Application of Modern Wood Product Glulam in Timber Frame With Tenon-Mortise Joints and Its Structural Behavior

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Abstract: Tenon-mortise joint is widely used in traditional timber structures around the world. This paper summarizes the results of an experimental study of the structural behavior of tenon-mortise joints made with glulam and CNC technology instead of traditional material and manual work. 30 full-scale tenon-mortise joints were manufactured and tested under monotonic loading, and the effects of dimension, shape, processing error and adhesive were evaluated. It was found that the round rectangular shaped tenon-mortise joints were comparable with traditional joints in terms of structural performance, but were time and labor saving. The variability of the proposed tenon-mortise joints was lower, which would benefit the design value. Applying adhesive between tenon and mortise increased the average stiffness by 4.3 times and average moment capacity by 27.4%, respectively. The gaps between wood members had little effect on the capacity and stiffness in monotonic bending but may influence the energy dissipation ability in cyclic bending. This study showed the feasibility of combining the traditional joinery method with modern wood products and manufacturing technology, which may promote the application of tenon-mortise joints in modern timber structures.

Keywords: Tenon-mortise joint; moment carrying capacity; beam to column connection; semi-rigid joint; timber structure

1 Introduction

A tenon-mortise joint is a joinery method used to connect two wood members. The tenon refers to the projection at the end of a member and the mortise to the hole carved in the counterpart member. The tenon and mortise usually fit exactly and the joint is strong enough to carry the intended load. This joint is used around the world with a very long history. Archaeological evidence in *Hemudu* site (Zhejiang, China) shows that the inhabitants date back to nearly 7000 years ago had developed timber structures where tenon-mortise joints had been well developed [1,2], that was even in the Neolithic era!

The tenon-mortise joint is extensively used in traditional timber structures, especially in East Asia, like China, Japan and Korea. As an integration of artistry and function, it provides essential vertical and lateral resistance to make the building stand against loads. There are many variations of this connection, among which the most complex and beautiful one is the “Dou-gong bracket” [3], which is a set of members interlocked together with several kinds of tenon-mortise joints. Many traditional timber structures still stand in existing, like the oldest timber structure, the *Hōryū-ji* temple (Nara, Japan) [4], the tallest timber structure *Yingxian* Wood Pagoda (Shuozhou, China) [3], these heritages demonstrate the structural ability of the tenon-mortise joint.

However, fabrication of the tenon-mortise joint is rather labor intensive and prohibitively complicated [5], on the other hand, with the development of modern connection technologies, like the dowel type connection, shear plate and glue-in rods etc., tenon-mortise joint is now rarely used in modern timber structures. But recently see a revival of the application of tenon-mortise joints in timber structures either independently or together with other types of connection. Thanks to the development of computer

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numerical control (CNC) manufacturing technology, it is now rather easy to manufacture tenon-mortise joints and needs less labor and less time. Moreover, the processing error is significantly reduced by the CNC technology. This makes the tenon-mortise joint an available option for modern timber structure again. For example, The *Tamedia* office building in Switzerland by Shigeru Ban, presents creative manipulations of structural type with the concept of tenon-mortise based joinery technology [6].

The tenon-mortise joint can transfer moment between beam and column semi-rigidly. Efforts have been made to investigate the structural behavior of this joint. For example, Yao et al. [7] studied the semi-rigid characteristic of the tenon-mortise joints under cyclic loading and established the evolving rules for stiffness. Ogawa et al. [8] developed a theoretical model to estimate the influence of gap on the mechanical performance of tenon-mortise joints. Because the beam-column frame acts as the lateral load resisting structure, lot of investigations were also focused on the shear resistant performance of timber frame with different tenon-mortise joints. Chun et al. [9] investigated several kinds of tenon-mortise connected beam-column frames under dynamic load. King et al. [10] investigated the structural performance of some artificially degraded tenon-mortise joint and also studied the lateral performance of the frame, it was found that the structural performance of the frame was dominated by the characteristic of tenon-mortise joints. Tennon-mortise joint were also popular in Europe. However, they did not try to avoid using metal connectors and dowels in combination with the tenon-mortise joints tenon-mortise joint. In spite there were some research works reported like [11], like other parts of the world, the design method was not included in the design code.

