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Experimental and Numerical Study on Methods of Testing Withdrawal Resistance of Mortise-and-Tenon Joint for Wood Products

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Abstract: Withdrawal resistance of the mortise-and-tenon (M&T) joint is an important indicator to evaluate the strength of the M&T joint. Generally, the T-shaped specimen is usually used to measure withdrawal resistance using tensile methods, but there has not been testing standard until now. In this study, the methods of measuring withdrawal resistance of the M&T joint were investigated systematically. A new method used to determine the withdrawal resistance of M&T joint was proposed to be named as the compressive method. In addition, withdrawal resistances of M&T joint determined using tensile and compressive methods were compared based on experiments and the finite element method (FEM). The experimental results showed that the effects of the testing method and glue on withdrawal resistance of M&T joint were statistically significant, specifically, the withdrawal resistance measured using tensile method was higher than the one determined by the compressive method. Meanwhile, the results of FEM also confirmed the experimental results in a visible way. The results of FEM indicated that the withdrawal resistance of the M&T joint was influenced by tenon member length; specifically, the withdrawal resistance of the M&T determined by tensile method increased with the increasing of tenon member length. In summary, the results of the study make sense in the measurement of withdrawal resistance of the M&T joint in practice, and in theory, the study will contribute to instructing the design of furniture structures.

Keywords: withdrawal resistance; mortise-and-tenon; furniture joints; finite element method

1. Introduction

The mortise-and-tenon (M&T) joint plays a vitally important role in the frame of wood products such as wood furniture, windows, and doors and influences the processing technology and structure safety of wood products. It is known that the strength of wood furniture frame does not rely on the strength of the members itself, but on the M&T joint [1–5]. There are usually three types of strengths used to evaluate the strength of the M&T joint, including withdrawal resistance, bending resistance, and rotating resistance. In both static and dynamic conditions, withdrawal resistance of M&T is always coupled with bending resistance and rotating resistance. Many studies have investigated the factors influencing the withdrawal resistance. Diler et al. [6] studied the withdrawal resistance of the T-shaped joint made from heat-treated pine (*Pinus sibirica*), common ash (*Fraxinus excelsior*), and iroko (*Chlorophora excelsa*) wood. The results showed that the withdrawal resistance of joints constructed from common ash and iroko wood were higher than that of the joint made from heat-treated wood. Heat-treated wood reduced the withdrawal resistance of the joint by 25%. Renbutsu and Koizumi [7] used greenwood shrinkage as a clamping pressure to increase the withdrawal resistance. The results showed that the

proposed shrink-fitted, glued, round M&T joint exhibited sufficient withdrawal strength, and after applying four humidity cycles to simulate seasonal variations in moisture content, withdrawal strength did not decrease significantly. In addition, Eckelman et al. [8] studied the withdrawal resistance of pinned and unpinned round M&T joints. The results showed that cross-pinned round M&T joints enhanced the withdrawal resistance, which would be usable in the construction of furniture where adhesive was unobtainable. A T-shaped sample is the one that is most used to measure the withdrawal resistance of M&T joint, but no standard describes the testing method, especially for the dimensions of the sample. In previous studies, the dimensions of samples varied among different researchers: normally the length of the mortise member of T-shaped sample ranged from 150 to 220 mm, and length of tenon member from 120–220 mm [6–9]. It is common sense that the size of the sample influences the mechanics of wood [10,11]. Therefore, it is well worth it to study the testing method of withdrawal resistance for the M&T joint to get the accurate value to instruct furniture structure design.

In this study, the main objective was to evaluate the withdrawal resistance of the M&T joint in a more accurate method. In order to realize this aim, specific objectives were to (1) put forward a new method measuring withdrawal resistance of the M&T joint, which was named as the compressive method; (2) determine and compare the withdrawal resistance of M&T joint measured by the compressive method and the tensile method; (3) evaluate the two testing methods using the finite element method; (4) evaluate the effect of length of tenon member on withdrawal resistance based on the finite element method. Finally, this study will contribute to testing the withdrawal resistance in a more accurate way and to instruct designing furniture structures.

2. Materials and Methods

2.1. Materials

Poplar (*Populus spp.*) was used in this study, which was bought from a local commercial wood supplier (Nanjing, China). The specific gravity (SG) was 0.413, measured according to ASTM D 2395 [12], and the moisture content (MC) was 12.30%, measured according to ASTM D 4442 [13], and it was conditioned and held at 12.30% before and during the experiment. The glue applied to join the M&T joint was polyvinyl acetate emulsion (PVAc) adhesive with 52% solids content, bought from a local adhesive company (Nanjing China).

