Effect of Tenon Size on Static Front to Back Loading Performance of Wooden Chairs in Comparison with Acceptable Design Loads

Halil Kılıç, Ali Kasal,* Tolga Kuşkun, Mehmet Acar, and Yusuf Ziya Erdil

The effects of tenon size were investigated relative to the front to back loading performance of Scots pine (*Pinus sylvestris* L.) chairs. Forty-five chair frames were constructed with mortise and tenon joints with 9 tenon sizes. Joints were assembled with a 65% solids polyvinyl acetate (PVAc) adhesive. The front to back loading performance of chairs was compared to the acceptable design load levels given in the American Library Association (ALA) specifications. Chair frames were structurally analyzed with the Finite Element Method (FEM) to obtain the moment acting on each joint under loading. The results indicated that a chair became stronger as either tenon width or length increased, but was most affected by its length. As a result of structural analyses, front leg to side rail and back leg to side rail joints carried approximately 73% of the total moment that was induced under the front to back loading. According to the comparison results with acceptable design loads, chairs constructed with 40 mm × 50 mm tenons could meet light service (domestic usage), while the chairs constructed with 50 mm × 50 mm tenons could meet medium service. The chairs constructed with other sizes could not meet any acceptable levels, and thus need reinforcement.

Keywords: Chair; Mortise and tenon joints; Front to back loading; Finite element method (FEM); American Library Association (ALA)

*Contact information: Department of Woodworking Industrial Engineering, Faculty of Technology, Muğla Sıtkı Koçman University, Muğla, Turkey; *Corresponding author: alikasal@mu.edu.tr*

INTRODUCTION

Chairs are used in a number of rooms in homes (living and dining rooms), in schools and offices (with desks), and in various other workplaces. Chairs are made of a wide variety of materials, such as wood, metal, plastic, and composites. Wooden chairs are used more often in homes. People generally prefer using wood chairs because they are natural, aesthetical, and lightweight compared to other materials. However, being lightweight brings some mechanical problems in terms of strength. In earlier research, many scientists have investigated these problems, focusing on the weakest part of chair construction, *i.e.*, joints.

There are many joint types for constructing/assembling furniture parts, and many of them are used in chair construction. The mortise and tenon is one of the common joint techniques and has been used for thousands of years by woodworkers around the world to join pieces of wood, mainly when the adjoining pieces connect at an angle of 90°. Moreover, archaeological research revealed the fabrication of an ancient joint dating back 7,000 years (Tegel *et al.* 2012).

In this study, the strength of chairs constructed with different sizes of mortise and tenon joints was investigated. The strength of the joints represents the strength of the entire system of a chair frame. Hence, the joints that are the most critical parts of the chair should have adequate strength. Acceptable design loads that a chair is expected to undertake should be set properly to develop a reliable system. However, design loads have never been developed for sofa frames or chairs. Hence, it is necessary to obtain estimates of such loads from other sources. Perhaps the best source of such information comes from the "GSA test method for upholstered sofas" (Eckelman and Erdil 2001) and "The use of performance tests and quality assurance programs in the selection of library chairs" (ALA 1982). Both specifications utilize a cyclic stepped increasing load method in which the strength and durability test is conducted by a certain number of cycles in every step, and the load is incrementally increased if a previous step is successfully completed, and the test continues until a failure occurs. Test type, loads, load increments, and acceptance levels were specified to give estimates to the performance of a product. A problem exists in using the loads specified in this method for static design purposes. Therefore, the relationship between cyclic load strength and static load strength, which is needed for design purposes, has not been clearly defined. However, previous testing experience has shown that cyclic load strength should not be assumed to be higher than 50% of the static load strength (Eckelman and Erdil 1999). Likos *et al.* (2013) investigated the effect of cross-sectional tenon geometry on static and cyclic load capacities of side chairs constructed with mortise and tenon joints. As a result, it was deduced that chairs with mortise and tenon joints constructed with round, rectangular, and diamond-shaped tenons had static load to cyclic passing load ratios of 56.5, 66.8, and 69.2, respectively. Furthermore, experimental results indicated that a useful relationship existed between the static and cyclic performance of round mortise and tenon joints, which may simplify the design process for a chair that must pass cyclic performance tests. Kuşkun (2013) investigated the tenon size effect on the strength of chair frame joints and the relation between the static and cyclic loading forms; and it was demonstrated that the cyclic performance of a chair is found to be equivalent to 56% of the static strength.

