Mechanical Performance Analysis of Double-dovetail Joint Applied to Furniture T-Shaped Components

Wei Wu, Wei Xu,* and Shuangshuang Wu

T-shaped mortise and tenon members are the main structure of traditional Chinese furniture. In this paper, the double-dovetail joint used for face-to-face joint of rubber wood (*Hevea brasiliensis* Muell. Arg) is transformed into a new type of double-dovetail joint and rounded double-dovetail joint for T-shaped members of point joint structure. The ultimate pull-out test and bending strength test were carried out on the two structures and three structures of oval mortise, round rod mortise and right angle mortise. The results show that the ultimate pull-out force of the round double-dovetail joint is 39% higher than that of the double-dovetail joint, and the bending resistance capacity is 8.9% higher, and the strength and stability are better than those of other split mortises and tenons, which proves that this structure can be used in actual production, and also proves that the mortise and tenon connected by the surface has the possibility of transforming into a point connection structure. The concave structure of the rounded double-dovetail joint makes the mortise and tenon fit well, the tenon squeezed tight, and a good bonding effect was achieved. This structure can also provide greater friction and resistance, delay rubber adhesive failure and improve the stability.

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INTRODUCTION

Solid wood furniture is popular due to its natural and environmentally friendly properties, as well as its durable and naturally variable patterns. The development of solid wood furniture faces issues of price, resource reserves, and personalization (Zhan and Dai 2018; Wu *et al.* 2021). In this context, design research centered around green design is particularly important (Wu *et al.* 2021). Traditional Chinese furniture has a beautiful shape, exquisite decoration, and an extremely exquisite structure (Wang *et al.* 2020; Wang *et al.* 2021). The mortise and tenon can form a stable structure through the protruding tenon and concave mortise, and with the continuous development of society, and the continuous renewal of art and culture, the mortise and tenon structure is also being updated. Moreover, the mortise and tenon structure is not only a structural form to support furniture, but also a carrier of art and culture, and has been the cultural accumulation and essence of the Chinese nation for thousands of years (Ling and Jin 2020; Gu *et al.* 2022; Hu *et al.* 2022). The strength of mortise and tenon joints greatly affects the strength, processing technology, and structural safety of wooden furniture frames (Smardzewski *et al.* 2014; Gu *et al.* 2016; Hu *et al.* 2020). At present, the use of mortise and tenons is still constrained by processing and difficulty in achieving modularity and substitutability.

At present, traditional Chinese solid wood furniture still uses mortise and tenon joints with complex production processes, so there is still a lot of research space for the modern improvement of mortises and tenons. There are different opinions on the improvement methods, and Lin advocates preserving or extracting and restructuring morphological elements in Ming Dynasty-style furniture (Lin *et al.* 2017). Xu *et al.* (2000) argued that solid wood furniture should give up design, decoration, and other forms and that the focus should be on structural strength and mechanization. Guan (2007) believes that while fully preserving the traditional style and external characteristics of furniture, efforts should be made to maximize the proportion of machinery or semi-machinery during the processing process and reduce manual operations. Huang *et al.* (2019) believes that the design of mortises and tenons should achieve disassembly, standardization, modularity, and replaceability. Carl (2008) believed that mortise and tenon joints are only three-dimensional structures that can be simplified into two-dimensional structure. In general, Chinese scholars prefer to retain the elements of traditional Chinese furniture, to retain the artistic and cultural value of traditional furniture, but the redesign of mortise and tenon is easy to lacks innovation. Due to the lack of understanding of the culture and art of mortise and tenon, foreign scholars are pursuing the beautiful lines and simple forms of mortise and tenon, and they dare to innovate the redesign of mortise and tenon.

In the process of wood processing, there are often small scraps left over. These small materials have proven highly suitable as the connecting components for split tenons. The adoption of this method not only effectively saves materials and reduces resource waste, but also confers significant advantages of modularity and replaceability to the product. Furthermore, through careful design, the structural strength of these split mortises and tenons are on par with that of traditional integral mortises and tenons, ensuring stability and safety in their application. Subsequent research has uncovered that the variety of split mortises and tenons designed based on T-shaped components are vibrant (Ali *et al.* 2017; Yin *et al.* 2023). Gu *et al.* (2019) used split elliptical tenons and circular tenons in fast-growing poplar T-shaped components, which enhance the mechanical properties of the structure. Aman *et al.* (2008) demonstrated through experiments that the strength of mortise and tenon construction optimized by modern industrial technology is superior to that of traditional mortises and tenons and can improve wood utilization efficiency. Li *et al.* (2021) pointed out that round mortise and tenon joints have higher wood utilization and labor productivity than square flat mortise and tenon joints and are also more suitable for industrial production. Of course, the split mortise and tenon has many advantages compared to the whole mortise and tenon, but there are also some problems that need to be solved regarding the design. For example, round rod mortise is easily damaged when disassembled (Liu *et al.* 2019). Specifically, the mechanical strength of mortise and tenon joints is not as good as that of oval mortise and the drawing performance of double-dovetail mortise is weak.

The dovetail mortise has better vertical stretching than double-dovetail mortise (Li 2019), and the force is more uniform in the pull-out test than that of oval mortise, and the strength is higher than that of round rod mortise. It has been found in the study of related literature that there have been relatively few studies on dovetail mortise and double-dovetail mortise. In particular, the double-dovetail mortise is limited to practical applications and lacks data and validation from experimental studies (Tang and Guan 2021; Fu *et al.* 2022). It is also found that most scholars have only studied the bending properties of traditional dovetail mortise with a focus on wooden structures in construction (Chen *et al.* 2019). Theoretical and simulation studies on dovetail mortise are also very limited.