2.2. Description of the Specimens

All specimens used in this study were processed using a computer numerical control (CNC) machine with an accuracy of 0.01 mm (WPC, Shanghai, China). T-shaped M&T joint specimens used to measure withdrawal resistance by the tensile method were composed of mortise member and tenon member. The mortise was drilled in mortise member, and tenon was machined in tenon member. Figure 1 shows the dimensions of mortise member and tenon members of T-shaped specimens. The dimensions of mortise member are 150 mm (length) × 40 mm (width) × 30 mm (thickness) with a mortise measured as 30 mm (depth) × 30 mm (height) × 16 mm (width). For tenon member, the dimensions are 100 mm (length) × 40 mm (width) × 30 mm (thickness) with a tenon measured as 30 mm (length) × 30.2 mm (height) × 15.8 mm (thickness). The tenon fit between mortise and tenon was chosen according to processing technology of a real M&T joint, i.e., the mortise width and tenon thickness are 0.2 mm clearance fit, and the mortise height and tenon width are 0.2 mm interference fit. The specimens used in the compressive method composited of a mortise member and a tenon. The dimensions of mortise member and tenon are as the same as those of specimens used in the tensile method. All samples were conditioned in a humidity chamber controlled at 20 ± 2 °C and $50\% \pm 5\%$ relative humidity (RH) for two weeks.

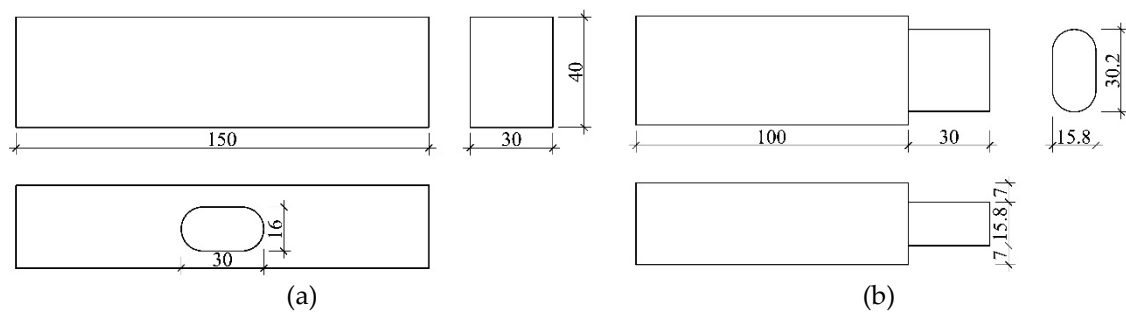


Figure 1. Dimensions of T-shaped samples composed of (a) mortise member and (b) tenon member. (unit mm).

2.3. Testing Methods

The equipment used in this study was a 20-kN universal testing machine (AGS-X, Shimadzu, Kyoto, Japan) with a steel mold designed by the authors. Figure 2 shows the setups for measuring the withdrawal resistance of the M&T joint by tensile and compressive methods. The loading speed was 0.5 mm/min, controlled by displacement methods until the M&T joint reached the maximum load. The maximum load and failure modes were recorded for further analysis.

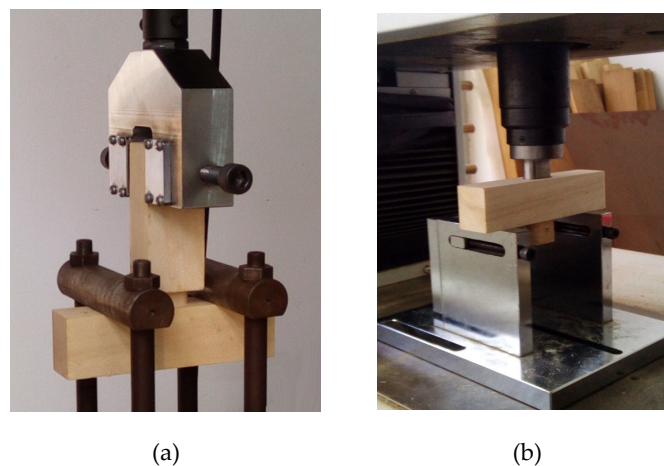


Figure 2. Setups for determining withdrawal strength of a mortise-and-tenon (M&T) joint by (a) tensile method and (b) compressive method.

