SHEAR AND BENDING PERFORMANCE OF MORTISE AND TENON CONNECTION FASTENED WITH DOWEL

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ROHANA H, AZMI I & ZAKIAH A. 2010. Shear and bending performance of mortise and tenon connection fastened with dowel. Mortise and tenon are commonly used to connect beams and columns, and reinforced with wooden dowel. The strength of the joint is affected by the type, size and position of the dowel and also the timber species. This paper reports on the performance of mortise and tenon using two different types of dowels, namely, wood and steel. Structural size mortise and tenon manufactured using kempas, fastened with 20.6 mm diameter dowels were loaded in shear and bending. Connections were tested until failure. The European Yield Models (EYM) concept was applied when analysing the results. The strength of mortise and tenon fastened with steel dowels was higher than those fastened with wood dowel in both shear and bending tests. Based on failure mode, steel dowel exhibited yield mode I_m when loaded in shear and bending, while wood dowel failed in mode III_s when loaded in shear and mode IV when loaded in bending.

Keywords: Failure mode, *Koompassia malaccensis*, structural timber joint

ROHANA H, AZMI I & ZAKIAH A. 2010. Prestasi ricihan dan lenturan bagi sambungan tanggam dan puting yang dikuatkan dengan pasak. Tanggam dan puting biasanya digunakan sebagai penyambung antara rasuk dengan tiang dan dikuatkan dengan pasak kayu. Kekuatan sambungan ini dipengaruhi oleh jenis pasak, saiz dan kedudukannya serta spesies kayu. Kertas kerja ini melaporkan tentang prestasi tanggam dan puting yang menggunakan dua jenis pasak iaitu pasak kayu dan pasak keluli. Tanggam dan puting bersaiz struktur yang diperbuat daripada kempas dan diperkuat dengan pasak berdiameter 20.6 mm dibebankan secara ricihan dan lenturan. Kesemua sambungan diuji sehingga gagal. Konsep *European Yield Model* (EYM) digunakan dalam analisis. Tanggam dan puting yang ditahan dengan pasak keluli lebih kuat daripada yang ditahan oleh pasak kayu dalam kedua-dua ujian ricihan dan lenturan. Berdasarkan mod kegagalan, pasak keluli menunjukkan mod I_m apabila dibebankan secara ricihan dan lenturan manakala pasak kayu menunjukkan mod III_s apabila dibebankan secara ricihan dan mod IV apabila dibebankan secara lenturan.

INTRODUCTION

Mortise and tenon is the most common type of connection for joining beam and column members in timber frame structures for industrialised building system. Bolted or screwed joints apply pressure over a smaller area and the associated holes tend to weaken the structure. A mortise and tenon joint consists of a tongue that slots into a mortise cut in the mating piece of timber which can be pegged as reinforcement. Mortise and tenon joint is well known as one of the traditional methods of timber construction. However, the present design code of practice for timber—MS 544 (SIRIM 2001) or BS 5268 (BSI 2002)—does not include the design for mortise and tenon.

In Malaysia, the mortise and tenon joint is constructed by carpenters based on experience as the design code for structural connection of mortise and tenon is not available. However, the design of timber joint using metallic connectors is given in MS 544 Part 5. The load carrying behaviour of mortise and tenon joints made of Malaysian tropical timber with regard to rigidity, load capacity and ductility is not well documented. To date, only Said *et al.* (1992) has reported the performance of the mortise and tenon joint, and wood dowels using Malaysian timber, namely, nyatoh (a species of Sapotaceae), ramin (*Gonystylus* sp.) and rubberwood (*Hevea brasiliensis*) for furniture manufacturing.

Brungraber (1985) was the first to highlight the performance of mortise and tenon in timber structural framing system. He studied mortise and tenon using wood dowel as an individual

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joint, together with full-scale frame testing, finite element analysis of joint behaviour and a computer model that incorporated connection behaviour. He found that the dowels and mortises failed before the tenons and concluded that increasing the dowel diameter was the most effective way to increase the strength and stiffness of mortise and tenon connection. Erikson (2003) explored the behaviour of traditional wood-dowel timber frame structures subjected to lateral load and concluded that their stiffness was highly dependent on the stiffness of the individual pegged connections. Investigation on mortise and tenon joints were investigated by other researchers (Bulleit *et al.* 1999, Sanberg *et al.* 2000, Erikson 2003, Miller 2004, Erdil *et al.* 2005, Shanks & Walker 2005, Walker *et al.* 2008).

