Experimental and Numerical Studies on the Cantilevered Leg Joint and its Reinforced Version Commonly Used in Modern Wood Furniture

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The cantilevered leg joint commonly used in modern wood furniture was studied by numerical and experimental methods. A novel joint was proposed and compared with the typical joint commonly used in the cantilevered leg. Both of them were made of beech wood (*Fagus orientalis.* Lipsky). The experimental results showed that the bending moment capacity of the novel joint was remarkably higher than the typical joints, which confirmed that the novel structure had a better mechanical performance. The numerical analysis was conducted according to GB/T 10357.3 standard, the results showed that the stresses of the typical joint were mainly concentrated on the wooden components, while the stresses of the novel joint were concentrated on the metal connectors. The stress concentration obtained by the finite element method (FEM) was consistent with the failure modes of the experimental tests, which provides a reliable method for evaluating and optimizing the novel furniture structure.

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INTRODUCTION

The joints are the most critical but sensitive parts of a furniture piece; thus, they should be assessed after the determination of final dimensions of the members (Eckelman 2003). Traditional furniture joints are exquisite and complex, and they join the wood components, *e.g.* posts, stretchers, and panels, at required points. Applying specific joinery methods and carved patterns make all components play the dual role of decoration and strengthening the structural stability (Zhu *et al.* 2022a). With the transition of fashion trends and consumer aesthetic orientation, modern wood furniture structure has gradually become simplified. The rail or stretcher members have been eliminated, *i.e.*, the cantilevered leg directly connected to the panel member, which is one of the primary load-bearing joints in whole furniture frames. In addition, the cross-section of the post leg and the thickness of the panel member have been vividly decreased. Thus, higher aesthetic and rigidity requirements of furniture joints have been put forward for modern wood furniture to ensure that the joints resist the internal and external load under different service conditions (Eckelman 1978; Zhou *et al*. 2018; Zhao *et al*. 2020). Research has shown that the stability of the furniture frame is directly affected by the joint type, which can be divided into a permanent joint or a mountable joint (Uysal *et al.* 2015; Xi *et al.* 2020; Fu *et al.* 2021a,b).

The permanent joints are usually composed of mortise-and-tenon (M-T) members with different wood species (Smardzewski 2008; Záborský *et al.* 2017), glue line thickness and distribution (Kasal *et al.* 2013; Ratnasingam and Ioras 2013; Džinčić and Živanić 2014), fits (Wang and Lee 2014; Elek *et al.* 2020), and tenon geometry (Demirci *et al.* 2020), which has been widely used since ancient times (Wu *et al.* 2020). Hence, the M-T joints, especially those connected by rectangular or round blind-tenon, are favored by woodworkers and consumers due to the advantages of externally invisible and outstanding static and dynamic strength performance under a reasonable engagement (Zhang *et al.* 2001; Erdil *et al.* 2005; Likos *et al.* 2013; Chevalier *et al.* 2019). However, the M-T joints are not suitable for the wooden components with quite small sections or shallow panels, as they have been shown to affect the strength performance (Kasal *et al.* 2016). In addition, the glue line of permanent joints is quite difficult to repair, which may risk reducing the transportation efficiency and can lead to the scrapping of entire furniture frames (Uysal *et al.* 2015; Wang *et al.* 2020; Zhu *et al.* 2022b).

Various kinds of mountable joints and the relative technical rules can be produced from this kind of research. Podskarbi *et al.* (2017) pointed out that the external invisibility of a newly designed furniture connector is an important criterion to measure whether a furniture item meets the aesthetic requirements. This is important because exposed metal connectors are completely different from wood material in their color, coating, texture, and other decoration aspects (Wu *et al*. 2021; Tao and Yan 2022; Peng and Yan 2022; Zhao and Yan 2022). In addition, the strength stability is also a significant index to measure the feasible of furniture connectors. The finite element method (FEM) has been widely used to evaluate the mechanical strength performance of wood, bamboo, wood furniture structures, and newly designed furniture connectors (Chen and Wu 2018; Li *et al.* 2020; Liu *et al.* 2020). Branowski *et al.* (2018) designed and tested the load limit capacity and failure mechanisms of two novel fasteners that were used to connect the leg with the seat. Krzyżaniak *et al.* (2021) proposed novelty-designed three-dimensional (3D) printed fasteners characterized by external invisible and mountable to connect the furniture L-type joints. The effects of the internal mounting forces and the selected materials on the stiffness and bending moment capacity *via* the numerical and experimental methods were analyzed. Objective comparisons of experimental tests with numerical simulation have been conducted by researchers to analyze the results and stress distribution more intuitively and clearly.

