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THE EFFECT OF GLUE AND GLUELINE THICKNESS ON THE STRENGTH OF MORTISE AND TENON JOINTS

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ABSTRACT

This study was carried out in order to determine the effects of glue, glueline thickness and moisture content on the strength of mortise and tenon joints. The polyvinyl acetate (PVAc), urea-formaldehyde (UF) and phenol resorcinol (PR) glues were used, combined with three different glueline thicknesses. At the same time the effect of the moisture content of the wood was investigated by using wood material conditioned to 8, 12, 15% moisture contents. The results of the experiment showed that the strength difference between tight fitting and loose fitting joints was 28% if phenol resorcinol (PR) glue was used, 11% with UF glue and negligible with PVA glue. The effect of the moisture content of the wood when the joints were assembled did not depend on the adhesive used. If 12% is taken as the standard moisture content, increasing it to 15% weakened joints by 15% and decreasing it to 8% strengthened them by 6%, irrespective of the adhesive. Test results indicate that strongest joints are obtained when a close tolerance is maintained between the tenon and mortise.

KEY WORDS: adhesives, mechanical properties, strength, wood, furniture joints

INTRODUCTION

Although rectangular mortise and tenon joints are commonly used for joining the back leg and the side rail of a chair frame construction, there is little information available that can be used to design the joints that characterize this construction. Previous studies have defined some of the factors that affect their strength. For example, the strongest joints are obtained when a close tolerance is maintained between the tenon and mortise (Milham 1949, Dupont and Werner 1963). Optimum joint strength was obtained when glue was applied to both the tenon and sides of the mortise (Dupont and Werner 1963). Flexibility and bending strength of rectangular mortise tenon joints was investigated by Hill and Eckelman (1973). They concluded that bending strength of mortise and tenon joints is the function of wood species, and mortise and tenon dimensions. Ors and Efe (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. (2001) designed and tested school desks and chairs for developing and 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 (Haviarova et al. 2001a, 2001b).

Later, Tankut et al. 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 (Tankut et al. 2003). Furthermore, Smardzewski et al. (2004) developed a numerical model of a frame construction using dowel and tenon and mortise joints. They determined values of stresses in joints of the loaded furniture piece and identify places with the greatest effort (Smardzewski et al. 2004). More recently, Tankut et al. found out 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 (Tankut and Tankut 2005).

These studies are of particular value in that they provide fundamental insights into the characteristics of mortise and tenon joints. Because of the limits of the studies, however, they do not provide a complete picture of the effects of the construction parameters on the strength values of these joints.

As we enter into an era of engineered furniture, it will be necessary for designers to create joints with specified strengths. This study was undertaken, accordingly, to obtain estimates of the strength of mortise and tenon joints over a range of glueline thicknesses, moisture contents and adhesives.

MATERIAL AND METHODS

In this study, the joints were assembled with three types of glue, using wood with three levels of moisture content. The glueline thickness on each face of the tenon was varied in three steps. With 4 replicates for each combination of the main factors the experiment contained 3 x 3 x 3 x 4 = 108 joints. All the parts required for the "T" joints used in this experiment were cut from straight grain beech wood (*Fagus orientalis* L.) free from defects and conditioned to a nominal 12% moisture content.

The 45 x 3 x 3 cm leg members and 35 x 5.5 x 2.5 cm rail members were then divided into three groups for further conditioning at 35, 65, and 85% RH corresponding to approximate equilibrium moisture contents of 8, 12 and 15% in beech. The changes in moisture content produced small changes in the external dimensions of the members but, as the mortises and tenons were not machined until the wood moisture content had stabilized at the new level, the initial fit of the joints was not affected.

The rectangular end mortises were cut with a mortising machine with an orbital tool action. All mortises were cut to the same nominal dimensions, namely, length 4 cm, depth 2 cm and width 1 cm. The rectangular end tenons, which were cut on a tenoner, had the following nominal dimensions: width 3.975 cm, length 1.9875 cm and thickness varying in three steps between 0.975 and 0.998 cm. The clearance at the bottom of the mortise and at each end of the mortise was, therefore, 0.0125 cm nominal, in each joint. 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 Fig. 1. The use of these particular terms is justified by their common use in the woodworking industry.