So far, the structural performance of tenon-mortise joints has still not been fully revealed and the design method has not been established, either. It is hard to tell how much moment can be taken by a tenon-mortise joint in service, and the design and application of timber structures with tenon-mortise joints are based on empirical methods. In practice, tenon-mortise joints are usually treated as hinge joint. This assumption was sometimes clearly unreasonable, for example a timber pavilion would have no lateral resistant ability if the semi-rigid characteristic of tenon-mortise joints were not taken into considerations.

Nowadays, many modern wood products like glulam are developed and used to fabricate large-size structural members. These modern products reduce the influence of strength reducing defects, and the property variability are significantly smaller than round timber or sawn lumber. If tenon-mortise joints are applied between these members, there may be different characteristics with joints between traditional timbers.

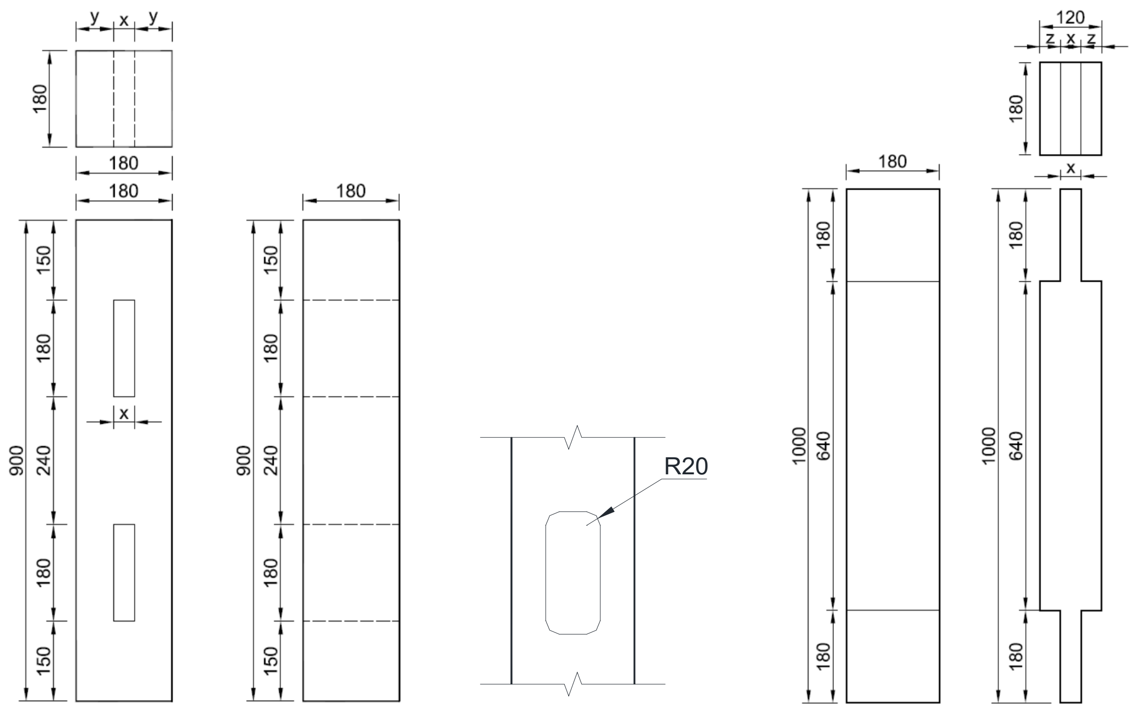
No matter how complex a tenon-mortise joint is, it can always break down into some basic types, of which, the most common one is the straight tenon-mortise joint, whose tenon tongue and mortise hole are both a rectangular. In this study 30 straight tenon-mortise joint specimens were manufactured with glulam by a CNC machine. These joints were tested under monotonic loading, the effects of the tenon dimension, shape, processing error and glue on the structural performance of the tenon-mortise joints were evaluated. The failure modes of the joints were observed and the moment-rotational angle relationship was established. The observation of this study provides more understanding to the straight tenon-mortise joints and provides a reference for further theoretical study to quantify the structural performance. It will benefit the design of modern timber structure using tenon-mortises joints and promote the utilization of the traditional style timber structures.

2 Material and Methods

2.1 Materials and Specimens

No.1 Canadian Douglas Fir dimension lumber was used to manufacture glulam by a local company. The adhesive was one-component polyurethane (PUR). To eliminate unnecessary influence, all of the laminations were intact pieces without finger joints. The mechanical properties of the glulam were evaluated by full-scale specimen tests, the ultimate compressive strength parallel and perpendicular to grain were 45.96 MPa and 3.26 MPa, respectively.