A complete 2×2 factorial experiment with 15 replications per combination was designed to investigate the effect of testing methods on withdrawal resistance of glued and unglued M&T joints. In addition, the glue, testing method, and their interaction on mean withdrawal resistances were analyzed using the analysis of variance (ANOVA). Mean comparisons using the protected least significant difference (LSD) multiple comparison procedure with SPSS 22 software (Nanjing, China) at the 5% significance level.

2.4. Finite Element Model

The finite element models of the two testing methods for measuring M&T joint withdrawal resistances were established by computer aid engineering software (ABAQUS 6.14-1, Dassault, Nanjing, China) to further study the difference between them. The details of modeling methods and mechanical parameters were described specifically in former study [14–17]. In addition, the effect of tenon member length on withdrawal resistance of M&T joint was investigated using a numerical method.

3. Results and Discussions

3.1. Withdrawal Resistance of M&T joint

Table 1 shows that the two-way interaction of glue and testing method was not significant for withdrawal resistances of M&T joints with significance level higher than 0.01. Therefore, the main effects on withdrawal resistances were further analyzed. The main effect mean comparisons (Table 2) indicated that glue and testing method significantly influence the withdrawal resistances of M&T joints. In addition, Table 2 shows that the withdrawal resistances of the M&T joint measured by the tensile method were significantly higher than the ones measured by the compressive method, no matter whether the M&T joints were glued or unglued or not. The withdrawal resistances of glued M&T joints are significantly higher than those of unglued M&T joints in tension and compression, accordingly.

Table 1. ANOVA of results of withdrawal resistance of M&T joint.

Source	F-value	Significance
Glue	9.060	< 0.01
Testing method	361.566	< 0.01
Glue × Testing method	4.148	0.055

Table 2. Mean comparisons of withdrawal resistance of M&T joint.

Glue	Testing Method	Mean (N)	COV
Unglued	Tension	597 (A)	20.7
	Compression	421 (B)	15.8
Glued	Tension	4414 (A)	11.2
	Compression	3499 (B)	20.6

3.2. Failure Modes

The unglued M&T joints did not show obvious damage when withdrawal resistances of joints reached their maximum loads. Figure 3 shows the typical failure modes of the tested glued M&T joint. In the case of withdrawal resistances of M&T joints measured using tensile method, fibers of mortise and tenon were all torn. In addition, the end of the mortise facing the shoulder of the tenon was glued with the shoulder of the tenon by the glue overflowed, to some extent, which increased the withdrawal resistance of the M&T joint [18,19]. This was one of the reasons why the withdrawal resistance of the M&T joint measured by the tensile method was higher than that measured by the compressive method. However, in the case of withdrawal resistance of the M&T joint measured by the compressive method, the end of the mortise was split, but the tenon was not damaged.

According to the withdrawal resistance values and their failure modes, the following assumptions can explain this phenomenon. For the unglued M&T joint determined using the tensile method, the withdrawal resistance mainly depended on the friction force of the joint, and the withdrawal resistance was relatively lower, so the tenon member still kept in its elastic stage, and the energy loss is limited. However, for the glued M&T joint, the withdrawal resistance is approximately 8 times that of the unglued M&T joint, so it can be inferred that the glued M&T joint was in its plastic stage, and the energy loss was higher than the unglued M&T joint.

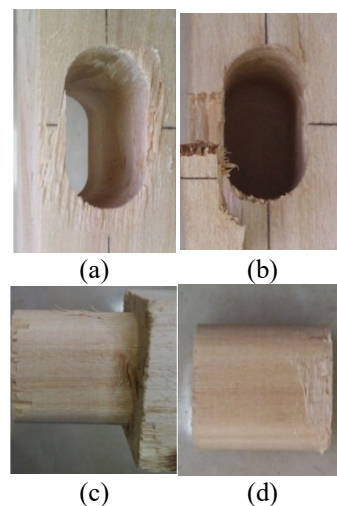


Figure 3. Failure modes of the M&T joint (a) mortise of tensile specimen, (b) mortise of compressive specimen, (c) tenon of tensile specimen, and (d) tenon of compressive specimen.

3.3. Finite Element Analysis

Figure 4 shows the stress distributions of the T-shaped M&T joint in different stages during the tensile test based on FEM. Figure 4a was the initial state in which the load was not applied. Figure 4b shows the state before the tenon was pulled out. Figure 4c shows the stress distributions of the T-shaped M&T joint that was just pulled out with the load reaching the maximum value. Finally, the tenon that was completely pulled out is shown in Figure 4d.