In the context of the presented investigations, limited research has been conducted on the stability and internal stress distribution of the cantilevered leg joint, which is widely used in modern wood furniture. Therefore, the primary purpose of this study was to propose a novel joint of cantilevered leg joints used in wood furniture characterized by external invisible metal connectors and higher structural strength based on the typical connect types. Three specific objectives were summarized. First, a novel cantilevered leg joint using mental corner braces was designed and proposed, which is different from the typical joint mounted by rectangular shim. Second, experimental tests were conducted to obtain the bending moment capacity of two types T-shaped specimens of cantilevered leg joint. Third, numerical models of the cantilevered leg chairs, assembled by the typical and novel joint, were established and calculated to evaluate the internal distribution and maximum magnitude stress *via* FEM when subjected to three loading types.

EXPERIMENTAL

Materials and Equipment

Beech wood (*Fagus orientalis.* Lipsky) lumber obtained from a local wood supplier (Nanjing, China) with the dimensions of 3,000 mm × 200 mm × 100 mm (length × width × thickness). The lumber was stored in a conditioning room for at least 52 weeks. The average specific gravity of the lumber was 0.68 g/cm^3, and the moisture content was conditioned to 9.22%, according to the ASTM D2395 (2017) and D4442 (2020) standards. The metal connectors, including rectangular shim and corner braces, were made of low-carbon steel. The metal connectors were obtained from a local commercial shop (Nanjing, China). The equipment used in this experiment included a computer-numerical-control based (CNC) machine (WPC; ULI, Shanghai, China) with an accuracy of 0.01 mm, a universal testing machine (AG-X 20kN; Shimadzu, Kyoto, Japan), and its affiliated clamps.

Configurations of the Cantilevered Leg Joint

Typical cantilevered leg joint

Compared with the traditional connection types, such as M-T or the most popular eccentric connector, the metal shim and screws have been widely adopted to connect the cantilevered leg joints, as shown in Figs. 1a and 1b. This adoption has been primarily because the panel members are relatively shallow and the sections of post member are quite small. Two screws are vertically inserted into the post member to connect the rectangular shim with it. Another four screws are inserted through the shim in the opposite direction, connecting the shim and wood panel member. The specific assembly procedures are shown in Fig. 1c.

The typical cantilevered leg structure is superior with respect to the convenient assembly and a wide scope of application. The joint can be mounted by simple steps and is suitable for various kinds of wooden components. However, the screws provide the holding force of wood in this joint type, which may become a concern as softwood becomes the mainstream furniture material. In addition, the exposed metal shim may not meet the aesthetic requirements for the modern wood furniture. Thus, it is urgent to put forward a novel joint that satisfies the mechanical strength for safe use and meets the aesthetic requirements such as being externally invisible.