In analysing the joint capacity, the European Yield Model (EYM) is commonly used. A series of equations based on the yield theory was developed by Johansen (1949) and expanded by Larsen (1973). It enables prediction of the yield mode and resistance of dowel-type connections. However, the EYM was developed based on the double shear strength of mechanical joint behaviour which may not be applied to mortise and tenon joint. At present, designers only consider using steel dowel as fastener for mortise and tenon joints as outlined in BS 5268 and the American National Design Specification for Wood Construction (AFPA 2005). Due to a lack of proper guidance and references, designers may wrongly characterise the behaviour of mortise and tenon connection using other types of dowels.

The joint strength of mortise and tenon connection is dependent on the width of the tenon, the width of the timber, timber species, size and type of dowels. Hence, it is beneficial to evaluate the behaviour and strength properties of mortise and tenon joint using different dowel materials. This paper reports on the performance of mortise and tenon joints fastened using wood and steel dowels.

Theory of bending moments of mortise and tenon joints

Mortise and tenon joints are commonly simplified as pin-jointed connections. However, the bending moments in mortise and tenon do provide some resistance. The tenon member will rotate around the corner of the tenon shoulder once a bending moment is applied to a single dowel connection. It is acting at a lever-arm from the effective centre of rotation to the dowel centre line. The effective centre of rotation is at the corner of the tenon shoulder located at B (Figure 1), creating an effectively solid hinge point (Shanks 2005).

Moment rotation at A is determined by equation 1.

$$M_A = P_1\,d_1 = P_2\,d_2 \qquad (1)$$

where

P_1 = value of force at 900 mm from mortise face

P_2 = value of force at centre of dowel

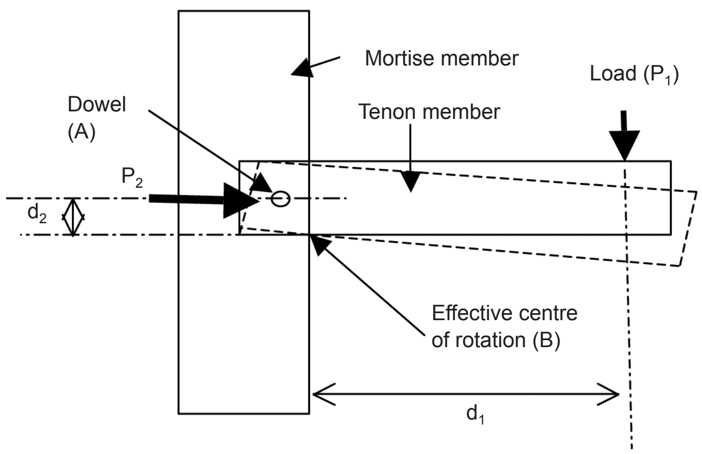

Figure 1 Schematic diagram of mortise and tenon joint subjected to bending load

d_1 = perpendicular distance of load to the centre of rotation
d_2 = perpendicular distance of centre of dowel to the centre of rotation

European Yield Model (EYM)

EYM models the deformation of timber connection beyond the elastic region (Figure 2). This model is used to predict the load-carrying capacity of a single dowel per shear plane when loaded perpendicular to the axis. The load-carrying capacity also depends on the material properties of the dowels and the geometries of the connections (AFPA 2005). The AFPA (2005) requires design values to be taken from the smallest values calculated from all applicable yield modes.

MATERIALS AND METHODS

Materials

All mortise and tenon joint specimens were manufactured using Malaysian tropical timber, *Koompassia malaccensis* or commercially know as kempas. The timber sections were visually graded. Specimens that were of uniform quality with relatively straight grains and free from knots and splits were selected. The timber beam with tenon section and column with mortise section with hole for dowels were prepared by a local timber manufacturer. These specimens were kept in controlled room at 20 °C and 65% relative humidity. The wood dowels (20.6 mm diameter) were ordered from the same manufacturer. In an ideal mortise and tenon joint, it is very important that the tenon fits as perfectly as possible for the joint to have maximum efficiency. Therefore, every specimen was measured and checked so that the joints fit without inducing any force. Two types of dowels were used: wood dowel from kempas and mild steel dowel.