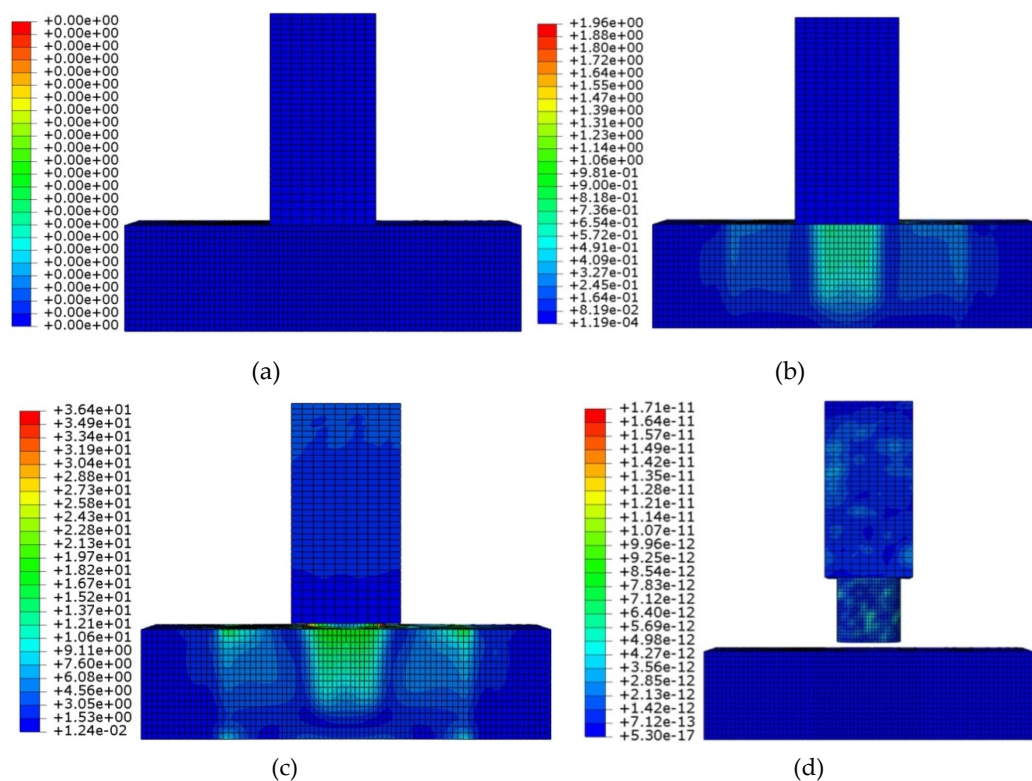


Figure 4. Stress distributions of the M&T joint measured by a tensile method based on the finite element method (a) initial state, (b) starting loading state, (c) maximum load state, and (d) final state. (unit: MPa).

Figure 5 suggests stress distributions of M&T joint in different stages during the compressive test based on FEM. Figure 5a shows the initial state that the load was not applied, so the stress of the specimen was zero. Figure 5b shows the loading state. Figure 5c shows the stress distributions of the T-shaped M&T joint that was just pulled out, when load reached the maximum value. Finally, the tenon that was completely pulled out is shown in Figure 5d.

