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The Effects of Joint Forms (Shape) and Dimensions on the Strengths of Mortise and Tenon Joints

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Abstract: Until recently, detailing of joints was largely a matter of tradition, based on trial and error methods. However, in the engineering design of furniture, it is necessary for designers to create joints with a specified strength. This study was undertaken accordingly, to obtain the strength of round tenon/round mortise, rectangular tenon/rectangular mortise and rectangular tenon/round mortise joints assembled under nominally identical conditions with different end configurations. In addition, each end configuration was compared at rail widths, each with 2 widths of tenon. The results showed that rectangular end mortise and tenons are about 15% stronger than both round end mortise and tenons and rectangular end tenons fitting into round end mortise joints. Meanwhile, joint geometry has a significant effect on the strength of those particular joints. As tenon width and length were increased, the strength of the joint was correspondingly improved. The type of mortise and tenon end has an appreciable effect on the breaking strength of the joints as rectangular end mortise and tenons are stronger than round end mortise and tenon joints; however, this does not limit the use of round end mortise and tenon joints in chair construction. It may actually be advantageous to use round end tenon and mortise joints for the front leg/side rail joint in a chair frame as the internal stresses may be more uniformly distributed over the rounded ends of the mortise, thus reducing the risk of splitting the leg member. The third type of construction, with a square end tenon fitting into a round end mortise, was, however, less satisfactory.

Key Words: Mortise and tenon joints, furniture, chair frame

Lambalı-Zıvanalı Birleştirme Direnci Üzerine Birleştirme Şekil ve Boyutunun Etkisi

Özet: Yakın zamana kadar birleştirmeler ile ilgili detaylar çoğunlukla deneme yanılma metotlarına dayalı geleneksel bir kapsamda değerlendiriliyordu. Günümüzde mobilya mühendislik tasarımında önceden belirlenmiş dirençte birleştirmelerin sağlanması gerekli görülmektedir. Bu bakımdan, çalışmada nominal olarak aynı şartlarda ve farklı biçimlerde yuvarlatılmış lamba-zıvana, dikdörtgen lamba-zıvana, dikdörtgen zıvanalı/yuvarlatılmış lambalı birleştirmelerin direnç değerleri araştırılmıştır. Ayrıca, her uç biçimi farklı kayıt genişliklerinde ve iki zıvana genişliğinde karşılaştırılmıştır. Sonuçlar dikdörtgen zıvanalı birleştirmelerin hem yuvarlatılmış zıvanalı hem de dikdörtgen zıvanalı/yuvarlatılmış lambalı birleştirmelerden yaklaşık % 15 daha dirençli olduğunu göstermiştir. Ayrıca; birleştirme geometrisi birleştirmelerin direnci üzerinde önemli derecede etkili çıkmıştır. Zıvana genişliği ve uzunluğu arttıkça birleştirmelerin direnci iyileşmiştir. Lambalı zıvanalı birleştirmelerde uç formlarının birleştirme direnci üzerinde fark edilir derecede etkili olduğu görülmüştür. Örneğin, dikdörtgen lambalı zıvanalı birleştirmeler yuvarlatılmış lambalı zıvanalı birleştirmelerden daha dirençli bulunmuştur. Fakat bu durum yuvarlatılmış lambalı zıvanalı birleştirmelerin sandalye konstrüksiyonlarında kullanımını kısıtlamaz, bilakis yuvarlatılmış lambalı zıvanalı birleştirmeler iç gerilmeleri yuvarlatılmış zıvanalara daha yeknesak dağıtarak ayak elemanlarındaki çatlama riskini düşürürler ve bundan dolayı sandalye iskeletlerinde ön ayak/yan kayıt bağlantılarında kullanılabilirler. Ancak üçüncü tip birleştirme şekli olan dikdörtgen zıvanalı/yuvarlatılmış lambalı birleştirmeler sandalye konstrüksiyonları için tatminkâr bulunmamıştır.