Sample preparation

The column and beam were prepared using kempas of dimensions 200 × 200 × 1200 mm and 100 × 150 × 1000 mm respectively. A rectangular mortise hole of dimensions 41 × 100 × 150 mm was cut out of the column while the tenon of dimensions 41 × 89 × 150 mm was prepared on the beam. A plan view of the mortise and tenon is shown in Figure 3.

Shear test

To determine the effect of shear loading on the mortise and tenon joint, the specimens were set up as shown in Figure 4. Five linear voltage displacement transducers (LVDT) denoted as 1, 2, 3, 4 and 5 were mounted on the beam and column. Shear loading was applied perpendicular to the grain of the beam, at 125 mm from the face of the column. The beam was also propped at 900 mm from the face of the column member.

Bending test

The configuration of bending test set up is shown in Figure 5. The actual test is shown in Figure 6. Five linear voltage displacement transducers (LVDT) denoted as 1, 2, 3, 4 and

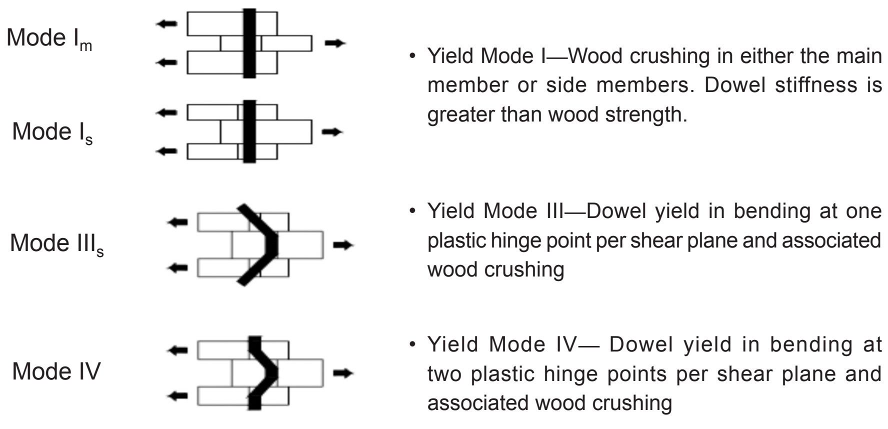

Figure 2 EYM double shear timber-to-timber failure modes

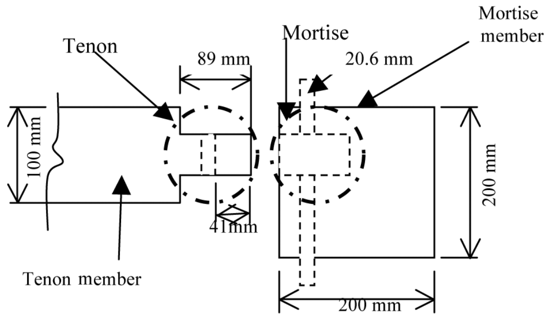

Figure 3 Plan view of mortise and tenon configurations

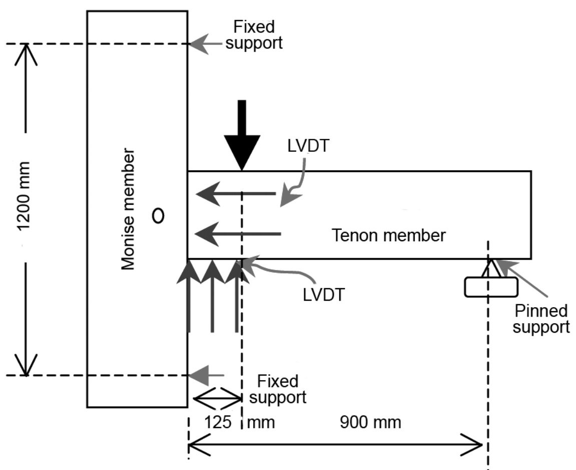

Figure 4 Configuration of shear test

5 were mounted on the column and beam to measure the respective displacements. Loading was applied in the direction perpendicular to the grain of the beam at 900 mm from the face of column member.

RESULTS AND DISCUSSION

Shear test

The shear capacity of the joint using steel dowel was higher than that using wood dowel (Figure 7). The characteristics of the load versus displacement graph for joints using both types of dowels were rather similar except that one was higher than the other. This indicates that both types of dowels act as extended rigid loading pins which can transfer the load applied through the dowel to the tenon. This shows that the capacity of dowel timber frame is highly dependent on the stiffness of the individual pegged connections.