The clearance between the face of the tenon and the mortise was set at three levels to give glueline thickness corresponding to a tight fit, a sliding fit, and a loose fit allowing some movement of the tenon in the mortise. To achieve these qualitative levels of fit in this particular dimension, the tenons were cut 0-0.0050 in, 0.0076-0.0125 in and 0.0152-0.0250 cm under size, respectively.

The dry fit of each joint was checked before assembly, and found to correspond to the classification of fit described above. After machining, the three sets of parts were returned to 35, 65 and 85% RH conditions, respectively, to maintain the required moisture contents right up to the time of assembly.

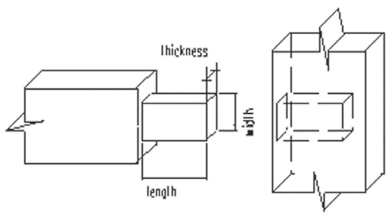

Fig. 1: Nomenclature of mortise and tenon dimensions

Each set of conditioned parts was further subdivided into three groups for assembly with phenol resorcinol (PR), polyvinyl acetate (PVAc) and urea-formaldehyde (UF) glues. Adhesives were applied liberally to all faces of the tenon and to the sides and bottom of the mortise. The glues were applied both to the tenons and mortises 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 moisture content of the joint members has been included as a variable in this experiment although, to limit the size of the experiment, it has been assumed that both components of a joint have similar moisture contents at the time of assembly.

After assembly, the joints were returned to their respective storage conditions at 35, 65 and 85% RH for one day so that the glue could set or cure before there were any significant changes in the moisture contents of the parts. Finally, all joints were conditioned at 65% RH for one month to allow sufficient time for the moisture content of the joints assembled from dry and damp wood to return to an equilibrium level of approximately 12%.

"T" joints (Fig. 2) were tested in a universal testing machine fitted with a cast aluminum alloy angle plate to support the leg section while the rail section was loaded by means of a stirrup attached to the machine cross head which was raised ½ in/min during the test. The load which produced a sudden discontinuity in the load/deflection curve, corresponding to the failure of the glue bond on the faces of the tenon, was noted and used to calculate the breaking strength of the joint. The position of the joint during the test is shown diagrammatically in Fig. 3.

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 2003). 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

$$f = F \times L \text{ Nt.cm}$$

where
F = applied load (Nt.).

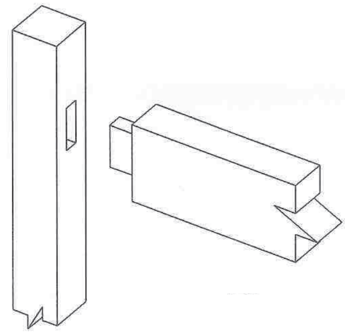

Fig. 2: Rectangular end tenon, rectangular end mortise

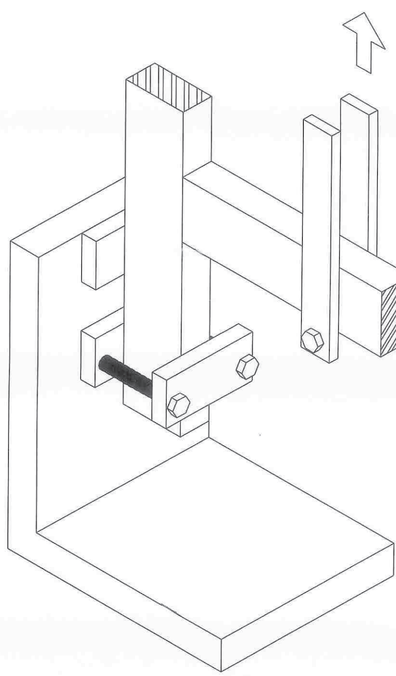

Fig. 3: General configuration of the test setup used in the study

RESULTS AND DISCUSSION

The data obtained in this study provide needed information concerning the bending strength of mortise and tenon joints. The mean breaking strengths of the joints assembled with different glues and glue thicknesses are given in Tab. 1. When a standard the analysis of variance (ANOVA) method was applied to the data, the three factors, types of glue, moisture content of the wood and glueline thickness on the face of the tenon had highly significant effects, but that the glue/glueline thickness effect was the only interaction of any significance (Tab. 2).