Columns with a cross section of 180 mm × 180 mm and length of 900 mm (parallel to grain), and beams with a cross section of 120 mm × 180 mm and length of 1000 mm were manufactured. The depth to width ratio of the beam was 3: 2, which was in agree with the recommendation given by the *Yingzao Fashi* (Treatise on architectural methods or state building standards) compiled by Li [12,13] during Song dynasty, nearly one thousand years ago. Two mortises were carved in a column and both ends of a beam were processed into tenon tongues. All of the tenon tongues were processed directly with Joinery Machine K2i (Hundegger). However, for mortise, a round rectangular hole with a fillet radius of 20mm were firstly milled in the column, then the mortise holes in all specimens except one group (Group B80CH) were trimmed manually into rectangular shape by removing the extra wood in the round corner. Fig. 1 shows the detailed dimension of some specimens.



(a) Columns (b) Round rectangular mortise (c) Beams

Figure 1: Details of some specimens

Totally 30 tenon-mortise joints were manufactured. Tab. 1 provides the detailed information of each test group. Group B80 was the control group with 6 replicates. For other test Groups, there were 3 replicates in each Group. The Groups B60 and B40, whose tenon width were different with B80, were design to investigate the effect of tenon width on the structural behavior of the tenon-mortise joint. Groups L120 and L60 were both stub tenon-mortise joints with varying tenon length to investigate the effect of tenon length. Group B80CH with round rectangular tenon and mortise was in order to evaluate the influence of tenon shape. Groups B80E2 and B80E4 had different tenon heights were designed to evaluate the influence of gaps from manufacturing error or shrinkage due to changing of moisture content. Group B80G was identical to B80 in geometry, but adhesive (PUR) was manually applied to the tenon before assembling, the adhesive application rate was about 180 g/m^2 according to the actual adhesive consumption and spreading area.

Table 1: Detailed information of specimens

No.	Group ID	Design dimension (mm)			Replicates	Remarks
		Width	Length	Height		
1	B80	80	180	180	6	Control
2	B60	60	180	180	3	Effect of width
3	B40	40	180	180	3	
4	L120	60	120	180	3	Effect of length
5	L60	60	60	180	3	
6	B80CH	80	180	180	3	Effect of shape
7	B80E2	80	180	178	3	Effect of gaps
8	B80E4	80	180	176	3	
9	B80G	80	180	180	3	Effect of glue

The actual dimensions of the mortise were roughly the same with the design dimension, however, the dimensions of tenon were slightly smaller than the design dimension. This was because the hand trimming process would not produce surfaces smooth enough in the mortise hole, and it was found that if the dimension of tenon was close to the deign value, the tenon cannot be inserted into the mortise. The average value of actual width for 80 mm, 60 mm and 40 mm wide tenon tongue were 79.98 mm, 59.42 mm and 39.40 mm, respectively. And the actual height for 180 mm, 178 mm and 176 mm high tenon tongue were 178.38 mm, 176.44 mm and 174.52 mm, respectively.

2.2 Methods

As shown in Fig. 2, the testing frame consisted of a steel reaction frame used to anchor the specimen and another steel portal frame used to anchor the hydraulic actuator. At each end of column, one thick steel plate was fastened to the reaction frame with 2 anchor bolts which press the column tightly to the reaction frame. Two rib-stiffened steel arms were used to clamp the column from top and bottom ends, and some thin steel plate were inserted into the gap between the upper arm and top end of the column to prevent any possible vertical movement. The vertically placed hydraulic actuator was attached to the right part of the beam with a rectangular steel cage. There was a one-way hinge between the cage and the actuator, and a ball hinge between the actuator and the portal frame. This eliminated the possibility of introducing undesirable extra moment. The actuator had a loading capacity of 250 kN and a stroke range of 250 mm.

