can be predicted from Eq. (4) and by assuming this occurs when the outermost-fasteners reach its ultimate strength. After this loading stage, the strength and the stiffness of connection decreases since the outermost fasteners become incapable to attain more loads. Experimental maximum moment resistance (M_{ex}), and predicted maximum moment resistances (M_{th}) are presented in Table 2. Bolt arrangement 6V gives higher moment-resistance than bolt arrangements 6H and 6C. This is potentially caused by long distance along the grain between bolts that prevents wood splitting at low capacity. On the other hand, bolt arrangement 6H yields the lowest experimental moment resistance. The effective capacity of single bolt significantly decreases when more than one bolt is placed in a row. This situation is generally known as row effect on strength. The row effect on strength 6H is much more dominant in bolt arrangement than in bolt arrangement 6C or in 6V.

Some important parameters that obtained from experimental moment-rotation curve such as joint rotation, ductility, and the stiffness (slope of moment-rotation curve) are summarized in Table 3. Bolt arrangement 6V has the highest stiffness, the highest ductility, and the highest maximum joint rotation among the three arrangements. Connection ductility of bolt arrangement 6V is 4.1, while the ductility of the other arrangements is less than two.

Predicted moment-rotation and experimental curve are presented in Fig. 6. For small angle of joint rotation, elastic range, predicted moment-rotation curves show a very good agreement with the experimental curves for all bolt configurations (see Fig. 6). However, for large of joint rotation, prediction curves show deviation with the experimental results. Predicted moment-rotation curves give higher moment-resistance than that of experimental curves. Moreover, only bolt arrangement 6V gives similar maximum joint rotation between the experimental and predicted curves. Bolt arrangements 6H and 6C fail at lower joint rotation than those predicted. This deviation is caused by wood-splitting failure occurs before the outermost-fasteners reach its maximum strength. When wood-splitting occurs, some fasteners contribute less lateral force or even zero lateral force.

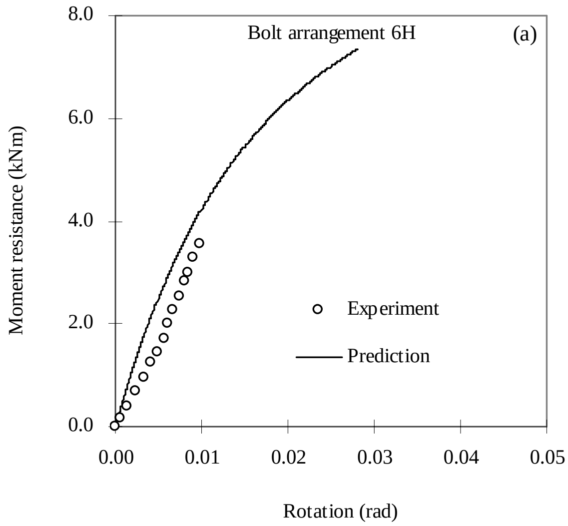
Table 2 Maximum moment resistance of multiple-bolt connections

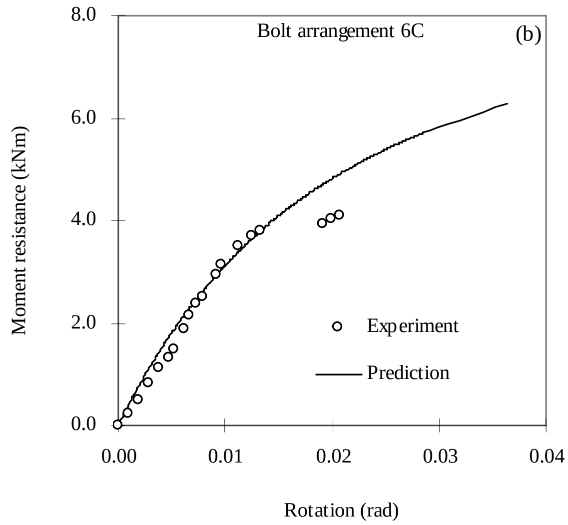
Specimen	Maximum moment resistance (kNm)		
	M_{ex}	M_{th}	M_{ex}/M_{th}
6H	3.61	7.34	0.49
6C	4.11	6.30	0.65
6V	4.40	6.64	0.66

Table 3 Rotation (θ), ductility (Δ), and stiffness (k) of multiple-bolt connections

Specimen	Rotation (rad)		Δ	Stiffness (kNm/rad)	
	θ_{Yield}	θ_{Max}		k_e	k_p
6H	0.009	0.009	1.0	369	-
6C	0.012	0.021	1.7	299	26
6V	0.007	0.029	4.1	419	68

k_e: elastic moment stiffness; k_p: plastic moment stiffness; θ_{Yield}: rotation at intersection point between elastic and plastic lines; θ_{Max}: maximum rotation; and $\Delta = \theta_{Yield}/\theta_{Max}$





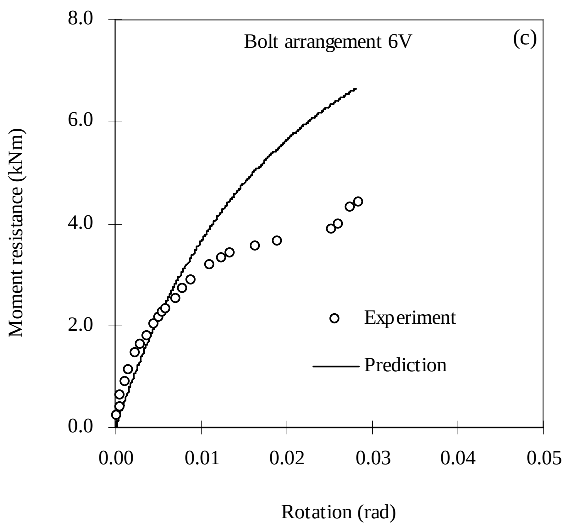


Fig 6 Moment-rotation curve of multiple-bolt connection:
(a) Bolt arrangement 6H
(b) Bolt arrangement 6C, and
(c) Bolt arrangement 6V

6. Conclusion

Three kinds of bolt arrangement are studied regarding to its effect on flexural behavior of timber connection. Predicted moment-rotation curve is analyzed based on test results of single bolted connection and the principle of energy conservation. Test results indicate that bolt arrangement 6V, which has long distance along the grain between bolts, gives the highest moment resistance among the three bolt arrangements. Bolt arrangement 6V also has the highest stiffness, the highest ductility, and the highest maximum joint rotation among the three considered bolt arrangements. Predicted moment-rotation curves show a good agreement only in elastic stage. At plastic stage, large joint rotation, predicted curves differ from experiment because wood-splitting has not considered in the analysis.

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References

1. Kochkin, V.G., and Loferski, J.R. (2005). Modeling the nonlinear moment-rotation relationship of a nail plate connector. J. Wood and Fiber Science, 37(3): 514-520.
2. Foschi, R.O. (1974). Load-slip characteristics of nails. Wood Science, 7(1): 69-76.
3. Chui, Y.H., and Li, Y. (2005). Modeling timber moment connection under reversed cyclic loading. Journal of Structural Engineering. ASCE. 131(11): 1757-1763.
4. Li, Y., and Chui, Y. H. (2001). Empirical models depicting wood grain angle effect on load-embedment response of wood. *J. Test. Eval.*, 29(3), 265-270.
5. EUROCODE 5. (1995). Design of timber structures European pre-standard ENV 1995-1-1: general rules and rules for building, CEN, European Committee for Standardization, Brussels.