The article designs a round double-dovetail joint based on furniture T-shaped members. It is hoped that it can provide design ideas for the improvement and development of the traditional tenon and mortise structure in solid wood furniture and add new forms for the combination of mortise and tenon structure. The prototype design (double-dovetail joint) and the improvement of structure, according to the mechanization requirements (rounded double-dovetail joint), are compared with three kinds of split mortise and tenon. This comparison was used to explore the effect of round double dovetail on the mechanical properties of furniture T-pieces. This study provides a theoretical basis for practical application and aims to prove the feasibility of these innovative design ideas.

EXPERIMENTAL

Materials

Rubberwood (*Hevea brasiliensis* Muell. Arg) used in the test was purchased from a commercial timber supplier in Nanjing, Jiangsu Province, China, with specifications of 2 000 mm× 150 mm× 40 mm (length× width × thickness), moisture content 9.76 to 10.16%, and gas dry density 0.63 to 0.68 g/cm^3. The test adhesive was Henkel Baide Panda brand polyvinyl acetate emulsion adhesive (PVAc universal type). The solid content was 50%, the viscosity was 17.5 Pa·s, and the pH was 4.78.

Description of the Specimens

The test piece used was made of rubberwood board after being planed to form the reference surface. The specimens were then processed by longitudinal and cross-saws into small mortise and tenon specimens, both of which were 120 mm × 40 mm × 30 mm (length × width × thickness). Only defect-free materials without the medullary heart part were used. All specimens were placed in a constant temperature and humidity box with a temperature of 20 °C and a relative humidity of 55% (produced by Jinghengyu Instrument and Equipment Manufacturing Co., Ltd., model: HHS250). Eight specimens were randomly taken out every 2 h to measure the moisture content until the two adjacent values were stopped at about 12%.

The mortise head was processed into a 45-mm mortise by a CNC machining center (WPC type CNC machine tool, machining accuracy of 0.01 mm, Shanghai Force CNC Electromechanical Co., Ltd.), and then processed into a 40-mm split mortise and tenon by a cross-cutting saw. After processing, the specimen was flat on all sides. In terms of machining accuracy, the error of specimen length was allowed within ±1 mm, and the error of width and thickness was allowed within ±0.5 mm (Wang *et al.* 2022) (Fig. 1).

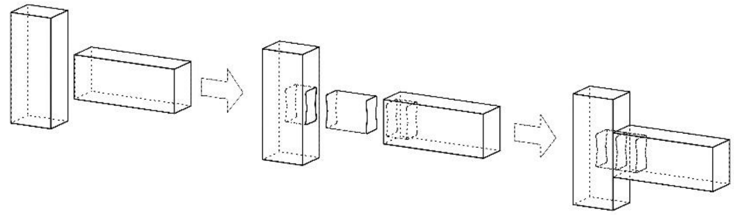

Fig. 1. Assembly mode of test piece

The double-dovetail joint is a structure designed for chairs. The design was inspired by the furniture designed by Italian designer Francesco and the plug-in dovetail designed by Li (Seid and Martinović 2014; Li *et al.* 2022) (Fig. 2). Francesco elongated the double-dovetail mortise and turned the originally flat double-dovetail mortise into a pin for joining two panels in a face-to-face joint, while Li also designed the dovetail mortise as a pin, but in an L-shape structure, which is a point-jointed structure. Both designs are very innovative, but they are still in the application stage, and there is no research data on either structure. However, Francisco's design proves that there is a practical basis for applying dovetails mortise or double-dovetails mortise in point-jointed structures.

(a) **(b)**

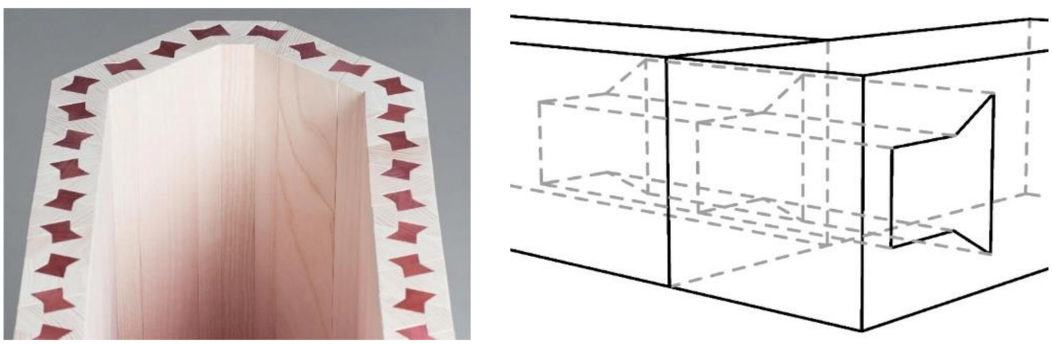

Fig. 2. Francesco's furniture (a) and L-shaped structure plug-in dovetail mortise (b)

The prototype (double-dovetail joint) of the design is to extend the double-dovetail mortise used for face-to-face joints and apply it as a split mortise and tenon to the T-shaped member. The dimensions of the specimen were chosen from those commonly used for split mortise and tenon and T-shaped structures in related articles to meet the needs of test strength and stability (Mohammad *et al.* 2013; Liu *et al.* 2020; Zhang *et al.* 2022). Therefore, the cross-sectional dimensions of transverse and longitudinal members are 30 mm×40 mm, the mortise shoulder is 5 mm, the length of the double-dovetail joint is 40 mm, the width is 30 mm, the thickness is 20 mm, the thickness of the neck of the tenon and the frontal head of the tenon is 3:4 (for reference to the dovetail mortise, the neck of the tenon is about 15 mm thick), and the inclination angle is about 9.5°, and the actual fit clearance after processing is -0.1 to 0.1 mm (Fit clearance = tenon size - mortise size). Because the machining equipment used was a 3-axis CNC from the college's woodworking lab, not a 5-axis CNC, the milling cutter used was 1.5 mm in diameter to restore the handmade effect as much as possible.

