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# Moment capacity of traditional and alternative T-type end-to-side-grain furniture joints

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**Abstract**

The bending moment capacity of traditional and alternative T-type end-to-side-grain joints constructed of Oriental beech (*Fagus orientalis Lipsky*), European oak (*Quercus borealis Lipsky*), and Scotch pine (*Pinus sylvestris Lipsky*) were investigated. Two-pin dowel and mortise-and-tenon joints assembled with polyvinyl acetate adhesive were considered as traditional adhesive-based joints, and minifix plus dowel and screw joints were considered alternative non-adhesive-based joints. Experimental results indicated traditional adhesive-based mortise-and-tenon joints yielded the highest bending moment capacity among the four types of tested joints, and that minifix plus dowel joints had the lowest bending moment capacity. Screw joints could produce higher bending moment capacities than traditional glued dowel joints. The bending moment capacity of minifix plus dowel joints was less sensitive to wood species change than mortise-and-tenon joints, dowel joints, and screw joints.

The load-bearing capacity and stiffness of joints in furniture construction will normally determine the furniture's strength and rigidity. Unfortunately, the seeming propensity of furniture frames toward failure has led to the belief that new, stronger joints are needed. However, within certain limits, joints are inherently neither weak nor strong. In fact, their strength is directly related to the loads that they must carry (Eckelman 1968).

Dowel joints are the most popular method of joining members together in wood furniture frame construction. In a typical furniture frame, dowel joints may be subjected to axial, shear, torsional, and bending forces. Bending forces are usually of most concern, however, because their magnitude may easily exceed the maximum theoretical resistance of a particular joint configuration (Eckelman 1979).

The moment capacities of a number of dowel joints and mortise-and-tenon joints have been investigated. A study of the bending moment capacity of T-type two-pin dowel joints (Eckelman 1971) indicated that the ultimate bending moment capacity ($M$) of the joint could be estimated by means of the expression $M = F \times d$, where $F$ = the ultimate direct withdrawal force of a single dowel and $d$ = the distance between resultant compression and tension forces vectors. It was pointed out (Eckelman 1970) that the ratio of design strength to ultimate strength based on fatigue requirements also needs to be established. It was suggested that the "fatigue limit" may be as low as 1/6 of the ultimate static strength of the joint.

The bending moment capacity and moment-rotation characteristics of T-type two-pin dowel joints constructed of solid woods and wood composites have been investigated (Zhang et al. 2001).

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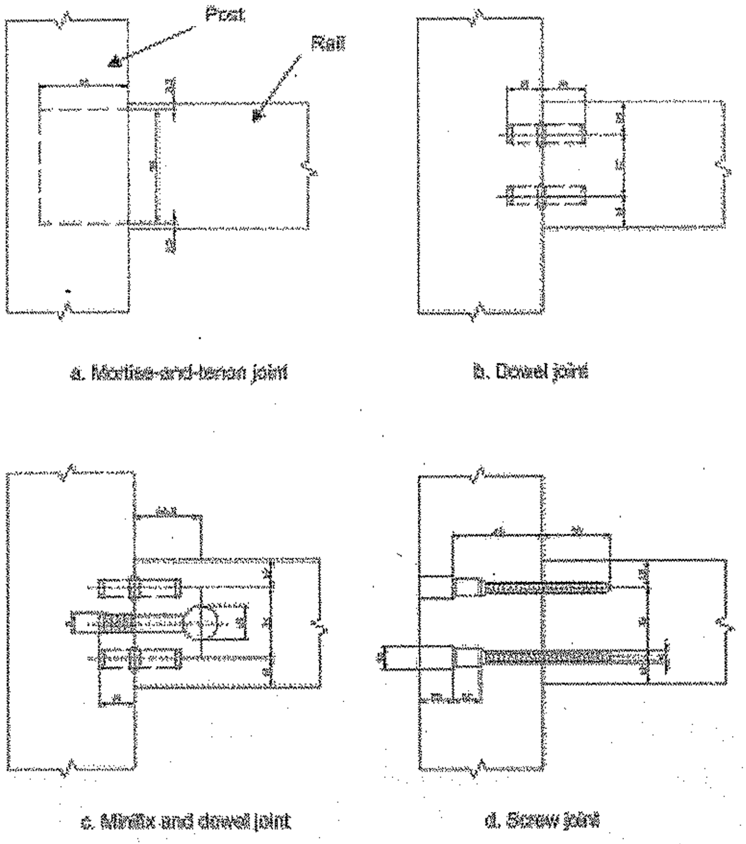