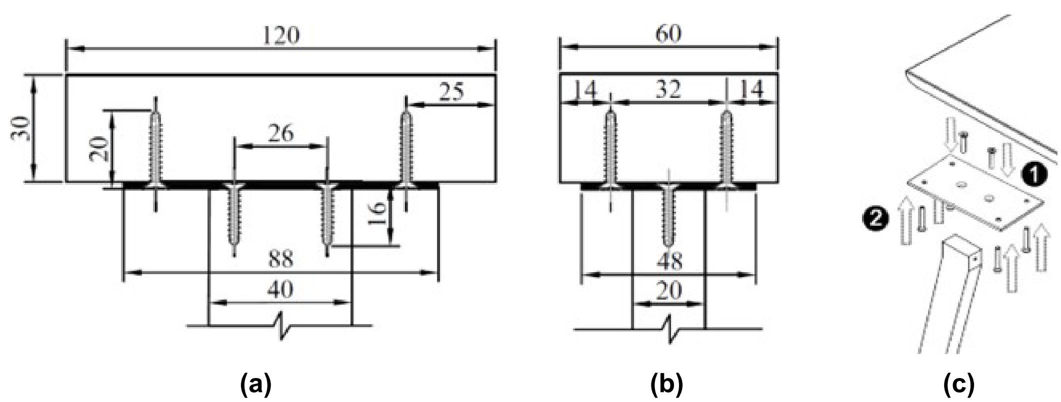

Fig. 1. Configurations of commonly used cantilevered leg joint: the a) dimensions of the front view (in mm), b) dimensions of the left view (in mm), and c) explosion diagram with the assembling procedures of the joints

Proposed novel cantilevered leg joint

Combining the advantages of the traditional M-T joint and the mountable rectangular shim joint mentioned above, a novel cantilevered leg joint was designed and proposed (Fig. 2). Rectangular M-T joints were machined on the post and panel members, respectively, and two metal corner braces with high rigidity were used to relieve the stress concentration and plastic deformation, as shown in Figs. 2a and 2b. The specific assembly steps were introduced in detail. Firstly, the corner braces were attached to both sides of the tenon. Secondly, two screws were firstly inserted into the post member through the relief holes of the corner braces. Thirdly, the tenon of the post leg was inserted to the mortise of the panel member. Lastly, another two screws were used to connect the corner braces and panel member (Fig. 2c). It is obvious that the structure was external invisible, *i.e.* the metal connectors were hidden in the wood furniture components and the user can self-assemble it with simple tools.

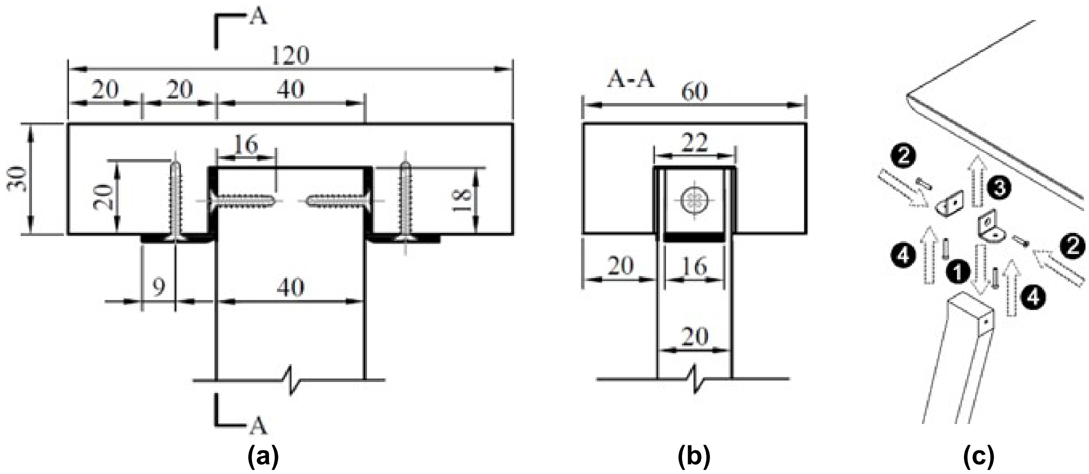

Fig. 2. Configurations of novel cantilevered leg joints: the a) dimensions of the front view (in mm), b) dimensions of the left view (in mm), and c) explosion diagram with the assembling procedures of the joints