The method in determining the nominal yield load for design was computed based on 5% diameter offset. The 5% offset yield is defined as the point where the load-deflection curve is intersected by a line parallel to the linear region of the load-deflection curve drawn at 5% offset of the dowel diameter. In cases where the offset line did not intersect the load-deformation curve, the maximum load was used as the yield load.

The average proportional limit when fastened with wood dowel was lower by 21.96% compared with steel dowel (Table 1). The maximum shear load when fastened with wood dowel was lower by 16% compared with steel dowel. This may be due to higher ductility of steel dowel compared with wood dowel. Observations on failure characteristics of joints showed tenon shoulder being torn in a rolling form (Figure 8). The same behaviour was also observed by Shanks (2005) when he loaded the joint connected using wood dowelled from green oak.

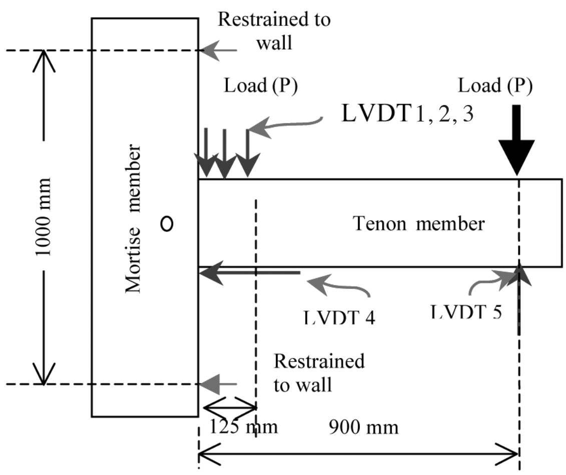

Figure 5 Configuration of experimental bending set up

Figure 6 Experimental bending set

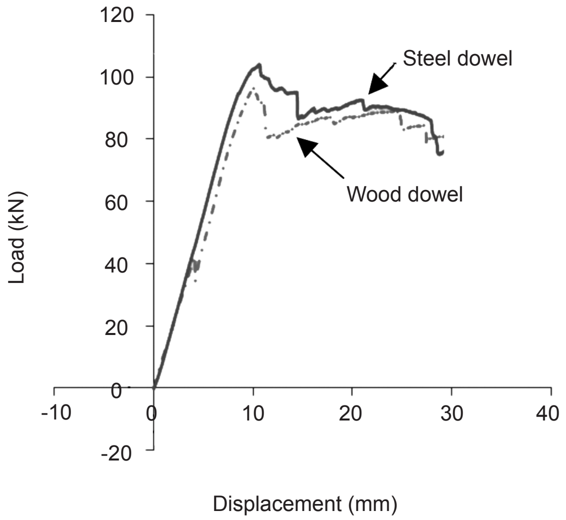

Figure 7 Typical graph of load versus displacement from shear test for steel and wood dowels

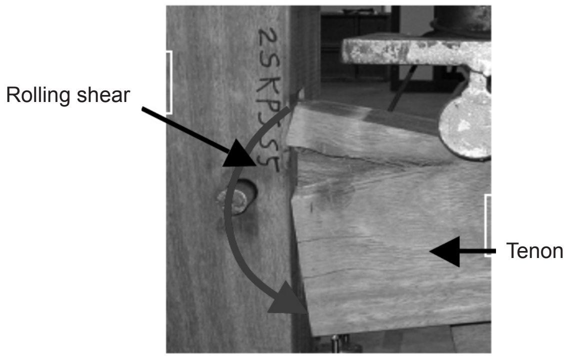

Figure 8 Rolling shear of tenon shoulder

Bending test

Figure 9 shows the typical load–displacement curve for joint with steel and wood dowel after the bending test. The graph shows three typical forms indicated as Part I to III. Part I is linear due to the elastic behaviour of the materials and joints. Part II shows non-linearity which is due to mortise, tenon or dowel failure. Part III shows smooth plateau (no increase in load even though there is movement in the joint) which may be associated with tenon end crushing on the mortise. The rotational responses were similar in all three tests for each type of dowel. The responses were approximately linear when loaded at 4.0 kN for steel dowel and at 2.8 kN for wood dowel.