Anahtar Sözcükler: Lamba-zıvanalı birleştirmeler, mobilya, sandalye iskeleti

Introduction

Mortise and tenon joints have been widely used for centuries and, despite the increasing use of dowel joints, they are still favored for many types of construction, especially for building chair frames (Alexander, 1994). Örs et al. (1998) compared the mechanical performance of traditional joints (dowel and mortise and tenon joints) with alternative joints (minifix and multifix) for furniture frame construction. They concluded that alternative joints performed better than the traditional joints under static loading. Haviarova et al. (2001a, 2001b) designed and tested school desks and chairs for developing and

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underdeveloped countries and they used round mortise and tenon joints for the construction. Their results showed that round mortise and tenon joints were efficient load carriers and highly resistant to cycling loading. Later Tankut et al. (2003) designed and tested bookshelf frames using round mortise and tenon joints. Their results indicated that this kind of joint provided high rigidity for bookshelf frame construction. Mortise and tenon joints have also been used for wooden building construction. Traditionally, rectangular mortise and tenon construction has been used; however, Eckelman et al. (2002) demonstrated that round mortise and tenon joints can be used by utilizing salvage material from small diameter tree stems.

Both mortises and tenons used in chair frames may be machined with either rectangular cut or rounded ends cut or with a combination of rectangular end tenons fitting into round end mortises (Figure 1). Generally, the type of mortise and tenon joint used in a particular factory is determined primarily by the machines available at the time. Very little consideration is given to the strengths of these types of joints because, apart from practical experience, information on the effect of constructional variables on the strength of mortise and tenon joints is limited. To remedy this lack of information, the experiment described herein compared the strength of round tenon/round mortise, rectangular tenon/rectangular mortise and rectangular tenon/round mortise joints assembled under nominally identical conditions. In addition, these 3 different end configurations were compared at rail widths, each with 2 widths of tenon.

Materials and Methods

Rectangular end mortises were cut with a mortising machine with an orbital tool action. Round end mortises, on the other hand, were cut on a standard router using hand feed between end stops. In particular, the round end tenons were machined on a router and the rectangular end tenons were cut on a tenoner.

In order to avoid confusion, the terms used throughout this study to describe the 3 main dimensions of the mortises and tenons are shown in Figure 2. The use of these particular terms is justified by their common use in the woodworking industry.

A "T" joint, with a symmetrical shouldered tenon (Figure 2), was selected as the basic test piece for this experiment and for the other experiments described in this study to correspond to the back leg/side rail joint in a typical chair frame. Both the 3 x 3 cm leg sections and the 5.5 x 2.5 cm and 7.5 x 2.5 cm rail sections were cut from straight grain beech wood (*Fagus orientalis* L.) free from defects and conditioned to 12% moisture content.

A factorial design was used for the experiment so that the strength of joints with the 3 different end configurations could be compared at rail widths, each with 2 widths of tenon, as follows:

3 cm width tenon on 5.5 cm width rail

5 cm width tenon on 5.5 cm width rail

5 cm width tenon on 7.5 cm width rail

6.5 cm width tenon on 7.5 cm width rail

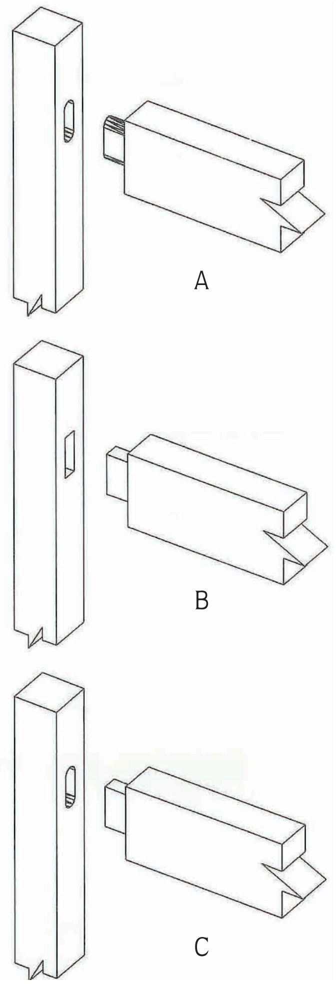

Figure 1. Joints used to determine the effects of rectangular cut and rounded ends. A: Round end tenon, round end mortise. B: Rectangular end tenon, rectangular end mortise. C: Rectangular end tenon, round end mortise.