The milling cutter is very brittle, resulting in a very long machining time, which is not conducive to mass production and defeats the original purpose of the design. Therefore, the double dovetail was optimized for ease of machining and efficiency. Due to the different radii of the tenon, rounding resulted in different tool diameters that could be used. The machining times for double dovetail joints with different fillet radii are shown in Table 1. When the radius of the milling cutter exceeds 2 mm, the reduction in machining time is no longer significant, so a corner milling cutter with a radius of 2 mm is most suitable. Most of the common split mortise and tenon on the market and in research are oval mortise, round rod mortise, and right angle mortise (Nurgul 2007) Therefore, these three kinds of split mortises and tenons were used as the control group, and the actual fit clearance after processing was -0.1 to 0.1 mm (Fig. 3).

Table 1. Comparison of Machining Times of Rounded Double-dovetail Joint with Different Radii

Radius (mm)	0	1	2	3
Total Processing Time (s)	1410	1194	582	416

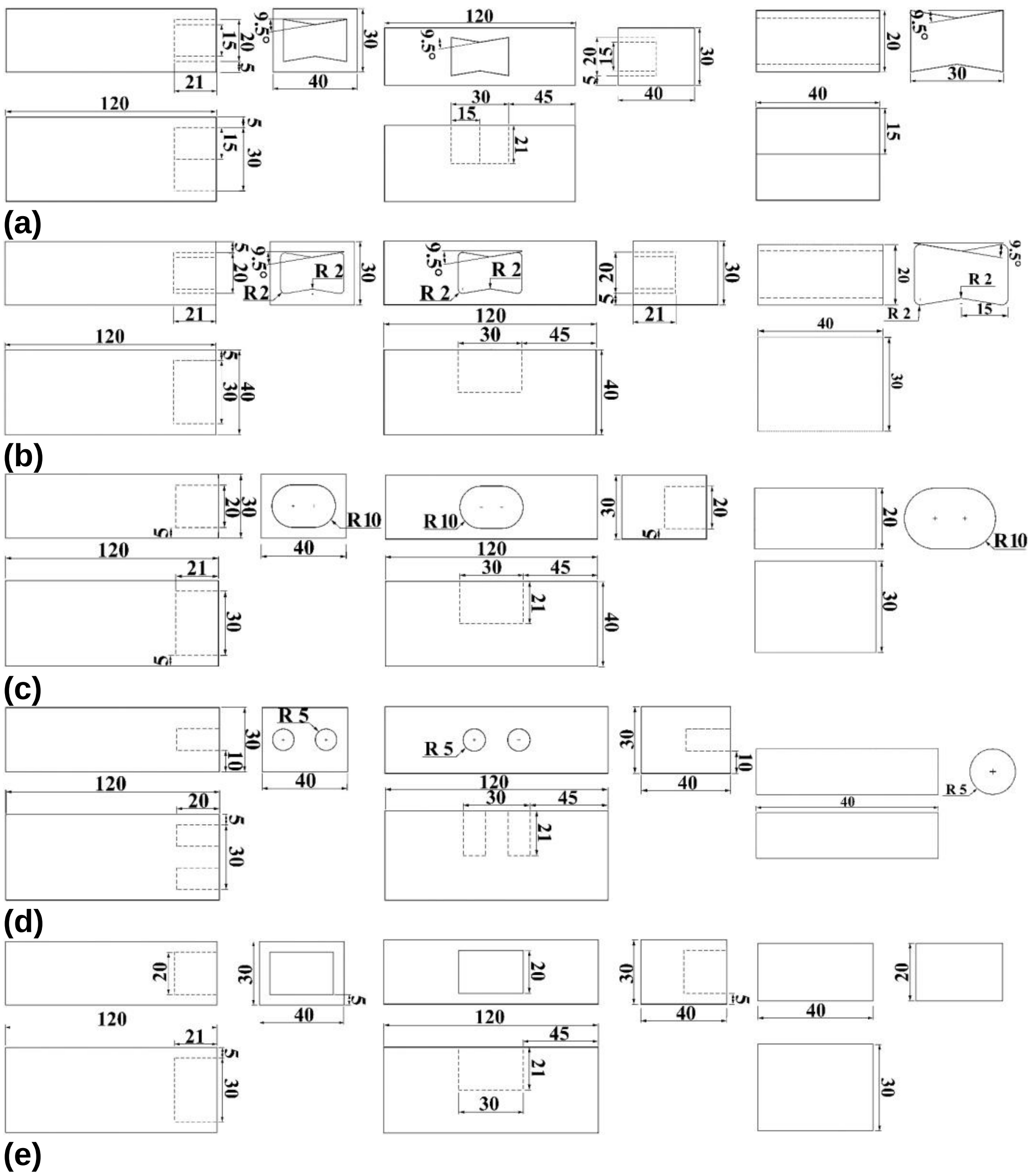

Fig. 3. Split mortises and tenons specimens include double-dovetail joint (a), rounded double-dovetail joint (b), oval mortise (c), round rod mortise (d), and right-angle mortise (e). (unit mm).

Testing Methods

There were 5 groups of test specimens, each group of 8 specimens, and a total of 40 specimens. Mortise and tenon are processed by WPC CNC machine tools, assembled after gluing, and only applied to the contact surface of the mortise and tenon. The amount of glue is 100 to 150 g/m^2 (Barboutis and Meliddides 2011), and only the round rod mortise extrudes a small amount of glue after assembly. All specimens were placed in a room at 24 °C for 7 days.