Tab. 1: Mean breaking strengths of mortise and tenon joints assembled with different glues and glueline thicknesses

Type of glue	Wood moisture content %	***Mean thickness of glueline cm***		
		0.0012	0.0063	0.0095
		Mean breaking strength ± SD Nt.cm		
PR	8	23,063 ±860	17,620 ±2059	17,047 ±1646
	12	20,915 ±2012	16,331 ±2219	14,898 ±3406
	15	16,760 ±1507	11,747 ±1516	11,269 ±1751
PVA	8	25,642 ±1711	27,791 ±1900	25,500 ±1516
	12	25,212 ±1929	24,066 ±1687	25,642 ±2579
	15	20,771 ±1711	23,207 ±2012	22,920 ±936
UF	8	26,358 ±1479	25,500 ±1782	25,500 ±740
	12	27,361 ±1646	25,069 ±1181	22,204 ±2163
	15	22,204 ±1711	21,344 ±1950	20,055 ±1812

Tab. 2: Analysis of variance (ANOVA) results

Source of Variance	Sum of Square	df	Mean Square	F Ratio	Level of Significance
Between glues	48,602	2	24,307	212	***
Between gluelines	4343	2	2166	19	***
Between moisture	15735	2	7873	69	***
Glues x glueline	5925	4	1478	13	***
Glue x moisture	596	4	149	1.3	NS
Glueline x moisture	435	4	115	1	NS
Glue x glueline x moisture	1089	8	138	1.2	NS
Residual	9374	81	115		
Total	86,099	107			

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

Because of the strong interaction between the type of glue and the fit of the joint, the main effects due to these two factors must be considered in conjunction with each other using the combined mean breaking strengths quoted in Tab. 3, ignoring the effects due to changes in moisture content of the wood. The mean strength of loose fitting joints assembled with phenol resorcinol (PR) glue was approximately 28% lower than the mean strength of well fitting joints assembled with the same glue. Furthermore, there was an 11% drop in the strength of loose fitting joints assembled with UF glue but the slight increase in strength of loose fitting joints assembled with PVA glue was not statistically significant.

Tab. 3: Mean breaking strengths of mortise and tenon joints showing glue/glueline thickness interaction effect, ignoring the effects due to changes in moisture content of the wood

Glue	Mean thickness of glueline cm 0.0012 Mean breaking strength ± SD Nt.cm	 0.0063	 0.0095
PR	20,246 ±3065	15,232 ±3171	14,690 ±3264
PVA	23,875 ±2811	25,021 ±2680	24,687 ±2094
UF	25,308 ±2752	23,971 ±2466	22,586 ±2791

Apart from glueline thickness, which had the greatest effect on joints assembled with the phenol resorcinol (PR) glue, the results show that joints assembled with PVA and UF glues had similar strengths but the performance of the phenol resorcinol (PR) glue was inferior to that of the other two glues for all conditions of assembly. Although all three glues were selected as representative of their particular type, the experimental results refer to tests on one sample of each type and they can not, therefore, be extended to include all glues of each type.

As PVA glues are based on thermoplastic materials, joints assembled with this type of adhesive may slide apart when stressed for long periods, due to creep or cold flow within the glueline. These effects can be considerably reduced by ensuring that the joints are well fitting, particularly on the faces of the tenon.

The relative flexibility of the PVA glue presumably allows some relative movement of the parts of the joint so that the internal stresses resulting from the applied load are distributed more uniformly between the glueline on the faces of the tenon and the points of contact between the wood of the mortise and tenon. In other words, the mechanical interlock between the mortise and tenon probably contributes more to the strength of joints assembled with PVA glue than it does in joints assembled with the less flexible UF and PR glues. With these latter glues, shear failure within the glueline on the face of the tenon may occur before the compression strength of the wood at the points of contact becomes effective. In addition, only one glue, representative of each type, has been tested, so that some caution is required in the extrapolation of the results to cover other makes of glue.

Previous studies (Eckelman 2003, Willard 1982) showed that the type of glue and the thickness of the glueline have the greatest effect on the strength of the dowel joints. With each of the glues used in investigations, the strongest joints were those assembled with well fitting dowels. There were, however, appreciable differences between the performance of the different types of glues used in conjuction with loose fitting dowels as some glues apparently has better gap filling properties than others.