Specimen Preparation

The T-shaped cantilevered leg joint composed of two wood members, the post and the panel, were constructed of beech wood with the dimensions of 150 mm × 20 mm × 40 mm (length × width × height) and 120 mm × 30 mm × 60 mm (length × width × height), respectively. The typical joint mounted by a rectangular shim fastened by six self-tapping screws and the novel joint mounted by corner braces with four self-tapping screws were prepared. The dimensions of hardware connectors used in the experiment are shown in Fig. 3. Due to the specimen configuration, two kinds of self-tapping screws with different lengths were adopted, among which screws measured 16 mm long with a diameter of 3 mm were used to connect the post member with rectangular shim and corner braces. The screws that measured 20 mm long with the same diameter were used to fastener the panel member with connectors. For each connect type of the T-shaped joints, 10 replications were prepared. The mounted joints are also shown in Fig. 3.

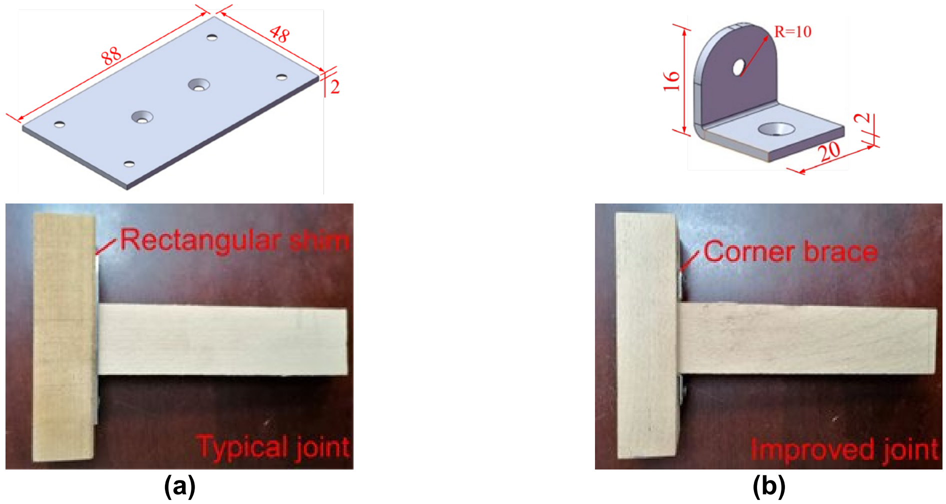

Fig. 3. The dimensions (in mm) and configuration of the metal connectors used in the T-shaped specimens: a) rectangular shim and b) corner braces

Experimental Tests

The cantilevered leg joints are primarily exposed to the bending force in daily use. To verify the effect of the novel joints, experiments were carried out to measure the mechanical strength performance of typical and novel joints. The testing set up is shown in Fig. 4. The panel of the T-shaped specimen was constrained by a metal fixture, and the cantilevered post was subjected by the force applied by the loading head of the testing machine. The bending forces transmitted through the post member can generate sizeable bending moments at the connecting joint. The loading position was 90 mm from the edge of the post by the loading head at a speed of 5 mm/min until the displacement reached 25 mm. The bending moment capacity was put forward to conduct an objective comparison of the typical joints and the novel joints according to Eq. 1,

$$M = F \times L \qquad (1)$$

where M is the bending moment capacity (N·m), F is the bending load (N), and L is the moment arm (m).

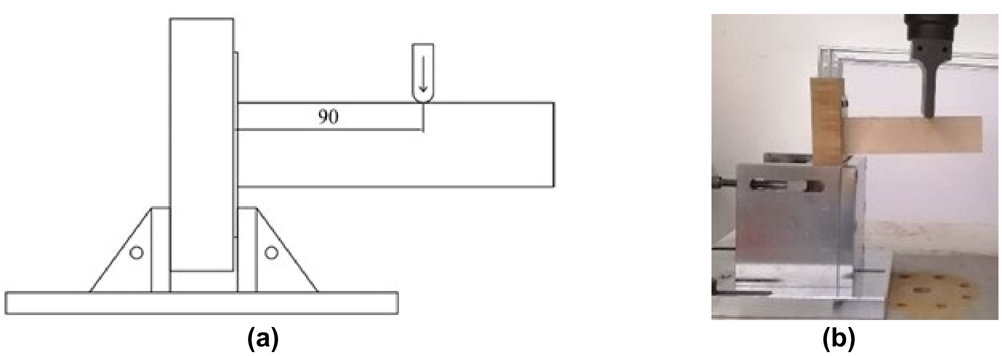

Fig. 4. The setup for measuring the bending load capacity of the T-shaped cantilevered joints: the a) schematic diagram (in mm) and b) photo