Because the bonding area directly affects the bonding strength of the mortise and tenon (Custódio *et al.* 2009). The bonding areas of the five split mortises and tenons are listed as a reference factor for subsequent test results (Table 1).

Table 2. Bonding Area of the Five Split Mortises and Tenons (π = 3.14) (unit m^2)

Specimen Number		Oval Mortise	Right Angle Mortise	Round Rod Mortise	Double-Dovetail Joint	Rounded Double-Dovetail Joint
Bonding Area	Lateral Side	0.33	0.40	0.13	0.32	0.39
	Top Surface	0.10	0.12	0.02	0.11	0.10
	Total	0.43	0.54	0.15	0.43	0.49

Ultimate Pull-Out Test

Results of tests using the Japan Shimadzu AG-X50KN universal electromechanical testing machine for the pull-out test are shown in Fig. 4. With a loading speed of 10 mm/min, at every 5 ms the load and corresponding displacement were sampled. A record was made of the maximum load and corresponding displacement value of each specimen. The equipment detected the fracture or the complete pull-out of the mortise when the test terminated for each group of 8 specimens. After completion of the test, the maximum load value was determined for each specimen in the group. Calculations were made of the average value, standard deviation, coefficient of variation, and positive and negative deviations.

The upper end of the transverse member of the T-shaped specimen was completely clamped by the upper chuck, and the lower fixture was fixed on both sides at an equal distance of the longitudinal member.

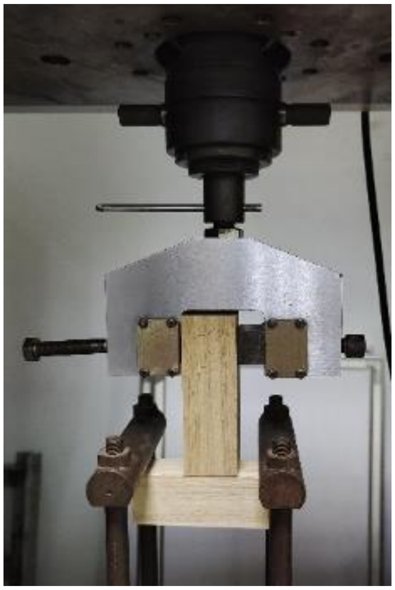

Fig. 4. Schematic diagram of specimen clamping

Bending Strength Test

Using the Japan Shimadzu AG-X50KN universal electronic mechanical testing machine for the bending test, the load loading speed was 10 mm/min. Load and displacement data were recorded every 5 ms. The maximum load was recorded for each specimen. Also recorded were the corresponding displacement values. The equipment stopped after it detected fracture or when the displacement reached 30 mm. For each group of 8 specimens, after the completion of the test, the maximum load value was counted for each group of specimens, and the average value and standard deviation were calculated (Fig. 5).

Fig. 5. Schematic diagram of specimen clamping

The test data uses the bending moment of failure as the index of bending bearing capacity. The higher the bending moment of failure, the higher the bending bearing capacity of the node. The bending moment of failure can be calculated by Eq. 1,

$$M = P \cdot L \tag{1}$$

where M is the bending moment of failure (N·m), P is the yield limit load (N), and L is the distance from the loading point to the base point (m).

One-Way ANOVA

ANOVA can be used to analyze experimental data that involves quantitative measurements. The SPSS software one-factor LSD ANOVA test (F-test) was used to evaluate the individual and comprehensive effects of the mechanical properties of mortise and tenon of different shapes. The F-test is used to check the amount of variation within each sample relative to the amount of variation between samples (α=0.05).

RESULTS and DISCUSSION

Ultimate Pull-Out Test

The failure forms of the five split mortises and tenons after the pull-out test are shown in Fig. 6. The specimens that were easier to observe were selected (the damage patterns of each type of tenon were shown). Table 3 shows the results of the ultimate pull-out test for different split mortises and tenons. The comparison chart of the maximum load of the five split mortises and tenons based on the test data is shown in Fig. 7.

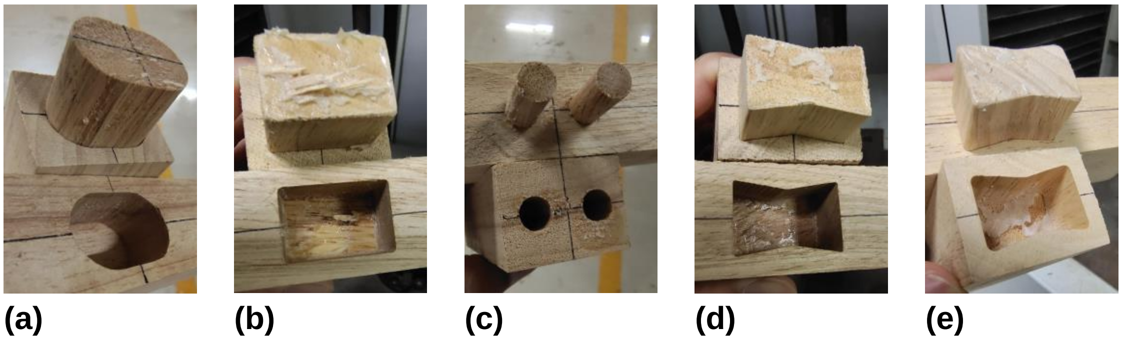

Fig. 6. Forms of destruction of oval mortise (a), right angle mortise (b), round rod mortise (c), double-dovetail joint (d) and rounded double-dovetail joint (d)