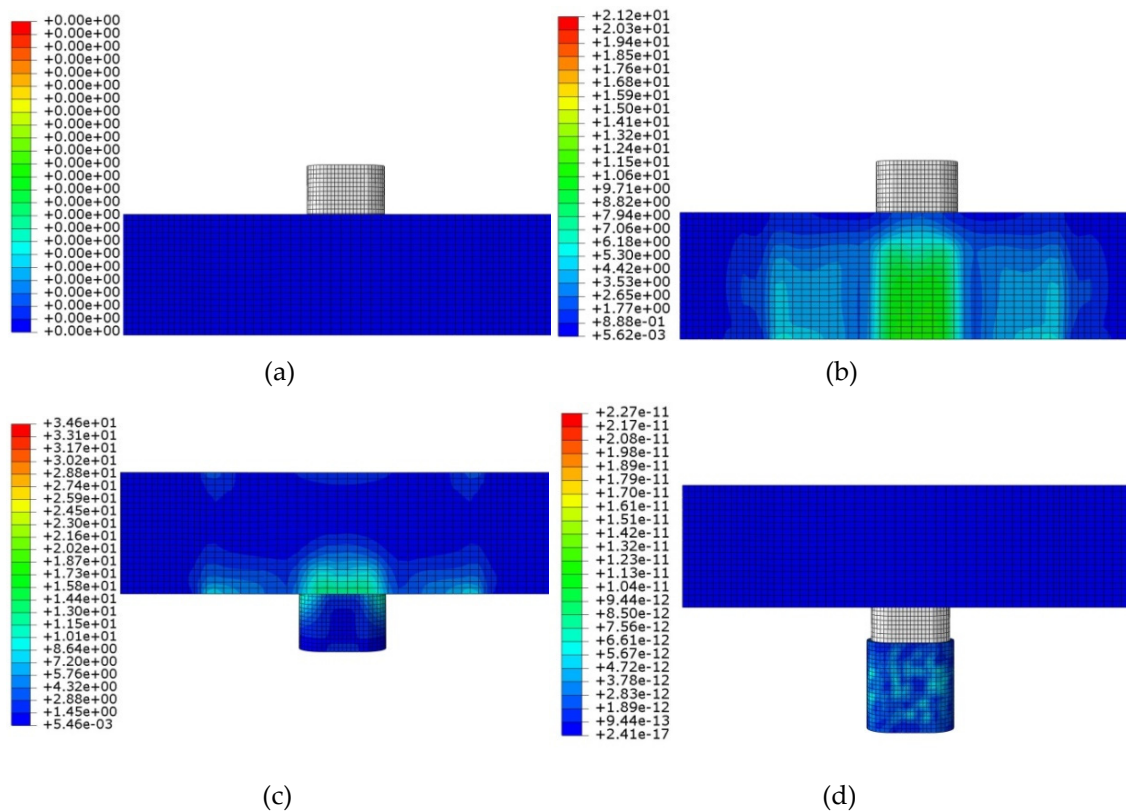


Figure 5. Stress distributions of M&T joint measured by a compressive method based on FEM (a) initial state, (b) starting loading state, (c) maximum load state, and (d) final state. (unit: MPa).

Comparing Figures 4c and 5c, the M&T joints all reached their maximum loads when measured by tensile and compressive method respectively. However, the stress distributions of the joint shown in Figure 4c was higher than those shown in Figure 5c, which is consistent with the experimental results that the withdrawal resistance of the M&T joint measured using the tensile method was higher than that measured by the compressive method. How did this phenomenon come to be? In the experimental section, the effect of the tenon shoulder can explain this phenomenon partly, but in the numerical section, the effect of the shoulder was not considered in the finite element model. Another factor must influence the withdrawal resistance of the M&T joint. Comparing the two testing methods, the main difference was the sample; specifically, the length of tenon member. For the sample used in the compressive method, the length of the tenon member can be regarded as zero. However, for the T-shaped sample used in the tensile method, the lengths of tenon members were different in previous studies [20–22].

In order to further study the effect of the length of the tenon member on withdrawal resistance, finite element models of T-shaped samples with different tenon member lengths were established. The length of tenon members ranged from 80 to 230 mm with an increment of 50 mm. Figure 6 shows the stress distributions of T-shaped samples reaching their maximum loads. For the mortise member, the stress distributions of all samples were nearly the same as each other, while, for tenon members, the stress distributions increased with the increase of tenon member length.