The Finite Element Model

Modeling

The numerical models of the cantilevered leg chair mounted by the typical and novel cantilevered joint were established to evaluate the stress distributions and deformation *via* SolidWorks 2017 (Dassault Systèmes, Vélizy-Villacoublay, France). The cantilevered leg chair was simplified with the aim to improve the quality and reduce the error of the mesh model. The simplification included deleting the furniture components that do not directly contact, providing strength to the cantilevered leg, and reducing the geometric continuity of the curved surface (Fig. 5a). However, the primary characteristic feature of the cantilevered chair was retained, *i.e.* the post leg directly engaged with the chair seat. The configurations of the simplified cantilevered leg chair model are also shown in Fig. 5a, in which the cross-section of the seat panel measured 480 mm × 440 mm, and the chair height was 408 mm. Table 1 illustrates the mechanical properties of materials of the metal connectors and the furniture elements. All these mechanical properties, which were tested in a previous study by authors, were assigned to the proposed numerical model (Hu *et al.* 2021). Considering the numerical calculation process and workload, the screw was chosen from the toolbox of software.

Table 1. Mechanical Properties of Beech Wood and Low-carbon Steel

Materials	Elastic Modulus (MPa)			Poisson's Ratios			Shear Modulus (MPa)			Yield Strength (MPa)
	E_L*	E_R	E_T	υ_{LR}	υ_{LT}	υ_{RT}	G_{LR}	G_{LT}	G_{RT}	
Beech Wood	12,205	1,858	774	0.502	0.705	0.526	899	595	195	53.62
Low carbon Steel	210,000			0.28			/			620.44

* E is the elastic modulus (MPa); υ is Poisson's ratio; G is the shear modulus (MPa); L, R, and T refer to the longitudinal, radial, and tangential directions of the beech wood, respectively.

The quality of mesh in the model directly affects the accuracy of the finite element simulation. According to the multiple attempts, the mesh based on curvature is more suitable for the analysis of the chair model, which supports further dividing finer elements at the joint and strikes a balance between the accuracy and the calculation speed. In general, a rough element with the size of 10 mm × 10 mm × 10 mm was used to model whole chair components. The minimum elements at the curved area were set to 8 mm, and the element size growth ratio was 1.5. The pre-calculations were operated to evaluate the mesh quality. According to the initial calculation result, a fine element size of 3 mm × 3 mm × 3 mm was used to model the cantilevered leg joint where stress is concentrated to prevent the stress singularity, and the element growth ratio was consistent with the rough elements. The quality of the mesh model was checked by the aspect ratio and the Jacobian ratio. The maximum aspect ratio of this model was 10.920 and the Jacobian ratio was 6.577, which met the analysis requirements (Wang *et al.* 2018). For all contact surfaces between the metal connectors and wooden components, a non-penetrating contact mode in the software was assigned.

Loading type

Joints of chair furniture are exposed to complex internal and external forces in daily use, and it is generally believed that these forces are related to the weight of users from the functional perspective (Yu *et al.* 2021). Therefore, three loading types on static load test of seat and posts were selected to evaluate the strength and durability of mounted cantilevered leg chairs according to the GB/T 10357.3 (2013) standard (Fig. 5). Meanwhile, relevant studies indicated that the number of overweight people has been increasing (Langová *et al.* 2019). Considering the misuse by consumers and the perspective of safety design, the forces of the IV level were selected to apply the load. The first loading type was a vertical load measured at 1,600 N applied at 100 mm from the edge of the seating panel. The second load type was a side load of 250 N and a vertical load of 1,000 N applied to the panel. The third load type was a back load of 500 N and a vertical load of 1,000 N. The three loading types produced internal resisting forces of the chair similar to those caused by the action of someone sitting, tilting sideward, or tilting backward, respectively.