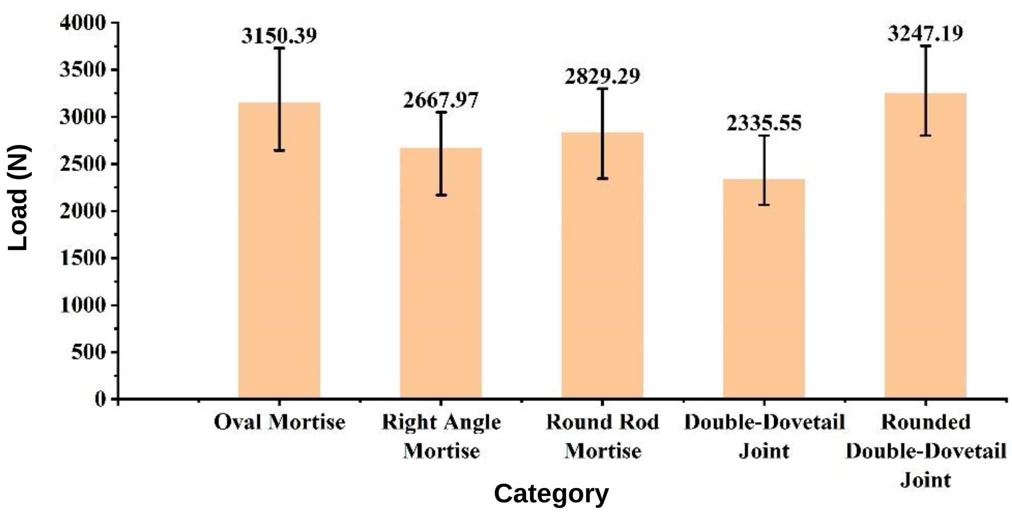

Fig. 7. Comparison of ultimate pullout resistance

Table 3. Ultimate Pullout Resistance of Each Group of Specimens (unit N)

Specimen Number	Oval Mortise	Right Angle Mortise	Round Rod Mortise	Double-Dovetail Joint	Rounded Double-Dovetail Joint
1	3050	2290	2510	2250	3370
2	2640	3000	2540	2380	3750
3	3230	2170	3350	2070	2800
4	3730	2900	2960	2410	3460
5	3560	2650	3300	2120	3070
6	2760	3050	2960	2800	3110
7	3340	2700	2670	2210	3320
8	2880	2590	2340	2450	3110
Average value	3150	2670	2830	2340	3250
Standard deviation	361	298.1	349.5	218.1	271.0
Coefficient	0.11	0.11	0.12	0.09	0.08
Positive deviation	581	381	471	468	506
Negative deviation	507	499	486	270	444

As shown in Table 4, the results of LSD analysis of different mortises and tenons showed that P<0.05 when F was 10.318, indicating that there was a significant difference between the five mortises and tenons. The results of the test have reference and analysis value.

Table 4. ANOVA Results for the Pullout Test

Source of Variation	SS	Df	MS	F	P
Category	4369139.551	4	1092284.888	10.318	< 0.001
Error	2964190.344	28	105863.941		
Total	8067052.780	39			

According to Table 3 and Fig. 7, it can be concluded that the order of average size of the maximum load of each group was rounded double-dovetail joint > oval mortise > round rod mortise > right angle mortise > double-dovetail joint. Firstly, these findings mean that the rounded double-dovetail joint can meet the national standard and has superior pull-out resistance in split mortise and tenon. Secondly, it is demonstrated that the traditional double-dovetail joint does not have good pull-out resistance and cannot be directly used in the connection of T-shaped members. However, after rounding the corners, the ultimate pull-out force of rounded double-dovetail joint is 39% higher than that of rounded double-dovetail joint.

The fibers of all five split mortises and tenons were destroyed (Fig. 6), and a moderate amount of glue application could be observed. After the split mortises and tenons were machined, their dimensions were measured. The measurements showed that the dimensional errors of the elliptical mortise and the round double-dovetail joint were minimized to -0.05 to 0 mm within a reasonable range of error. The actual fit clearance of the round rod mortise was the largest, mostly -0 to -0.1 mm. Right angle mortise and double-dovetail joint had a fit clearance of 0 to 0.1 mm, which is an interference fit. It should be influenced by the processing method. In the actual measurements, it was found that the dimensions of the pointed structure were generally larger than those of the rounded structure by 0 to 0.1 mm, and this difference could not be modified after subsequent modifications to the machining program and equipment. This resulted in increased assembly difficulty because the tenons were sharp-edged and the mortises were rounded.

It was also found that due to the difference in fit clearance caused by machining, the round rod mortise had a larger gap and the adhesive was more likely to be extruded, which resulted in more adhesive being retained in the sidewalls and less in the bottom of the tenon. Right angle mortise and the double-dovetail joint were found to have the tightest fit. Most of the adhesive was extruded into the bottom end of the mortise, with almost no adhesive on the side walls. The bottom ends of the right angled mortises have the most adhesive, which resulted in the most severe shear damage to their wood fibers. Oval mortise and rounded double-dovetail joint exhibited the most even distribution of adhesive. The amount of adhesive at the bottom of the rounded double-dovetail joint was less than that of the double-dovetail head, which suggests that the rounded double-dovetail tenon had a tighter fit.

Based on the data in Tables 2 and 3, when the corner ends of the mortises and tenons are rounded, the bonding area is larger (15.8% larger for rounded double-dovetail joint than double-dovetail joint), and the bonding strength is higher, which affects the overall mechanical properties of the structure (Erdil 2005; Custódio *et al.* 2009).