*Figure 1. — Diagram showing construction and dimensions of T-type joints.*

According to the test results, joints constructed of red oak and plywood had the highest bending moment resistance and the joints of particleboard had the weakest bending resistance. No significant differences on bending resistance between joints constructed of oak and plywood were observed. The ultimate bending moment capacity of the joint could be estimated by means of the formula $M = (d_1/2 + w/3 + e/3) \times T$, where $T$ = the ultimate direct withdrawal force of a single dowel, $w$ = the width of the rail, $e$ = the distance from the rail centerline to the neutral axis, and $d_1$ = the spacing between two dowels.

Mortise-and-tenon joints have been common for centuries. Despite the increasing use of dowel joints, they are still favored for many types of construction. Early versions of mortise-and-tenon joints were often constructed without adhesives. But today, these joints are most commonly assembled with adhesives. Adhesives develop needed strength because of the relatively short length of the tenon. Numerous variations of the basic joint exist, including the blind, barefaced, stub, keyed, pinned or pegged, open or slip, and haunched mortise-and-tenon joints (Feirer 1963).

Bending moment capacity comparisons of mortise-and-tenon and dowel joints (Milham 1949) demonstrated that the strongest joints are obtained when a close tolerance is maintained between the tenon and mortise; furthermore, the shoulder on the tenon has a pronounced effect on the bending moment capacity of the joint.

Dupont (1963) showed that optimum joint moment capacity is obtained when glue is applied both to the tenon and to the sides of the mortise. Also, wood moisture contents of 7 to 9 percent are most appropriate for fabricating these joints.

Sparkes (1968) concluded that square-end mortise-and-tenons or round-end mortise-and-tenons were equally effective but that a square-end tenon fitted into a round-end mortise produced joints that were 15 percent weaker than either of the other two. As tenon width and length increased, the moment capacity of the joint improved correspondingly.

Hill and Eckelman (1973) researched the effect of tenon length, tenon width, wood species, and different adhesives on the bending moment capacity of the joint. They demonstrated that a mortise-and-tenon joint becomes stiffer as either tenon length or tenon width is increased, and also that a shoulder on the rail member of a mortise-and-tenon joint contributes to the stiffness of the joint.

Ors and Altinok (1999) emphasized that the durability of a chair is not related to the strength of its structural members but is related to the loads carried by the mortise and tenons. This is according to the diagonal compression test result of standard-size chairs constructed of beech and pine.

Non-adhesive-based joints are common in furniture construction because they allow the furniture to be shipped in the knockdown condition and assembled on the site, which greatly reduces shipping costs. This is an important consideration both in the case of domestic and export furniture. In spite of their widespread use, limited studies have been conducted on the load-bearing capacity and stiffness of joints.

Eckelman (1978) researched the bending moment capacity and stiffness of dowel-nuts (or barrel-nuts) with through-bolt joints constructed of five wood species. Test results indicated that through-bolts with dowel-nuts formed high moment resistance joints, but they are less rigid than adhesive-based joints.

Hayashi and Eckelman (1986) researched the factors that govern the strength and stiffness of corner block with anchor bolt joints and developed estimates of the strength of this joint that could be used in the rational design of tables.

Ors and Efe (1998) investigated the mechanical properties of furniture fasteners used in furniture frame construction and demonstrated that joints constructed with minifix and multifix type fasteners are better than the traditional joint techniques.

Ozen and Efe (1995) investigated the strength properties of screw-nuts as a fastener element in the furniture industry. The length of the screw-nut linearly affected its holding strength. The ratio of pilot-hole diameter to screw diameter, screw thread pace, and screw thread height also affected the holding strength of the screw-nut.

Limited information is available on moment capacity performance comparisons among traditional adhesive-based joints such as mortise-and-tenon joints and dowel joints, and alternative non-adhesive-based joint types such as minifix plus dowel joints and screw joints. This study compares the bending moment capacities of traditional and alternative T-type end-to-side-grain furniture joints constructed with three different wood species that are common for furniture frame stock materials.