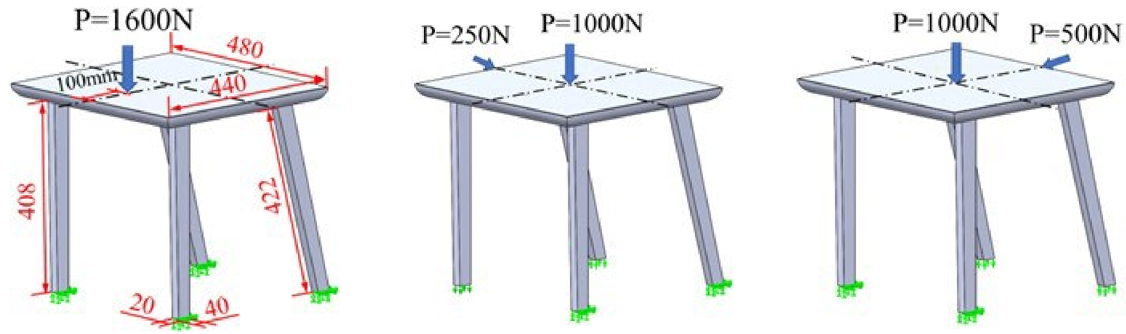

Fig. 5. The dimensions (in mm) and configurations of the cantilevered leg chair model and loading types in numerical simulation: a) loading type I, b) loading type II, and c) loading type III

RESULTS AND DISCUSSION

Bending Moment Capacities of Cantilevered Joints

The average deflection-bending load curves of the two types of joints obtained from the experimental tests are shown in Fig. 6. The maximum average bending load of the novel joint was 698 N, which was 62.4% higher than that of the typical joint (436 N). The results of the average bending moment capacity (BMC) were calculated according to Eq. 1. The BMC of the typical joint was 39.23 N·m (0.23), and the BMC of the novel joint was 62.82 N·m (0.09). The values in parentheses are coefficients of variation, which conveys that the novel joint was more stable than the typical joint.

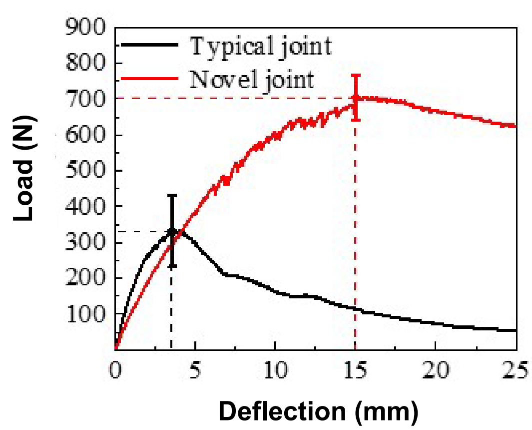

Fig. 6. The average deflection-bending load curves of the two types of cantilever leg joints

Further analysis combined with the failure modes (Fig. 7) was conducted. The bending load rapidly increased for the two joint types, and then the load of the typical joint declined at 3.5 mm because of the screw failure on the stressed side (Fig. 7a). Besides, plastic deformation occurred at the end of the wooden post member. The failure modes indicate that the strength of typical joints depends on the holding force of the screws. The load of the novel joint was continually increased until the loading head reached 15 mm, where the structure began to fail. Figure 7b shows the failure mode of the novel joint, which indicates that large deformation occurred at the stress side corner brace. This result was probably due to the geometric characteristics of the corner braces, where the bending region is prone to bear stress. Overall, compared with the holding force between screws and wood of the typical joints, the corner braces of novel joints bear more forces and prevent the development of plastic deformation, so that it shows a higher bending strength, lower coefficient of variance, and better structural strength stability.