According to Tankut and Chen, when the mortise and tenon profile has a concave shape, the mortise wraps around the tenon better (Tankut and Tankut 2005; Chen *et al.* 2016). According to Fig. 8, two peaks are first found in all five curves. Joining Fig. 6 for analysis, the curves drop significantly after the first peak, indicating that it is the failure of the factor that plays a major role in the strength of the mortise and tenon. At this time it is the failure of the adhesive. The subsequent peaks occur because of a combination of friction and stress, but as the tenon is pulled out more, there is less friction and stress. In Fig. 8, it is also found that the curves of the double-dovetail joint and rounded double-dovetail joint exhibited a relatively smooth curve before reaching the maximum peak. This is due to their special profile shape, as the adhesive breaks down gradually and unevenly, the tenon does not remain completely vertical to be pulled out, and the tenon is tilted to make the mortise and tenon tighter, which results in more friction and stress compared to the other split mortises and tenons.

The coefficient of variation can represent the mechanical stability of the structure to some extent (Hu *et al.* 2020), and it can be concluded that the order of pullout stability was rounded double-dovetail joint > double-dovetail joint > right angle mortise = elliptical mortise > round rod mortise.

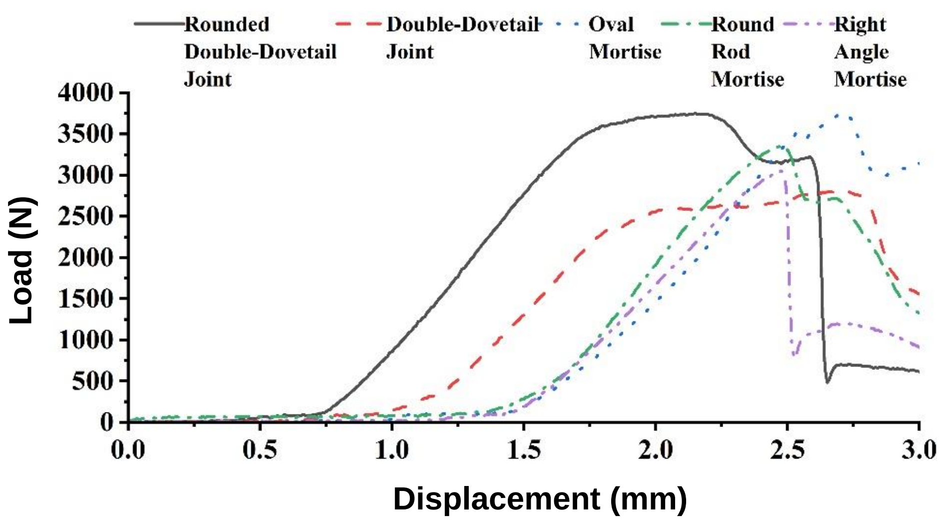

Fig. 8. Comparison of ultimate pullout resistance

Table 5. Bending Resistance of Specimen in Each Group (unit N)

Specimen Number	Oval Mortise	Right Angle Mortise	Round Rod Mortise	Double-Dovetail Joint	Rounded Double-Dovetail Joint
1	659.38	434.38	600.00	628.13	587.81
2	618.75	475.94	581.25	562.50	628.13
3	503.13	500.00	493.75	475.00	568.75
4	693.75	553.13	550.00	568.75	575.00
5	612.50	496.88	425.00	546.88	645.00
6	600.00	470.00	509.38	590.63	688.44
7	571.56	519.06	390.63	575.00	602.50

8	665.31	445.63	530.00	603.75	658.75
Average	615.55	486.88	510.00	568.83	619.30
Standard Deviation	56.29	36.33	67.93	42.68	40.10
Coefficient	0.09	0.07	0.13	0.08	0.06
Positive Deviation	78.20	66.25	70.00	59.30	69.14
Negative Deviation	112.42	52.50	119.38	93.83	44.30

Bending Strength Test

The failure forms of the five split mortises and tenons after the bending test are shown in Fig. 9.