## Materials and methods

The four types of T-type end-to-side-grain joint constructions (two traditional and two alternative joints) studied are shown in **Figure 1**. In general, each joint specimen consisted of two members: a post and a rail. Both members of each joint were constructed of the same type of material and measured 150 mm long by 55 mm wide by 22 mm thick. The members were cut from quartersawn lumber. The traditional joints were the mortise-and-tenon joint (**Fig. 1a**) and the two-pin dowel joint (**Fig. 1b**). Alternative joints were the minifix plus dowel joint (**Fig. 1c**) and the screw joint (**Fig. 1d**). Joint specimens were constructed of Oriental beech (*Fagus orientalis* Lipsky), European oak (*Quercus borealis* Lipsky) and Scotch pine (*Pinus sylvestris* Lipsky). A two-way 4 x 3 factorial experiment with 10 observations per cell was conducted to evaluate wood species (three levels) and joint type (four levels) effects on the moment capacity of the T-type joints. Thus, a total of 120 specimens were tested.

For the mortise-and-tenon joint (**Fig. 1a**), tenons measured 40 mm long by 50 mm wide by 8 mm thick. Mortises were machined into the posts with a hollow chisel bit mounted in a drill press. The tenons were machined on a table saw. All cuts were parallel to the sides of the rail and perpendicular to the surface of the table saw. Adhesive was liberally applied to all faces of the tenon and to the sides and bottom of the mortise.

Cleanly machined, 35-mm-long and 8-mm-diameter, multi-groove beech dowels with no loose or torn surface fibers were selected for the dowel joints (**Fig. 1b**). Depth of embedment of the dowel in the rail was 20 mm, and 15 mm in the post. The distance between the centerlines of the two dowels was 27 mm. Dowel-hole clearances were not measured, but all dowels fitted snugly in the holes. A liberal amount of adhesive was spread over the sides of the holes and all faces of the dowels.

For the minifix plus dowel joint (**Fig. 1c**), the rail end was attached to the post side with two multi-groove beech dowels and a minifix. The distance between the centerlines of the two dowels was 31 mm. The minifix connector was placed at the longitudinal centerline of the rail. No glue was applied to the dowels.

To connect the screw joint members together, 5-mm diameter by 70-mm-long Philips flathead wood screws were used (**Fig. 1d**). The screw diameter was 7 mm and 5-mm-deep pilot holes were bored into the post side and end of the rail. The depth of embedment of the screws in the rail was 30 mm, whereas the depth of the pilot holes in the post was 15 mm. The distance between the centerlines of the two screws was 31 mm.

The adhesive-based joints were assembled with polyvinyl acetate adhesive with 65 percent solids content. They were allowed to cure for a minimum of 2 days before testing. Following assembly, all specimens were stored in a controlled climate room with condition set to produce an equilibrium moisture content condition of 8 percent in the wood.

All of the bending tests were carried out on a universal testing machine. A concentrated load was applied to the rail of each specimen at a point 140 mm from the front edge of the post, i.e., the moment arm was 140 mm. The loading speed was 2 mm/min. Loading was continued until breakage or separation occurred in the specimens. The ultimate loads carried by joints were recorded in newtons (N). The ultimate loads were then converted to corresponding bending moment values by means of the expression, $M = F \times L$, where $M$ = bending moment (N·m); $F$ = ultimate applied force (N); $L$ = bending arm (m).

## Experimental models

A full linear model (Model [**1**]) for the two-way factorial experiment was first considered to test the influence of joint type and wood species on the ultimate bending moment capacity of the T-type end-to-side-grain joints. The form of Model [1] is:

$$M_{ijk} = \mu + T_i + S_j + (T \times S)_{ij} + \varepsilon_{ijk} \quad [1]$$

where:

$M_{ijk}$ = ultimate bending moment capacity (N·m)

$\mu$ = population mean ultimate bending moment capacity for all joint type-wood species combinations (N·m)