The capacity of the joint with steel dowel increased until it reached maximum load at 6.09 kN. Thereafter, the capacity decreased drastically, followed by a smooth plateau, which was associated with tenon end crushing on the mortise. The graph for the joint with wood dowel showed similar behaviour, with longer non-linear section but without distinct abrupt drop in load and shorter smooth plateau. The initial linear responses were governed by the rotation of dowel, until the tenon end got in contact with the mortise and the stiffness capacity of the joint increased due to bearing. The capacity of the joint with wood dowel showed lower value with maximum load at 5.32 kN. The rigid steel has pried the tenon hole but the flexibility and densifying of wood dowel allow the bearing to slowly dense and yield.

Table 2 shows that the bending moment at the centre of rotation of wood dowel, mortise and tenon joint is found approximately 12% lower than that of steel.

Failure mode of dowels

After the test for both shear and bending, the connection sections were cut to release the dowels in order to observe the mode of failure. The characteristics of the failure modes were compared with the Standard for Design of Timber Frame Structures and National Design Specification for Wood Construction (AFPA 2005).

Table 1 The summary of shear test for mortise and tenon joints using steel and wood dowels

Dowel (No. tested)	Proportional limit (kN)	Max load (kN)	5% Diameter offset (kN)	Failure mode (EYM)
Steel (3)	127.28	135.75	126.78	Mode I_m
Wood (3)	99.33	114.04	108.83	Mode III_s

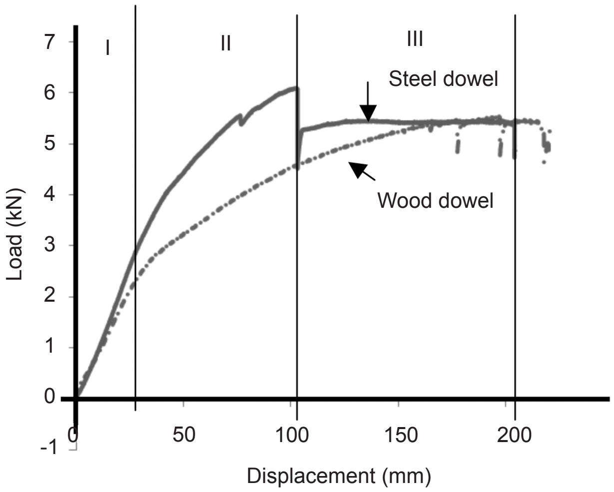

Figure 9 Typical load versus displacement curves

Table 2 Bending moment at centre of rotation

Dowel	Peak load (kN)	Bending moment at centre of rotation (kN mm)	Failure mode (EYM)
Steel	6.09	5481	Mode I_m
Wood	5.32	4788	Mode IV

For shear test, it was found that steel dowel remained in its original straight form but with some crushing effect in the middle member. However, the wood dowel was bent in the middle section with small cracks along its length. Based on these failure modes, the mode of failure for steel dowel can be categorised as Mode I_m, showing the wood crushing in the tenon member. This also shows that the steel dowel is stiffer than the tenon member. Connections dowelled with wood was found in Mode III, i.e. showing the wood dowel yield in bending at one plastic hinge point per shear plane and associated wood crushing in side member (Figure 10a).

For bending test, two primary failure modes were observed: dowel failure in bending or shear or a combination of both. Figure 2 shows the typical mode of failure for steel and wood dowels. The wood dowel is bent with two plastic hinge points per shear plane with crushing effect of the mortise. It can be characterised as failed in Yield Mode IV. Steel dowel was found to fail in Yield Mode I_m (Figures 2 and 10b). This agrees with the standards whereby this failure mode is typical of a stiff dowel. This indicated that mortise and tenon joint with steel dowel performed better than mortise and tenon joint with wood dowel.

Performance of mortise and tenon

Typical movements on the undersides of tenon during shear test were observed based on the three LVDTs which were positioned exactly under the tenon (Figure 11). LVDT1 and LVDT3 measures the displacement at the outer side (shoulder) of the tenon and LVDT2 measures the mid-section of the tenon. The displacement reading for LVDT2 was found to be minimum compared with those of LVDT1 and LVDT3. This is due to the rotational movement of the tenon (rolling shear) as shown in Figure 8. Behaviour of the tenon during testing was relatively uniform. The load displacement curve was plotted based on the readings from the LVDT 2. A typical graph is shown in Figure 12. The movement of tenon exhibited a linear load displacement response followed by the non-linear relationship. The displacement of tenon pegged with steel dowel was higher than that pegged with wood (Figure 12).