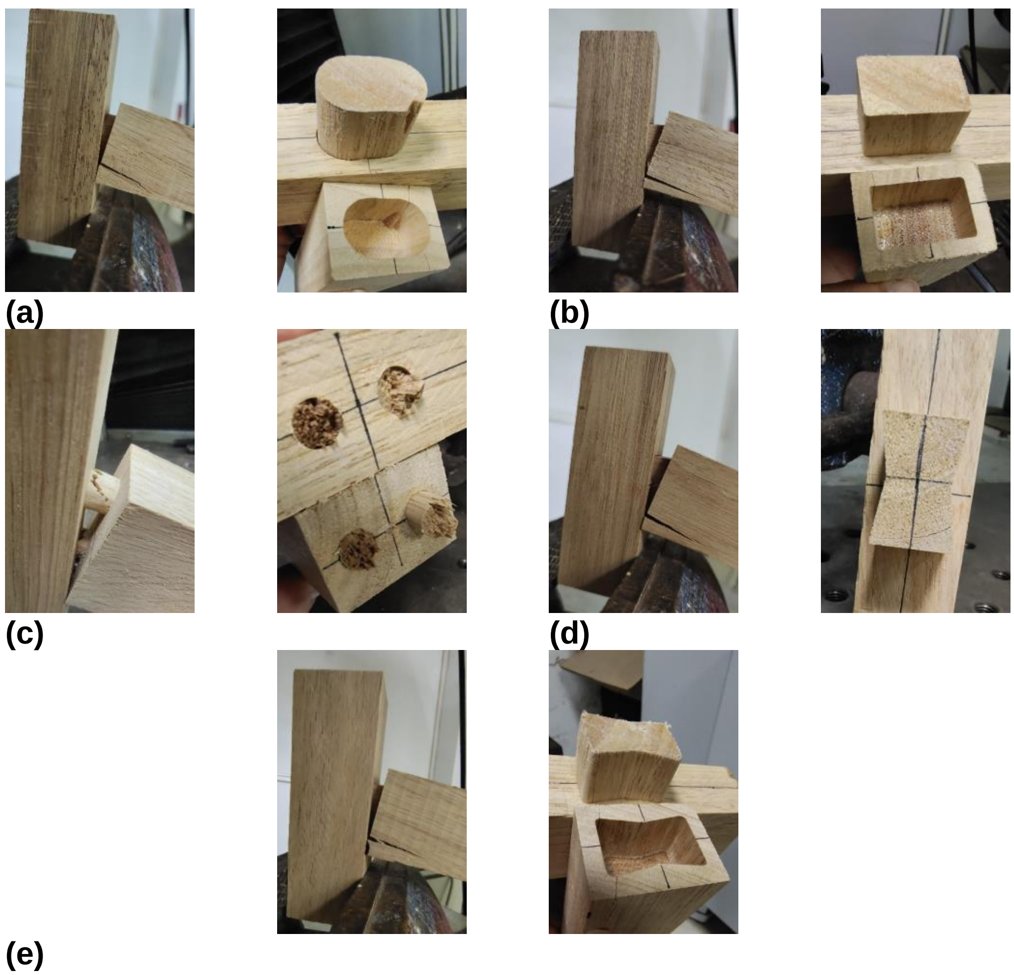

Fig. 9. Forms of destruction of oval mortise (a), right angle mortise (b), round rod mortise (c), double-dovetail joint (d) and rounded double-dovetail joint (e)

Table 6. Bending Moment of Specimen in Each Group (unit N·m)

Specimen Number	Oval mortise	Right Angle Mortise	Round Rod Mortise	Double-Dovetail Joint	Rounded Double-Dovetail Joint
1	593.44	390.94	540.00	565.32	529.03
2	556.88	428.34	523.13	506.25	565.32
3	452.82	450.00	444.38	427.50	511.88
4	624.38	497.82	495.00	511.88	517.50
5	551.25	447.19	382.50	492.19	580.50
6	540.00	423.00	458.44	531.57	619.59
7	514.41	467.16	351.56	517.50	542.25
8	598.78	401.06	477.00	543.38	592.88
Average	553.99	438.19	459.00	511.95	557.37
Standard Deviation	50.66	32.70	61.14	38.42	36.09
Coefficient	0.09	0.07	0.13	0.08	0.06

The specimens that were easier to observe were selected (the damage patterns of each type of tenon were shown). Table 5 shows the results of the five split mortises and tenons bending strength tests. Table 6 shows the bending moments calculated from Table 5. The comparison chart of the maximum load of the five split mortises and tenons based on the test data is shown in Fig. 7.

Fig. 10. Comparison of ultimate pull-out resistance

The LSD analysis of different mortises and tenons yielded a F of 11.352, corresponding to a $P<0.05$, indicating significant differences between the five mortises and tenons. The results of the test have reference and analysis value (Fig. 6).

Table 7. ANOVA Results for the Bending Strength Test

Source of Variation	SS	Df	MS	F	P
Category	116211.207	4	29052.802	11.352	< 0.001
Error	71659.743	28	2559.277		
Total	216474.586	39			

From Fig. 10 and Table 5, it can be concluded that the magnitude order of the bending resistance of the five split mortises and tenons was rounded double-dovetail joint > elliptical mortise > double-dovetail joint > round rod mortise > right angle mortise, the bending bearing capacity of rounded double-dovetail joint is 8.9% higher than that of double-dovetail joint.

The distribution of adhesive in right-angled mortise was not uniform (Fig. 9), which was attributed to machining clearance errors. Except for the round rod mortise, the mortise of the transverse members of the split mortises and tenons all showed cracking along the grain direction of the wood (Fig. 9). The tenon did not pull out of the vertical member, nor did it show significant tilting and bending deformation due to downward stress. The lack of deformation of the lower end of the mortise of the vertical member due to stress indicates that the bonding was good. This also indicates that the mortise shoulder strength was less than the bond strength and tenon strength. For T-shaped members, the mortise shoulder strength has a greater effect on the structural strength. The mortise shoulder thickness should be studied separately as an influencing factor in subsequent tests. The effect of dimensional errors due to machining on the bonding effect was attenuated in the bending test as compared to the ultimate pull-out test.

The round rod mortise was completely broken. The tenons of the oval tenon and double-dovetail joint showed cracking. Large pieces of wood shavings came off the tenon, and the lower end of the tenon of the double-dovetail joint was cracked. The tenons of the right-angle mortise and round double-dovetail joint showed no cracking, but a small amount of wood shavings were dislodged (Fig. 9). This indicates that the round rod mortise was the least strong, and the right angle mortise and round double-dovetail joint were the strongest. The shedding of wood chips shows that the adhesive had good bonding strength, which is also related to the nature of the wood itself. The cracking of the tenon in the double dovetail joint is due to its special profile shape and to the fact that the machining results in the corner of the tenon is an interference fit with the mortise, which is squeezed more tightly. As the pressure increases, the lower half of the tenon of a double dovetail tenon is gripped tightly by the mortise while being stressed downward by the mortise, and the upper half of the tenon is stressed upward by the mortise. The upward and downward tearing forces on the tenon from the mortise cause the tenon to crack more easily. Although the tenon of the rounded double-dovetail joint was subjected to the same two stresses from the top and bottom of the mortise, the fit clearance of the rounded double-dovetail joint was relatively larger and the tenon was squeezed less by the mortise, so the bottom half of the tenon did not crack. Chen's study mentioned that the clearance in the width direction of the dovetail mortise profile had a more significant effect on the bending properties, while the clearance in the length direction had the least effect on the bending properties (Chen *et al.* 2016), which also gives a basis for the fact that round double-dovetail joint is less susceptible to damage. The relationship between the strengths of adhesive strength, tenon shoulder strength, and wood strength is also the reason for the difference in damage forms.