$T_i$ = discrete variable representing effect of joint type

$S_j$ = discrete variable representing effect of wood species

$(T \times S)_{ij}$ = effect of interaction between two variables

$\varepsilon$ = random error term

$i$ = index for joint type, 1…4

$j$ = index for wood species, 1…3

$k$ = index for the replications, 1…10

Owing to the fact that the two-factor interaction term of the full model was found to be significant in the analysis of variance (ANOVA), the reduced model, Model [**1R**], was considered, namely:

$$M_{ijk} = \mu + (T \times S)_{ij} + \varepsilon_{ijk} \quad [1R]$$

## Results and discussion

The minimum, maximum, and mean ultimate bending moment capacities of the joints along with their coefficients of variation are summarized in **Table 1**. Average specific gravity values were 0.66, 0.69, and 0.52 for Oriental beech, European oak, and Scotch pine, respectively. Mortise-and-tenon joints failed with modes of glueline fracture, wood shear, and split mortises. Two-pin dowel joints failed with modes of glueline fracture, dowel surface shear (parallel to grain), and dowel fracture. Screw joints failed owing to withdrawal and bending of screws. For the minifix plus dowel joints, failure resulted from bending of bolts and the corresponding minifix part withdrawal from wood. In general, all joint failures occurred in 30 to 90 seconds. Adhesive-based specimens deflected faster than the non-adhesive types. Moment capacities of traditional

Table 1. — *Results of bending moment capacities of T-type end-to-side-grain joints tested for each combination of wood species by joint type.*

| Wood species and joint type | No. of tests | Minimum value | Maximum value | Mean value | Coefficients of variation |
|---|---|---|---|---|---|
| | | ---------- | (N·m) | ---------- | (%) |
| Scotch pine | | | | | |
| Mortise-and-tenon | 10 | 175 | 287 | 256 | 14 |
| Dowel joint | 10 | 77 | 105 | 93 | 8 |
| Minifix plus dowel | 10 | 35 | 70 | 49 | 32 |
| Screw joint | 10 | 77 | 182 | 109 | 30 |
| Oriental beech | | | | | |
| Mortise-and-tenon | 10 | 336 | 560 | 447 | 20 |
| Dowel joint | 10 | 112 | 154 | 133 | 9 |
| Minifix plus dowel | 10 | 49 | 84 | 66 | 17 |
| Screw joint | 10 | 224 | 336 | 294 | 14 |
| European oak | | | | | |
| Mortise-and-tenon | 10 | 203 | 399 | 302 | 21 |
| Dowel joint | 10 | 84 | 133 | 115 | 13 |
| Minifix plus dowel | 10 | 56 | 91 | 76 | 15 |
| Screw joint | 10 | 217 | 308 | 258 | 12 |

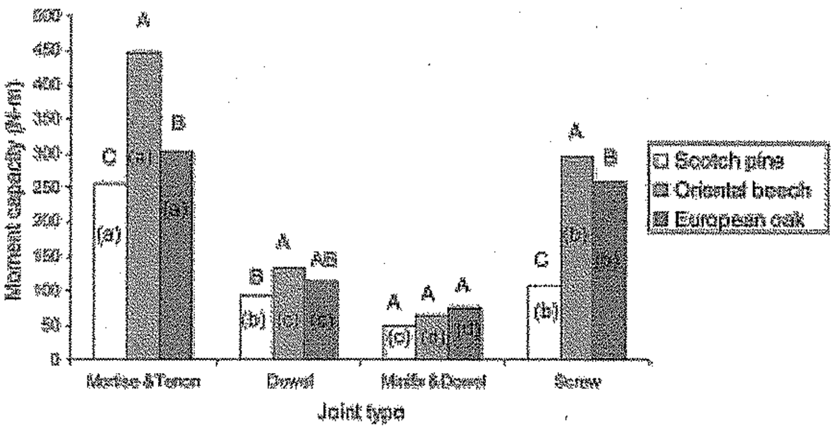


*Figure 2. — Mean comparisons of ultimate bending moment capacities of T-type joints. Capital letters show results within each of four joint types. Letters in parentheses show results within each of three wood species. Means with different letters are significantly different at the 5 percent significance level.*

joints sharply declined immediately after reaching their ultimate values, while moment capacities of alternative joints declined gradually instead of dropping sharply.