(a) (b)

Fig. 7. The failure mode of the experimental a) typical joint and b) novel joint

Stress Distributions of the Chairs Jointed by Cantilevered Joints

The chair models were calculated when subjected to three loading types with the aim of evaluating the stress distribution, magnitude, and deformations of two types of joint proposed before *via* the FEM. Figure 8 illustrates the equivalent stress distributions in the wood members or metal fasteners by outputting from SolidWorks, and the red represents the maximum von Mises stresses. As shown in Figs. 8a, 8b, and 8c, the maximum stress concentration of the chair with the typical joint occurred at the edge of the left front post (36.58 MPa), in the relief hole of the right front post connector (42.96 MPa), and at the upper end of the left front post (43.88 MPa) under the loading types I, II, and III, respectively. Among the diagrams, the stresses were primarily concentrated on the post components, regardless of which direction the force is applied. As is shown in Figs. 9d, 9e, and 9f, the internal stress distributions of the novel joints were primarily concentrated on the turning of the metal corner brace. The specific maximum von Moses stress values occurred at the rear corner brace of the left front post subjected to the loading types I and III, with the values of 135 and 136 MPa, respectively, and the front corner brace of the right front post subjected to the loading type II, with the maximum stress value of 163 MPa.

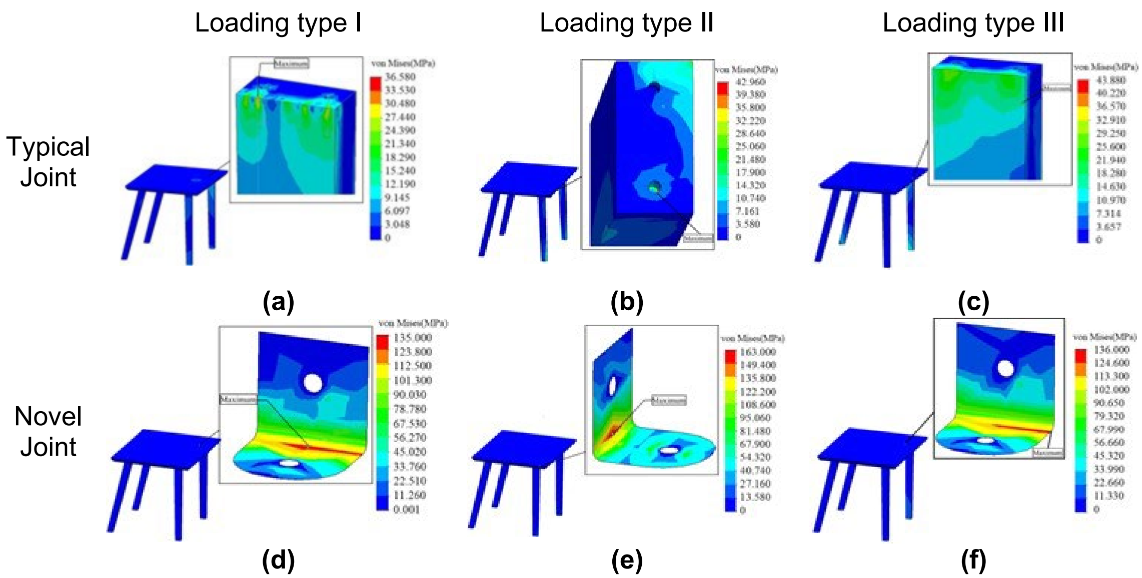

Fig. 8. The stress distributions of cantilevered chairs jointed by typical and novel joints

Obviously, both of the calculated maximum values of the two types of joints were less than the yield strength of the corresponding material, *i.e.* wood and low carbon steel. Therefore, neither joint will be damaged or fail in the loading process. Furthermore, the stress of the novel joint was remarkably higher than the typical joint by over 350% on average, which was primarily due to the connecting types and the geometric characteristics of the hardware fittings.