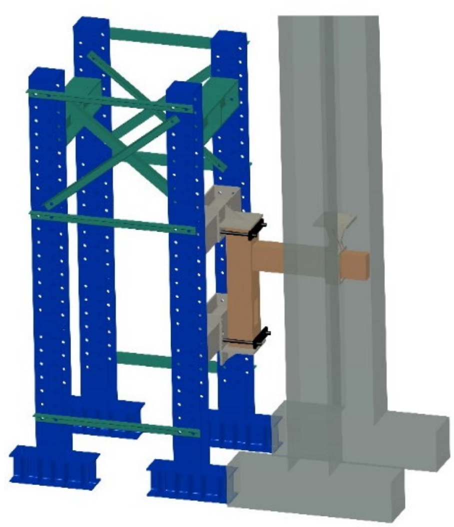


Figure 2: Anchoring and loading apparatus

The joints were loaded with the actuator in a displacement-controlled mode with a rate of 8mm/min at the crosshead. The controlling system was MTS (MTS Systems Corporation, USA). No preloading was performed before test. For Groups B80E2, B80E4 and B80CH, whose tenon tongue heights were less than the mortise, the beam was adjusted carefully to make sure it was horizontal. Similar study found that the load of tenon-mortised joint can keep increasing after yielding and see no peak bellow the angle of 0.10 rad [14]. In this study, after the actuator reached its limit, it will produce a rotational angle not less than 0.20 rad, which is sufficient for evaluating the load-carrying capacity of the joints. Thus, the specimens were loaded until the stroke range of the actuator was reached.

The applied load was measured by a built-in load cell of the hydraulic actuator and the measured data were output to a data logger TDS 530 (Tokyo Sokki Kenkyujo Co., Japan). Two displacement transducers were mounted to the upper and lower surfaces of the beam to record the relative horizontal displacement between column and beam. The output of these two transducers were used to calculate the rotational angle α between beam and column as $\alpha=(X_1-X_2)/h$, where h was the distance between the two transducers. Vertical displacement transducer Y1 was used to record the vertical displacement of the beam and the output was used to check test results. The position of the load and displacement transducers are shown in Fig. 3.

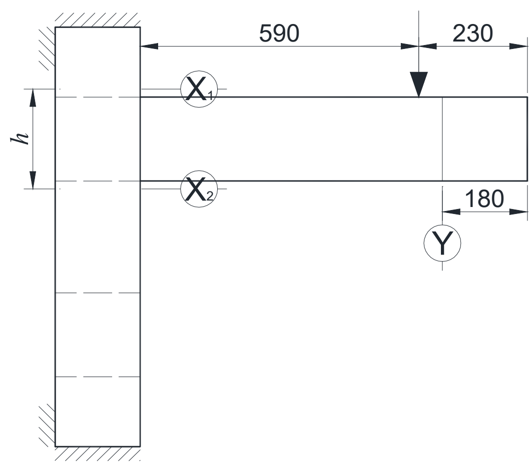


Figure 3: Schematic diaphragm of the test setup

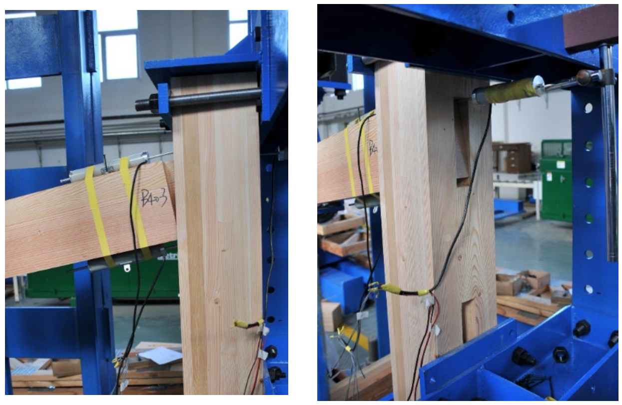
3 Results and Discussion

3.1 Failure Modes

As shown in Fig. 4, with increasing of the load, the rotational angle between beam and column gradually increased. For the through tenon-mortise joints, it was observed from other side of the mortise that the upper end of the tenon tongue deformed in compression perpendicular to grain due to compression between two members, and the upper end of tenon slipped towards the direction of beam. The lower surface of the tenon separated with the mortise, leaving a considerable gap there. For both of the stub and through tenon-mortise joints, the shoulder of beam eventually separated with the column. Finally, the pulling out and compression of the tenon featured the ultimate failure of the joints.