Steel dowel failure modes appeared to be without cracks or bent. The cracks were found in the tenon instead with an audible fracture of beam during testing. This meant that the tenon failure or wall crushing when dowelled with steel

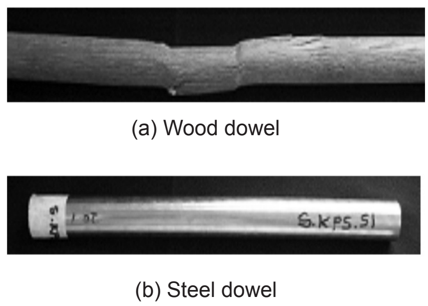

Figure 10 Form of dowels after testing

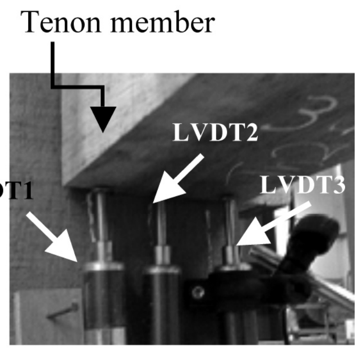

Figure 11 Position of LVDT2 underside of tenon

occurred without the yielding of the dowel. The reverse was found in wood dowel whereby small cracks and bent occurred in the dowel but no fracture was found in tenon (Figure 13). Even with the lowest strength capacity, the failure of wood-dowelled mortise and tenon connection was not as abrupt as steel. The gradual failure of wood dowels is due to the friction between the dowels, mortise and tenon surfaces since wood is an homogeneous material.

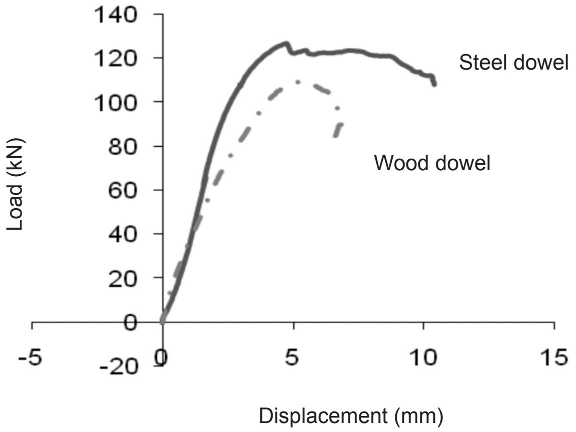

Figure 12 Typical underside displacement of tenon for different dowel materials plotted from LVDT 2

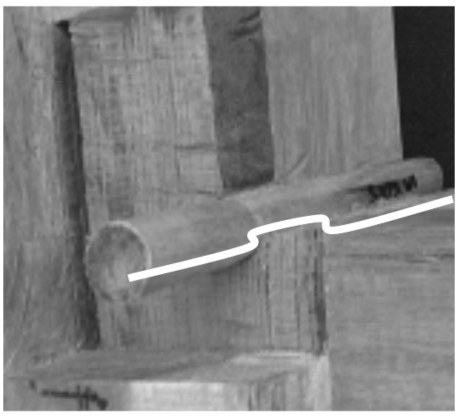

Figure 13 Cross-section of mortise and tenon joint showing small bent and cracks in wood dowel with no obvious crack in the tenon

CONCLUSIONS

Shear strength capacity of the mortise and tenon connection with single dowel, namely, steel and wood showed that the connection strength capacity of joint with steel dowel was higher than that with wood dowel. The difference in maximum load to 5% diameter offset for steel dowel was 6.6% and for wood dowel, 4.6%. Both bending and shear failure mode category of steel dowel was mode I_m while wood dowel was mode III_s when loaded in shear and mode IV when loaded in bending. The failure of the tenon when fastened with steel dowel occurred without the yielding of the dowel due to the stiffness of the material. Bending moment of mortise and tenon connection when fastened with steel dowel was found approximately 12% higher than when fastened with wood dowel. This indicated that mortise and tenon joint with steel dowel performed better than that with wood dowel.

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