Previous studies (Eckelman 2003, Willard 1982) also showed that apart from glue and glueline thickness, the other factor which had an appreciable effect on the strength of dowel joints was the moisture content of the dowel. A stronger joint is produced with dry dowels as they absorb water from the glue and swell in the hole, thus compensating for the shrinkage within the setting glue. Conversely, damp dowels introduce internal stresses in the glueline as they try to shrink away from the hole walls, reducing the effective strength of the joint. Similar effects occur when the component parts of mortise and tenon joints change their moisture contents as the relatively large difference between the movement of wood in the longitudinal and transverse directions will introduce internal stresses in the glueline which may detract from the effective strength of the joint.

Considering the effect due to moisture content, the combined mean results for all joints assembled from wood at each moisture content, ignoring all other variables, were shown in Tab. 4. Taking joints assembled with wood conditioned at 65% RH with an equilibrium moisture content of approximately 12% as the standard, these mean results show that a 6% increase in joint strength has been achieved by the use of wood conditioned at 35% RH. On the other hand, joints assembled from wood conditioned at 85% RH were approximately 15% weaker than the standard joints. As the leg and rail members were selected at random from the pile of machined parts, a difference in the growth ring direction in the parts conditioned at high and low humidity can not account for difference in performance. Presumably, the swelling of both members as the low moisture content joints took up water in coming to equilibrium at 65% RH had a less damaging effect on the glueline than the shrinkage as the joints dried out from 15% moisture content.

Tab. 4: The effect of moisture content on the mean breaking strength of mortise and tenon joints, ignoring all other variables

Relative humidity %	Equilibrium moisture content %	Mean breaking strength ± SD Nt.cm
35	8	23,780 ±3938
65	12	22,411 ±4538
85	15	19,138 ±4521

These results were obtained from joints assembled with both parts at the same nominal moisture content but it is probable that a greater drop in strength would occur if the tenon had a substantially higher moisture content than the mortise member as the greater shrinkage of the tenon would place a greater tensile stress across the gluelines between the faces of the tenon and the mortise.

CONCLUSIONS AND SUMMARY

These experiments revealed the construction methods that should be followed to produce the strongest rectangular mortise and tenon joint. Also, the range of variables examined in this study provides valuable data concerning the strength of particular sizes of mortise and tenon joints. Thus, providing information on the effect of such variables as the type of glue, glueline thickness and moisture content of the wood, manufacturers can select the conditions of assembly which are most likely to produce consistently strong joints on the production line.

One aspect of joint design that has been considered in this study is the degree of fit between the tenon and mortise. This factor may be considered as partly geometrical in that the level of fit is determined by the sizes of the machined parts, and partly related to the assembly techniques, as the sizes of the machined parts may change between the time of machining and the time of assembly as a result of moisture content changes. Even small gaps up to 0.0063 cm on the faces of the tenons had an appreciable effect on the strength of the joints assembled with the PR and UF glues, but gaps up to 0.0095 cm had no effect on the strength of joints assembled with the PVA glue.

While the machining of the joint can be planned for any thickness of glueline desired, variations from planned dimensions will alter the thickness of the glueline. Extreme accuracy of machining is difficult to maintain. A tight-fit between the tenon and mortise is essential to the construction of robust durable joints. Namely, the closeness of fit between tenons and mortises is quite important since the tighter the joint the stiffer the structure.

The results have shown that changes in the moisture content of the wood occurring after assembly, can have an appreciable effect on the breaking strength of the joints. For instance, joints assembled from wood at 15% equilibrium moisture content and subsequently conditioned to 12% equilibrium moisture content were 15% weaker than similar joints assembled from wood at 12% equilibrium moisture content. Presumably, greater effects could occur if both parts of the joint were at different moisture contents at the time of assembly as the differential movement as they come to a common equilibrium could be greater, thus increasing the internal stresses on the gluelines.

The results obtained from these experiments have demonstrated the effects of the different construction features and assembly conditions on the strength of mortise and tenon joints assembled under ideal laboratory conditions. The main difference between laboratory techniques and factory techniques is the efficiency of gluing and it must be emphasized that the selection of good quality materials, and the time spent in ensuring accuracy of fit of the parts will be wasted if the final gluing is not carried out carefully to ensure a complete glue film in the joint.

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