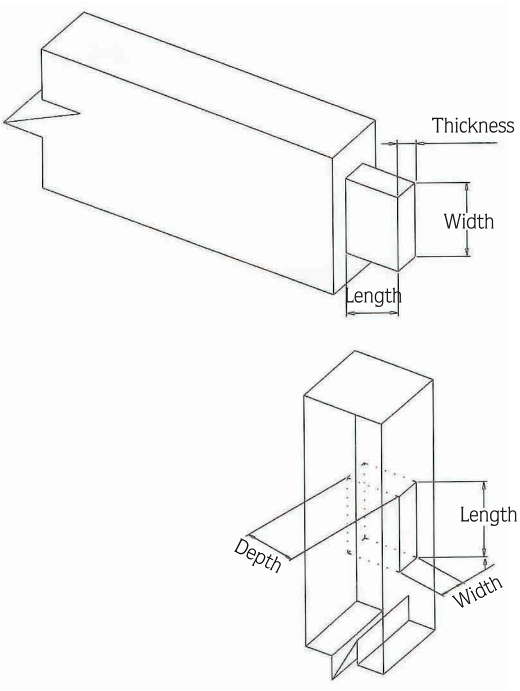

Figure 2. Nomenclature of mortise and tenon dimensions.

In addition to these factors, levels of clearance between the mortise length and the tenon width were chosen to give a good fit with a 0.005 cm glue line and a loose fit with a 0.025 cm glue line in this dimension.

The clearance on each face of the nominal 1 cm thick tenon was approximately 0.005 cm and the clearance between the nominal 2 cm length of the tenon and the bottom of the hole was approximately 0.025 cm for all joints. The clearances for this study were obtained from Eckelman (1991).

Allowing for variations in joint design and allowing 4 replicate joints for each design, the experiment was planned with 3 x 4 x 2 x 4 = 96 test pieces. In fact, only 80 test pieces were assembled with half of the rectangular tenon/round mortise joints omitted because the 0.5 cm gap between the rectangular end of the tenon and the round end mortise would swamp any effects due to a slight change in the clearance on this dimension.

The machined parts were stored at 22 ºC and 65% RH for between 3 and 14 days before assembly (FPL, 1999). Polyvinyl acetate (PVAc) glue was used for the assembly of the joints used in this study. The glue was applied both to the mortise and to the tenon to ensure complete coverage so that any variations in strength could be attributed to the geometrical construction of the joint rather than to erratic assembly conditions. After gluing, each joint was clamped up with just enough pressure to bring the rail shoulder into contact with the face of the mortise for not more than 1 min while the excess glue was removed. The joint was then taken from the clamp and conditioned for 14 days at 22 $^{?}$C and 65% RH before testing to destruction on a universal testing machine. For this test, the machine was fitted with a cast aluminum alloy angle plate to support the vertical leg member of the joint while the horizontal rail member was loaded by means of a stirrup attached to the machine crosshead, which was raised 4 mm min^{-1} during the test (Eckelman, 1970; Eckelman et al., 2004). The position of the joint during the test is shown diagrammatically in Figure 3.