A two-way ANOVA general linear model procedure was performed for individual joint bending moment data with the full model (Model [1]) to analyze main effects and interaction factors on the mean of the ultimate bending moments. The ANOVA results indicated that the two-factor interaction was statistically significant at the 5 percent significance level. This interaction obscured examination of the main effects in the full model (Model [1]) because only factor combination could be considered. Therefore, the reduced model, Model [**1R**], which included the significant two-factor interaction term, was employed to explore the factors on the response variable "ultimate bending capacity."

**Figure 2** shows mean comparisons of ultimate bending moment capacities of tested T-type joints for joint type within each of the three wood species, and mean comparisons for wood species within each of the four joint types, considering the effect of joint type by wood species interaction. The results were based on one-way classifications created with 12 treatment combinations for each joint type by wood species. The protected least significant difference (LSD) multiple comparisons procedure at the 5 percent significance level was performed to determine the mean differences of those treatment combinations. The error mean square from the full model (Model [**1**]) factorial analysis was employed for all comparisons, i.e., the single LSD value of 34 N·m was calculated based on the error mean square of the full model.

Traditional glued mortise-and-tenon joints showed the highest bending moment capacity among the four types of joints tested within each wood species. Mechanical screw joints could produce higher bending moment capacities than traditional glued dowel joints for the size dowels used. Minifix plus dowel type joints showed the lowest moment capacity among joints evaluated.

The bending moment capacities of both mortise-and-tenon and screw joints were significantly affected by joint member wood species. The bending moment capacity of Oriental beech joints ranked the highest among three wood species for each type of mortise-and-tenon and screw joint, followed by the bending moment capacity of European oak joints and Scotch pine joints. These differences in moment capacities could be explained by differences in shear strength parallel to the grain of the wood of which the joints were constructed. Tests have shown (Hill and Eckelman 1973) a positive linear relationship exists between the bending moment capacity of mortise-and-tenon joints and the shear strength parallel to the grain of the wood in which the mortise is cut. Also, the ultimate withdrawal resistance of wood screws from the end grain of wood is positively proportional linearly to the shear strength of the wood parallel to the grain (Fairchild 1926, Cockrell 1933). In general, Oriental beech had the highest shear strength, followed by European oak and Scotch pine.

For two-pin dowel joints, Oriental beech joints showed significantly higher moment capacity than Scotch pine joints. Moment capacities of European oak joints fell between Oriental beech and Scotch pine joints. These indicated that the direct withdrawal force of single multi-groove beech dowels was affected by the wood species of the joints, i.e., the shear bond strength between dowels and joint members was affected by the wood species of the joint members. The moment capacity is governed by the withdrawal force of the dowel loaded in tension (Eckelman 1971, Zhang et al. 2001).

No significant differences in moment capacities were observed among minifix joints constructed of three wood species. This implies moment capacities of minifix joints were less sensitive to wood species changes than the other three types of joints. This could be due to relatively shallow minifix embedment in the post. This shallow embedment resulted in the moment capacity being less sensitive to wood shear strength changes.

## Conclusions

The bending moment capacity of adhesive-based and alternative non-adhesive T-type end-to-side-grain joints constructed of three wood species was investigated. Experimental results indicated traditional glued mortise-and-tenon joints yielded the highest bending moment capacity among mortise-and-tenon, two-pin dowel, minifix plus dowel, and screw joints. Minifix plus dowel joints had the lowest bending moment capacity among the joints evaluated. Mean comparisons showed that alternative screw joints could produce higher bending moment capacities than traditional glued two-pin dowel joints.

This study confirms the findings of other researchers (Fairchild 1926, Milham 1949, Sparkes 1968, Eckelman 1971, Hill and Eckelman 1973, Zhang et al. 2001) that the moment capacity of the joints was governed by different variables. For mortise-and-tenon and screw joints, the moment capacity was governed by the shear strength parallel to the grain of joint wood members. The bending moment of two-pin dowel joints was affected by the ultimate direct withdrawal strength of a single dowel, which is influenced by shear bond strength between dowels and joint members and shear strength parallel to the grain of wood dowels. The bending moment capacity of minifix plus dowel joints was less sensitive to wood member strength property change compared with the other three types of joints when the center minifix had 15-mm embedment depth in the joint post with the penetration direction perpendicular to the wood grain.

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