Figure 9 illustrates the deformation distributions of cantilevered leg joints calculated by the FEM. In loading type I and loading type II, the deformation distribution of chairs with the typical joint and novel joint was relatively uniform and similar, where the maximum deformation occurred at the front of the panel member and the rear post. In the loading type III, the maximum deformation of the chairs with the typical joint was concentrated at the rear end of the panel member, while the chair connected by the novel joint had the maximum deformation concentrated at the right front end of the panel member.

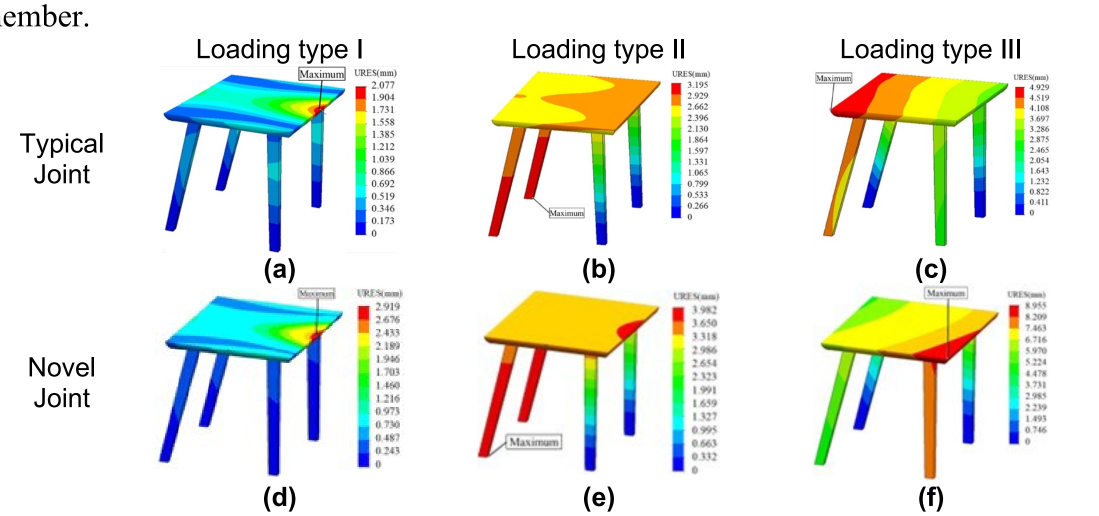

Fig. 9. The deformation distributions of the cantilevered chairs jointed by the typical and novel joints

According to the results of the FEM, the maximum stress value of the typical joint was concentrated in the wooden post member of the chair. On the other hand, the novel joint transferred the stress to the hardware connectors when subjected to the three loading types to achieve the expected improvement effect. The maximum stresses were still less than the yield strength of the wood material, so the structure will not be damaged in service. Furthermore, the stress distributions of the typical and novel joint output from the FEM were well consistent with the experimental failure mode.

The novel cantilevered leg joint possessed the obvious advantages of higher structure stability and convenience for assembly and processing. However, due to the adoption of the screws, the bending strength of the cantilevered joint may decrease after repeated disassembly. Thus, the structure by using embedded nuts will be further studied as a strategy to realize the effect of multiple disassembles of the structure without reducing the mechanical strength.

CONCLUSIONS

1. The experimental tests showed that the bending moment capacity of the T-shaped novel joints (62.82 N·m (0.09)) was much higher than the typical joints (39.23 N·m (0.23)), as well as being easier to assemble, more cost-effective, and with a lower coefficient of variance in terms of the mechanical performance.
2. The stresses of the chair connected by typical cantilevered leg joints were mainly concentrated on the wooden component, while the stresses of the chair connected by the novel joint were concentrated on the metal corner braces when subjected to three loading types specified in the GB/T 10357.3 (2013) standard.
3. The maximum stresses calculated by the finite element modeling (FEM) were consistent with the failure modes of the experimental results, and less than the yield strength of the materials. This indicated that the proposed novel joint was feasible when subjected to loads.

ACKNOWLEDGMENTS

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