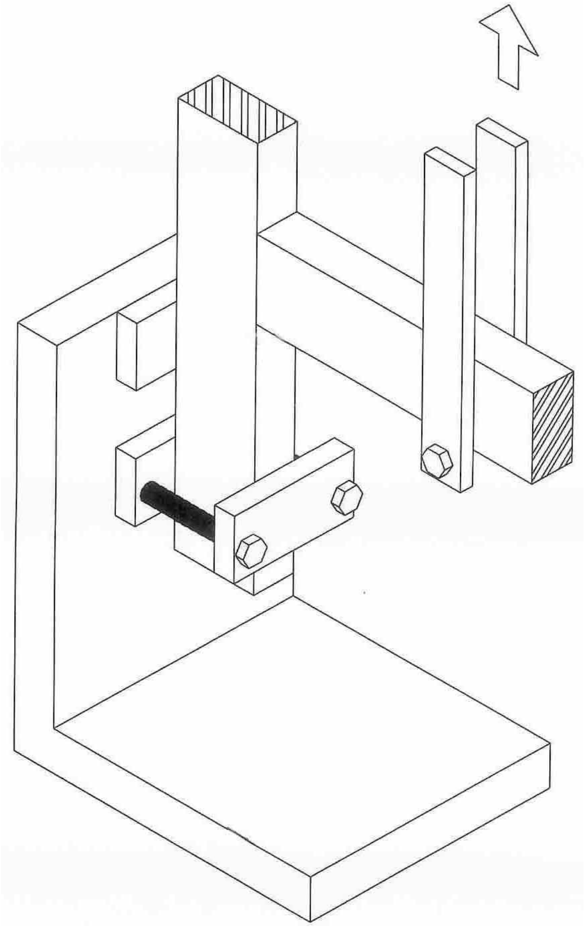

Figure 3. General configuration of the test setup used in the study.

The breaking strength of the joint is calculated as the product of breaking load and the distance between the point of application of the load and the face of the joint (Eckelman, 1991). The breaking strength is, in fact, the bending moment required to break the joint and it is expressed in units of Nt.cm (Eckelman, 1971).

In this study the moment arm (L = 20 cm) was measured from the point of load application to the face of the joints. Breaking strength or bending moment capacity, f, was calculated as

$f = F \times L$ Nt.cm

where

F = applied load (Nt.).

Results and Discussion

The mean breaking strengths of all joints are given in Table 1. The results for the round tenon/round mortise and rectangular tenon/rectangular mortise joints were analyzed statistically to isolate the effects due to joint dimensions, the type of machining of the joint ends and clearance between the ends of the mortise and tenon (Table 2). The rectangular tenon/round mortise results were excluded from the analysis because, for reasons already described, only half of the joints of this particular type were assembled.

Of the 3 factors considered in this experiment, both the shape of the ends of the mortises and tenons and the widths of the rails and tenons had highly significant effects on maximum bending moment of the joints, whereas the clearance between the width of the tenon and the length of the mortise had a negligible effect. Thus, the individual results for joints that are tight fitting and loose fitting in this dimension were combined into a single mean for each type of joint in Table 3.

The increased joint breaking strength resulting from an increase in tenon width and from an increase in rail width is obvious and was confirmed by the results obtained from analysis of variance in Table 2. The breaking strength of a joint is determined partly by the bond area, on the 2 faces of the tenon where the glue is stressed in shear when the joint is loaded in bending, and partly by distance between the center line of the rail and fulcrum of the joint, which, in this particular test piece, lies approximately along the line where the top edge of the rail meets the leg. It follows that an increase in rail width, which increases this distance, will increase bending strength, and an increase in tenon width resulting in an increased bond area will have a similar beneficial effect on the strength of the joints. In this instance, the 3 types of joints assembled with 5 cm tenons on the end of 7.5 cm rails were approximately 14% stronger than similar joints assembled with 5 cm tenons on 5.5 cm rails. For a

Table 1. Mean breaking strengths of rectangular end and round end mortise and tenon joints.

Rail width (cm)	5.5				7.5			
Tenon width (cm)	3		5		5		6,5	
Glue line fit (each end)	Tight	Loose	Tight	Loose	Tight	Loose	Tight	Loose
Type of joint	Mean breaking strength ± SD (Nt.cm)							
Round tenon, round mortise	17,300±1433	17,190 ±1479	21,770±810	21,540±1109	26,350±2229	24,640±2039	29,220±3032	29,340±2163
Rectangular tenon, rectangular mortise	20,170±1181	18,680±1516	26,360±3532	26,130±4119	30,370±5403	28,650±3208	36,440±3121	33,120±2357
Rectangular tenon, round mortise	15,930±1507	-	22,347±810	-	24,410±3647	-	30,250±2525	-

Table 2. Analysis of variance (ANOVA) results.