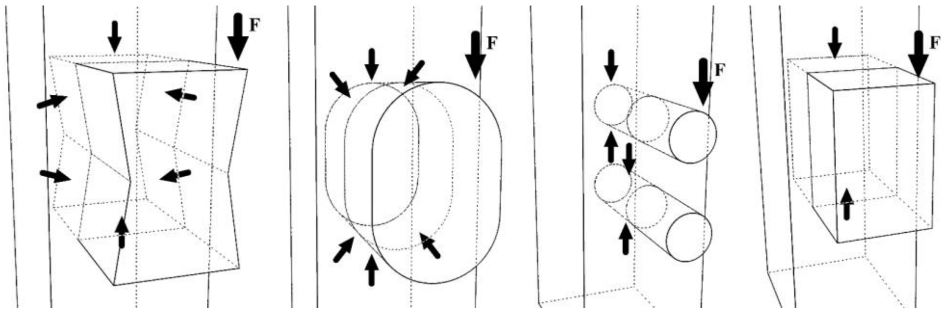

Fig. 11. The resistance provided by the split mortise and tenon groove to the mortise

The rounded double-dovetail joint and double-dovetail joint have a special profile shape (Fig. 11), which causes more friction and resistance to the tenon during bending. The other split mortises and tenons receive more uniform resistance.

It is precisely because of the special shape of double-dovetail joint and rounded double-dovetail joint that it has better stability, which also makes the curve of these two split mortises and tenons appear unlike the other three kinds of split mortises and tenons, and immediately after the failure of the structure, a cliff-like descent curve is formed (Fig. 12). The curves of double-dovetail joint and rounded double-dovetail joint are smoother after reaching maximum load failure. Moreover, according to the data in Table 6, it can be concluded that the structure still maintained good stability after failure. The order of size of stability was rounded double-dovetail joint> oval mortise> double-dovetail joint> round rod mortise > right angle mortise.

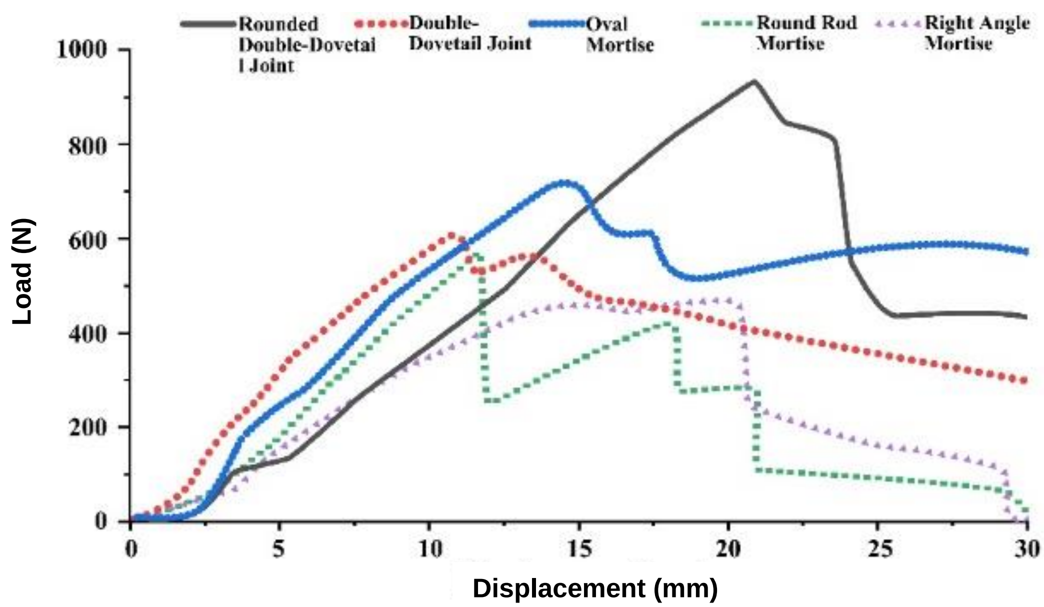

Fig. 12. Comparison of maximum bending resistance curves

CONCLUSIONS

1. The rounded treatment of the mortise and tenon caused it to be less prone to damage during testing, indicating its superior suitability for modern mechanized production methods. This modification not only streamlines the manufacturing process but also improves the overall durability of the joint.
2. The rounded double-dovetail joint exhibited exceptional strength and stability compared to other split mortises and tenons. Specifically, the ultimate pull-out force was 39% higher and the bending resistance capacity was 8.9% greater than the double-dovetail joint. These results demonstrated the potential for transforming surface-connected structures into point-connection configurations.
3. The concave profile of the rounded double-dovetail joint effectively wraps around the tenon, enhancing the fit and bonding effect. This design feature provides greater friction and resistance, delaying adhesive failure and improving the overall stability of the joint. However, it is noted that this tight fit may increase the susceptibility of the tenon to cracking; therefore, using a harder material for the tenon could mitigate this issue.
4. The successful application of the rubberwood rounded double-dovetail joint underscores its excellent mechanical properties. Future research should delve deeper into the effect of tenon shoulder thickness on the mechanical performance of this structure. Additionally, characterization analysis and finite element simulations will provide further insights into the stress distribution and failure mechanisms within the joint, enabling more optimized designs.
5. The round rod mortise is only used as a type of split mortise and tenon in comparison to other split mortises and tenons. In practice, it is used in a different area than other split mortises and tenons. The round rod mortise is often used in areas where less force is applied. It is a very practical, simple, more mechanical, and modular construction.

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