The joints were disassembled after test to check the status of tenon and mortise. The dominant phenomenon was the excessive local perpendicular deformation at the root of the tenon, as shown in Fig. 5. This damage was especially evident in the round rectangular tenon Group B80CH and was less visible in shorter tenons. For tenons of Group L60, only a narrow band of mark was noticeable. As shown in Fig. 6, the fibers at the top of the tenon fractured parallel to grain, this may be caused by the friction at the end part of the tenon. In some specimens, there were cracks visible at the side surface of the tenon, this may because compression at the root of tenon induced a tensile stress parallel to grain near the end of the tenon.

For Group B80G with glue, there was no recognizable difference in failure mode with other groups, however, the joints made series of brittle cracking sound in the process of loading.

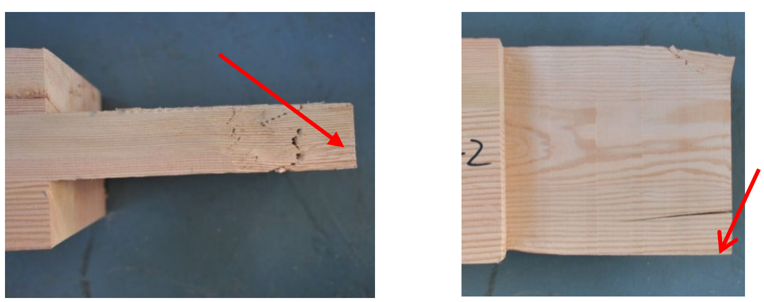


(a) Front view (b) Side view

Figure 4: Deformation of the tenon mortise joints

(a) Long tenon (b) Round rectangular tenon (c) Short tenon

Figure 5: Local compressive deformation of different tenons

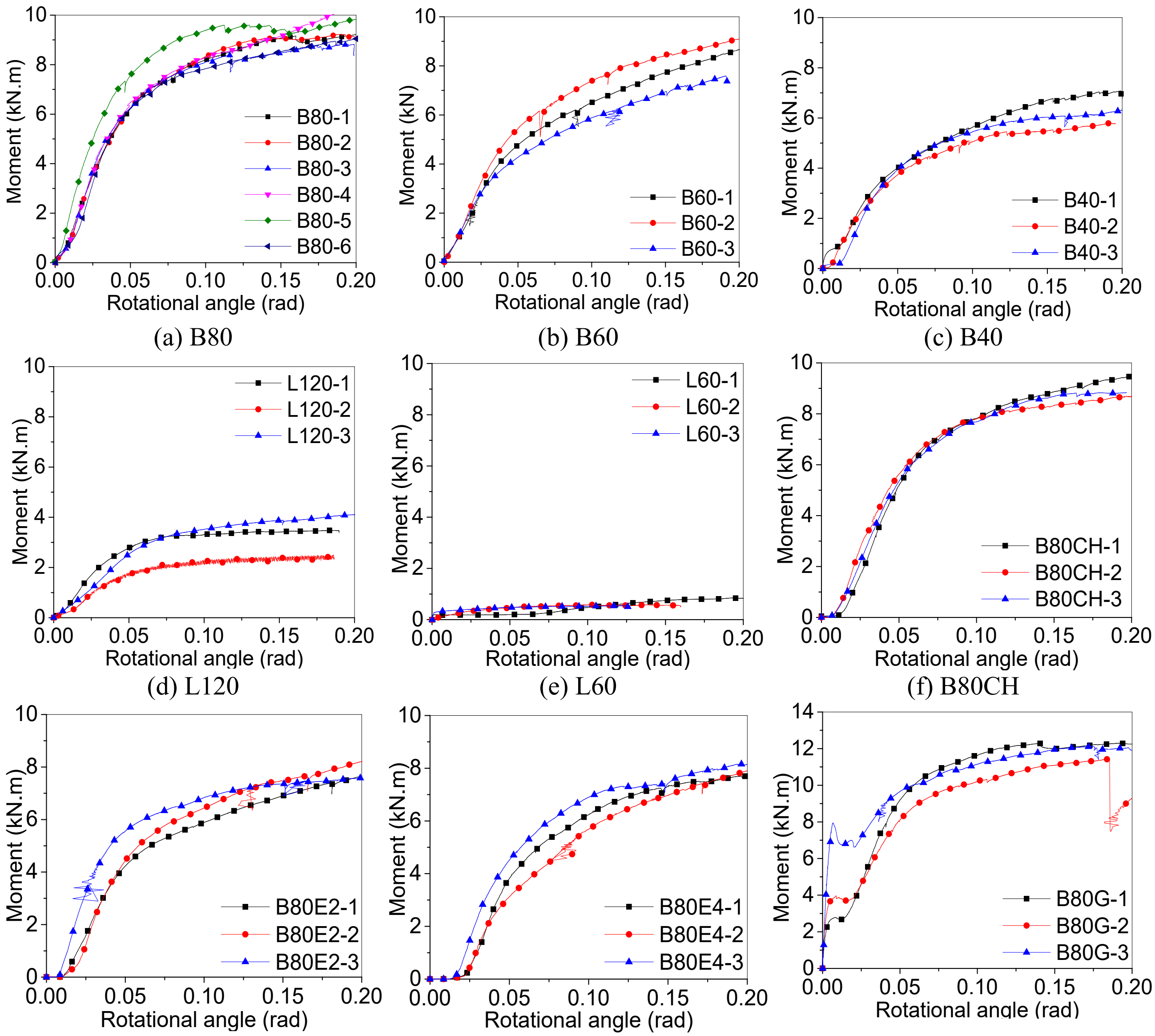


(a) Parallel to grain tensile fracture (b) Perpendicular tensile crack

Figure 6: Fracture failure of the tenons

3.2 Test Results

The intersection of the axes of beam and column was taken as the rotation center. The moment was calculated by multiplying the vertical load with the distance of load to the rotation center. The moment and rotational angle relationships of different specimens are shown in Fig. 7. The maximum moment of a specimen before the ultimate rotational angle