Source of Variance	Sum of Square	df	Mean Square	F Ratio	Level of Significance
Between dimensions	55,959	3	18,653	90.5	***
Between types	9110	1	9110	44	***
Between clearances	653	1	653	3.2	NS
Dimensions x types	859	3	286	1.4	NS
Dimensions x clearances	229	3	76	_	NS
Types x clearances	240	1	240	1.2	NS
Dimensions x types x clearances	229	3	76	_	NS
Residual	9700	48	202		
Total	76,979	63			

NS Not significant
*** Highly significant with probability less than 0.001

given width rail, a 1.5 cm increase in tenon width increased the bending strength of the joints by approximately 25%. Furthermore, the highest bending strength was obtained in the joints that had a combination of 7.5 cm rail width and 6.5 cm tenon width.

As already stated, changes in the shape of the ends of the mortises and tenons had a significant effect on the strength of the joints. Table 3 shows that the mean breaking strength of all round tenon/round mortise joints was approximately 15% lower than the mean breaking strength of corresponding rectangular tenon/rectangular mortise joints. In addition, joints assembled with rectangular tenons in round mortises were approximately 15% weaker than those assembled with rectangular tenons of similar dimensions in rectangular mortises. Meanwhile, the large semi-cylindrical gap between the rectangular tenon and round mortise is filled with glue, and therefore the strength of this type of joint does not result from the good mechanical interlocking of the parts but mainly from the excess use of the glue itself. Thus, rectangular tenon/round mortise joints should not be used for the construction of chairs.

Eckelman (2003) stated that 2 dowel pins, and mortise and tenon joints are commonly used to join a seat rail to a back post in a chair. In his study, he concluded

Table 3. Mean breaking strengths of rectangular end and round end mortise and tenon joints, excluding end clearance effect.

Rail width (cm)	5.5		7.5		
Tenon width (cm)	3	5	5	6,5	Mean all sizes
Type of joint	Mean breaking strength ± SD (Nt.cm)				
Round tenon, round mortise	17,300±1350	21,430±908	25,550±2144	29,330±2439	23,403
Rectangular tenon, rectangular mortise	19,360±1514	26,240±3555	29,680±4260	34,720±3107	27,500
Rectangular tenon, round mortise	15,930±1507	22,347±810	24,410±3647	30,250±2525	23,233
Mean of all end shapes	17,530	23,337	26,547	31,433	

that when the dowel diameter and depth of insertion increase, the joint strength will increase as well. The effects due to changes in dowel spacing are similar to those due to changes in tenon widths. The data obtained from Eckelman's dowel joint study compared with our findings, which showed that mortise and tenon joints are approximately 40% stronger than dowel joints assembled with 2 dowels, with the same rail widths, and with the tenon width the same as the dowel spacing. The difference is, however, not so great when a comparison is made between a tenon joint and a 3 dowel joint.

Eckelman (1980) provides a clear indication of the magnitudes of strength values that can be obtained from metal plate connectors used in furniture construction. When a comparison is made between the mortise and tenon joints in this study and metal plate connected joints from Eckelman's (1980) study, the metal plates are about 25% stronger than the mortise and tenon joints. Furthermore, the T-nut fastener reported by Eckelman (1998) is about 12% stronger than the mortise and tenon joints. However, the mortise and tenon joints are about 33% stronger than the glued corner block joint values obtained by Rabiej (1979).

Conclusion

From an engineering viewpoint, the most important conclusion that can be drawn from this study is that properly made rectangular tenon/rectangular mortise joints are approximately 15% and 30% stronger than round tenon/round mortise and rectangular tenon/round mortise joints, respectively. However, these results do not limit the use of round tenon/round mortise joints for the front leg/side rail joint in a chair frame, since they developed enough bending strength for construction. On the other hand, in the case of rectangular tenon/round mortise joints, bending strength does not develop from the good mechanical interlocking of the parts but mainly from the excess use of the glue itself. Thus, rectangular tenon/round mortise joints should not be used for the construction of chairs.

In this experiment, the widths of the rails and tenons had highly significant effects, whereas the clearance between the width of the tenon and the length of the mortise had a negligible effect on the bending strength of the joints. The highest bending strength was obtained in the joints that had a combination of 7.5 cm rail width and 6.5 cm tenon width.

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