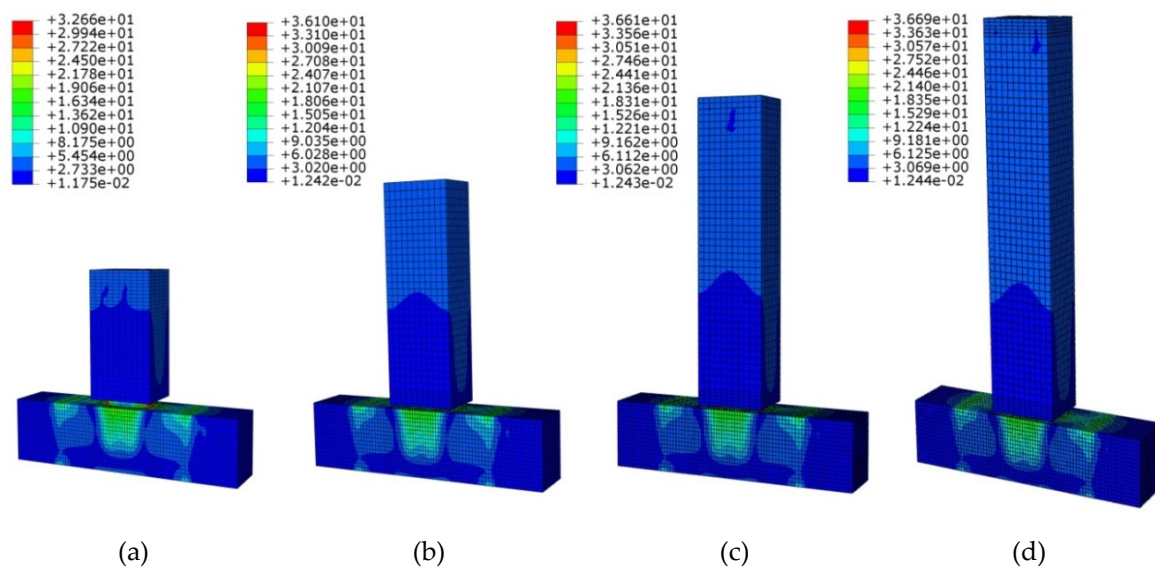


Figure 6. Stress distributions of T-shaped samples with different tenon member lengths (a) 80 mm, (b) 130 mm, (c) 180 mm, and (d) 230 mm. (unit: MPa).

In order to get a comprehensive comparison, withdrawal resistance and displacement curves of all samples were obtained by the post-processing function of ABAQUS. Figure 7 shows the withdrawal resistance and load curves of five types of samples including one compressive sample and four T-shaped tensile samples. From the whole view, the withdrawal resistances of all samples were nearly the same. However, from a local perspective, the withdrawal resistances increased in line with the increase of tenon member length. In other words, the withdrawal resistance measured by the compressive method was lower than that measured by the tensile method. For furniture structure design, researchers and engineers should choose an appropriate method according to the real situations.

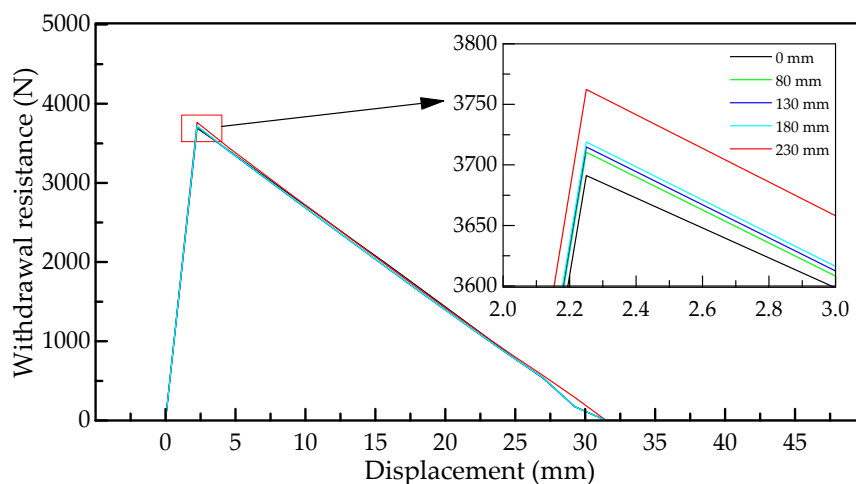


Figure 7. Effect of tenon member length on withdrawal resistance of M&T joint.

4. Conclusions

The methods of measuring the withdrawal resistance of the M&T joint were studied based on an experiment and the finite element method. A new method was proposed in this paper and compared with the existing testing method. The following conclusions were drawn.

1. The effects of glue and testing methods on withdrawal resistance of the M&T joint were statistically significant. The withdrawal resistances measured by the tensile method were higher than those measured by the compressive method, no matter whether the joints were glued or not.

2. The withdrawal resistance of the M&T joint increased gradually in line with the growth of the tenon member length based on the finite element method.
3. The compressive method proposed has an advantage in measuring the true withdrawal resistance of the M&T joint, while the tensile method suited to measure the withdrawal resistance of T-shaped samples for comparative experiments.

Further research will focus on the following points: (1) due to the heterogeneity of wood, additional tests will be repeated with more samples to make the conclusions more reliable; (2) the relationship between true withdrawal resistance and furniture structure will be studied to better instruct the furniture design.

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