was taken as the moment carrying capacity of the specimen. And the linear part (usually 15-40% of the ultimate moment, subjected to slightly change if obvious nonlinearity was observed in this portion) of the curve was fitted by linear function to find the initial stiffness. The average and coefficient of variance (COV) of moment and initial stiffness in each group are listed in Tab. 2. The COV of initial stiffness of Group L60 was not available because the moment of 2 specimens in this group were too small to produce a reasonable initial stiffness. The comparison of moment and stiffness of tenon-mortise joints with different tenon width and length are shown in Figs. 8 and 9, respectively. The gap size was converted to percentages of gap to tenon height, thus the actual gaps in Groups B80, B80E2 and B80E4 are equivalent to 1%, 2% and 3% of processing error, respectively. Then the moment and stiffness of specimens with different processing error are shown in Fig. 10.



(a) B80 (b) B60 (c) B40

(d) L120 (e) L60 (f) B80CH

(g) B80E2 (h) B80E4 (i) B80G

Figure 7: Moment and rotational angle relationships of different specimens

Table 2: Ultimate moment and initial stiffness of each test group

No.	Group ID	Ultimate moment		Initial stiffness	
		Average (kN.m)	COV	Average (kN.m/rad)	COV
1	B80	9.37	0.05	189.58	0.12
2	B60	8.45	0.09	126.20	0.12
3	B40	6.40	0.10	115.42	0.14
4	L120	3.36	0.24	49.09	0.48
5	L60	0.66	0.25	17.06	-
6	B80CH	9.00	0.05	154.65	0.04
7	B80E2	7.81	0.04	160.18	0.20
8	B80E4	7.96	0.03	157.49	0.03
9	B80G	11.94	0.04	1010.32	0.54

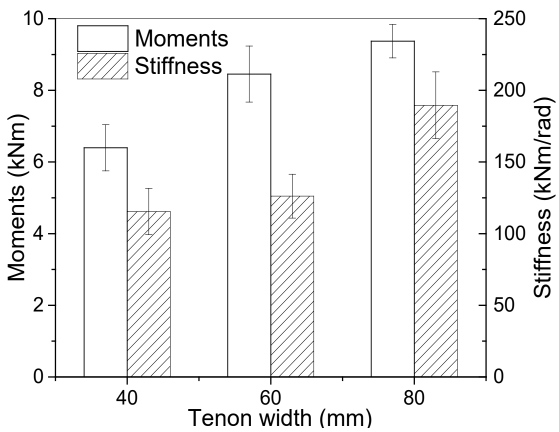


Figure 8: Moment and initial stiffness of tenon mortise joints with different tenon width

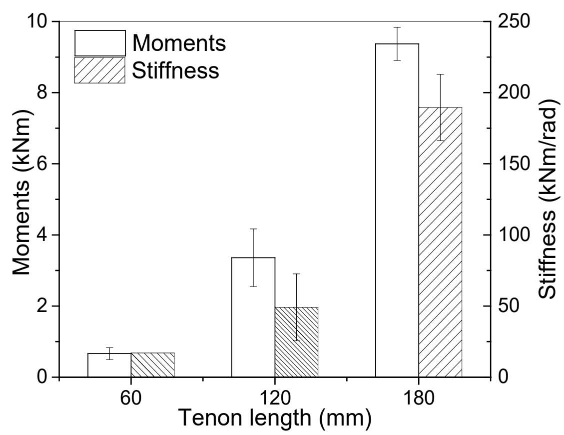


Figure 9: Moment and initial stiffness of tenon mortise joints with different tenon length

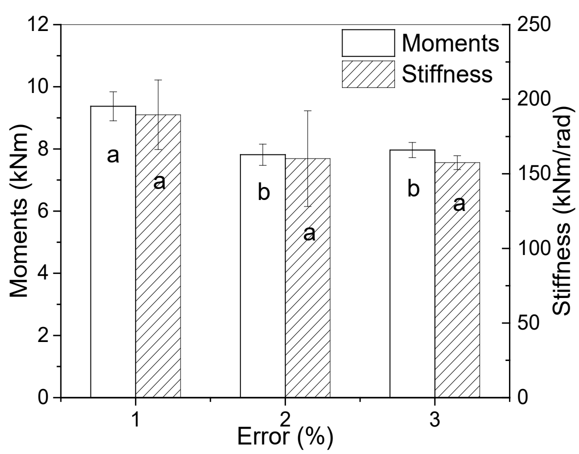


Figure 10: Moment and initial stiffness of tenon mortise joints with different processing error

3.3 Discussion

As listed in Tab. 2, COV of stiffness was mostly larger than that of the moment, this was reasonable because the stiffness was not only affected by the properties of wood but may also be influenced by the friction between tenon and mortise, which was rather sensitive to processing error. In general, the variability of the tenon-mortise joints was rather small. The maximum value of COV for the straight through tenon-mortise joints was only 0.09, this was because the COV of glulam was much lower than sawn lumber and round timber. A lower COV will induce a higher design strength for the same average. This indicated that tenon-mortise joints between modern engineering wood product members have more uniform behavior and higher design value.

As illustrated in Fig. 8, the moment of the straight through tenon-mortise joints was approximately positively correlated to the tenon width, however, the moment and the width were not proportional to each other. This revealed that the contact and friction forces between tenon and mortise at top and bottom surfaces was not the only source of moment resistance, but the friction between the side surfaces of tenon and mortise may also have some contribution, as shown in Fig. 11, actually, the moment M imposed on the tenon-mortise joint roughly has the relationship with contact force F_f and friction F_f on top and bottom surface and friction F_s on side surface as:

$$M = F_c h_x + F_f h_y + F_s = F_c(h_x + uh_y) + \int f_s dr_s \tag{1}$$

where h_x and h_y are the arms of force for contact and friction, respectively; μ is the friction coefficient, which is around 0.2 for wood to wood contact; f_s is the friction force at one point on the side surface and r_s is the corresponding distance to the rotation center. From the Eq.1 it was found that the contribution of friction on top and bottom surface of tenon to moment increases with the decrease of tenon length or increasing of tenon height, which creates a shorter arm of force h_x or longer arm of force h_y, and the contribution of friction on side surface depends on the gaps between tenon and mortise. The relationship between the initial stiffness of tenon- mortise joints with the tenon width was similar to the moment.

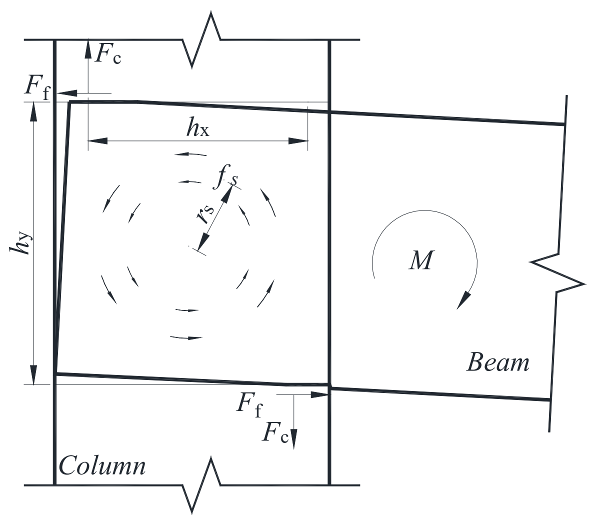


Figure 11: Sketch of the mechanism between moment and forces

As shown in Fig. 9, it can be found that both of the moment and initial stiffness dropped dramatically with decreasing of the tenon length. This was because the main source of moment resistance was from the contact force which was approximately centrally symmetrically distributed. Decreasing of the tenon length would not only cause decreasing of contact area, but also the force arm. Thus, it produced a quadratic effect on both the moment and stiffness.

The gaps or processing error also affect the structural behavior of tenon-mortise joints. The gap due to difference between tenon and mortise immediately closed at the very beginning of loading process. So, from Fig. 7, it was found that the amount of initial slip increased with the increasing of processing error. As for the moment and stiffness, it was found in Tab. 2 that both moment and stiffness of specimens in Group B80E2 and B80E4 were lower than that of the control group. However, the moment was not constantly decreasing with increasing of the processing error. ANOVA analysis was carried out to examine whether there was significant difference of moment and stiffness at different processing error, and the result was marked in Fig. 10. At the 0.05 level, the initial stiffness was not significantly different for different processing error, and for the moment, there was no significant difference between error 2% and 3%, but the moment of error level 1% was significantly different with other error levels. The reason behind this was that the gap was immediately closed at very beginning of the loading process, later the tenon and mortise would keep contacted tightly with each other, so each group of different processing error would behave similarly. But it is easy to predict that under dynamic load, when joints will bend in both negative and positive direction, the gap may cause pinch phenomenon and the harm the energy dissipation ability.

The moment was similar for Group B80CH and control group, further ANOVA analysis indicated that there was no significant difference between the moment of rectangular and round rectangular tenon-mortise joints. However, the stiffness of the rectangular tenon-mortise joints was about 18.4% lower than rectangular ones in control group. If notice that the surfaces of the round rectangular tenon-and mortise were both very smooth and the gap of B80CH was actually lager than the control group, the dimension of the round rectangular tenon can be increased a little to reduce the gap and it is supposed that this will improve the structural behavior, at least the initial stiffness. This finding is very important and practical in demonstrating that keeping the round corner of mortise as it is without further trimming can save lot of labor and time without decreasing the moment and stiffness significantly.

Compare to control group, the average moment carrying capacity of glued joints increased by 27.4%, and the initial stiffness increased by more than 4.3 times. This suggested that applying adhesive between the tenon and mortise will improve the structural performance obviously. However, it should be noted that the moment did not increase monotonically but reached a local peak at very small rotational angles, then it dropped and increased again. This was due to the non-simultaneously failure at the glue line and wood.

4 Conclusions

To investigate the structural behavior of the tenon-mortise joints manufactured with modern wood products and technology. 30 straight tenon-mortise joints were manufactured with glulam and milled into shape with a CNC machine. The effects of dimension and shape of tenon, the processing error or gaps and the effect of adhesive were evaluated experimentally. This study proves the feasibility of combining traditional joinery method with modern wood products and manufacturing technology, and may promote the application traditional style timber structures. The main conclusions are list as follows:

1. The round rectangular tenon-mortise joints have similar moments carrying capacity and stiffness with rectangular tenon-mortise joints. Considering it is more time and labor saving and easier to control the processing error, it is recommended to use the round rectangular tenon-mortise joints as a substitute of the traditional rectangular ones.

2. The structural behavior of tenon-mortise joints made with glulam shows lower variability. This indicates a larger design moment carrying capacity and stiffness, which makes the application of the tenon-mortise joints in modern structure more feasible.

3. Both the moment carrying capacity and stiffness increase with tenon length and width, and the tenon length contributes quadratically. Adding adhesive between the tenon and mortise interface may improve the moment carrying capacity and increase the initial stiffness by times, however the glue line may fail before the wood. The gaps due to processing error or shrinkage of wood have little effect on the moment carrying capacity and stiffness in unidirectional bending but may affect the bi-directional bending behavior.

4. It is recommended to include the semi-rigid behavior of the tenon-mortise joints into the whole model to complete the structural analysis of timber building. To develop the design method for this joint, more parameters need to be investigated by experiment or numerical analysis, and then reliability analysis was needed to determine the design value of stiffness and moments.

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