Early studies have shown that there are few factors that affect the strength of mortise and tenon joints. The study conducted by Ishii and Miyajima (1981) showed that there is linear relationship between the tenon length and tenon width (original article mentioned as "depth"; however, for the purpose of consistency the term "width" is preferred in this article) on bending moment capacity. Wilczyński and Warmbier (2003) researched the influence of joint dimensions on the bending strength and stiffness of mortise and tenon joints. The results showed that tenon length has much more effect compared to tenon width on the joint strength. In addition, the effect of tenon thickness was found to be minor. Oktaee *et al.* (2014) conducted a study to examine the effects of tenon geometry on the bending moment capacity of simple and hunched mortise and tenon joints under the action of both compression and tension loads. The most significant values were obtained from the joints constructed with 10-mm-thick tenons that were 37.5 mm wide and 30 mm long. Moreover, tenon length was found to have the greatest effect on joint capacity, whereas, tenon width was found to have a much smaller effect.

Comparative bending and fatigue strengths of rectangular mortise and tenon furniture joints made from oil palm (*Elaeis guineensis*) lumber against a few conventional furniture wood materials were evaluated. The results showed that the bending strength of the oil palm lumber joints were half the strength of the wooden joints. However, in terms of fatigue strength, joints made from oil palm lumber showed comparable performance with the other wood materials. The results also showed that the acceptable design stresses for rectangular mortise and tenon joints could be set at 20% of its bending strength (Rathanisgam *et al.* 2010).

Hajdarević and Martinović (2014) conducted a study that presents the numerical analysis of the effects of tenon length on the flexibility of mortise and tenon joints. The results indicate that a mortise and tenon joint becomes stiffer as the tenon length increases. In addition, results also revealed that the stiffness of joints in a frame had a considerable impact on the structure deflection. In a similar study that was conducted by Hajdarević and Busuladžić (2015), a stiffness analysis of a statically indeterminate wood-chair side-frame was performed with a 'linear elastic model' for orthotropic materials. The mathematical model was solved by a 'finite element method' and the matrix analysis of the structure was performed by a 'direct stiffness method'. The results indicated that the chair side frame becomes stiffer as the position of the stretcher is lowered and/or the stretcher cross-section is increased. A reasonable consistency was obtained between the numerical results and the direct stiffness method. In another study, a simple approach was developed for estimating the whole structure strength from the individual joint tests (Kasal *et al.* 2016).

A significant amount of chair frames manufactured in the Turkish furniture industry, particularly produced by small manufacturers, have been constructed of Scots pine (*Pinus sylvestris* L.) with mortise and tenon joints. However, there is little information available concerning the strength of chairs constructed of a softwood species. The rational design of chairs, to meet demanding service requirements, dictates that the design of the joints and members used in the construction of the chairs can be precisely determined as a function of the highest loads to be exerted in service.

The primary purpose of this study was to obtain practical information concerning the ultimate static front to back load performance of chairs constructed of Scots pine using different tenon sizes, and evaluate the performance of chairs against the acceptable design loads. Accordingly, the following questions were examined: How do tenon sizes (tenon width and tenon length) affect the ultimate static front to back loading performance of Scotch pine chairs? and could the ultimate static front to back loading performance of Scotch pine chairs meet the acceptable design load levels of the American Library Association (ALA) specifications?

EXPERIMENTAL

Experimental Design

This study incorporates the determination of static front to back loading performance of the chair frames, structural analyses of the chairs with the finite element method (FEM), and an evaluation of the strength values according to the acceptable design loads that were given in the ALA (ALA 1982) specifications. Overall, 45 chair frames (3 tenon widths, 3 tenon lengths, and 5 replications) in real size (1/1 scale) were constructed of Scots pine (*Pinus sylvestris* L.) with round edge mortise and tenon joints and subjected to static front to back loads.

A full linear model (Eq. 1) for the two-way factorial experiments was considered to determine the effects of tenon width and tenon length in back leg to side rail and front leg to side rail joints on static front to back loading performance of wood chairs. The form model is as follows,

$$F_{ijk} = \mu_1 + A_i + B_j + (AB)_{ij} + \varepsilon_{ijk} \quad (1)$$

where F_{ijk}, refers to static front to back loading performance (N) of chairs, μ_1 refers to population mean for the static front to back loading performance (N) for all tenon width-tenon length combinations, *A* refers to discrete variable representing the effect of tenon width, *B* refers to discrete variable representing the effect of tenon length, *(AB)* refers to the effect of the two-way interaction among the two variables, ε refers to random error term, *i* refers to index for tenon width 1,...,3, *j* refers to index for tenon length 1,...,3, and *k* refers to index for the replication, 1,...,5.

A two-way analysis of variance (MANOVA) general linear model procedure was performed for ultimate static front to back loading performance data of the chair frame to analyze the main effects and interaction on the mean of the ultimate static front to back loading performance. The least significant difference (LSD) multiple comparisons procedure at a 5% significance level was performed to determine the mean differences considering the tenon width, tenon length, and their two-way interaction that were statistically significant in the MANOVA results. The MSTAT-C software was utilized for the statistical analyses (MSTAT-C, Michigan State University, Version 1.0., 32 Bit, MI, USA).

Materials

All chair frames were constructed of Scots pine (*Pinus sylvestris* L.). Wood materials were obtained from commercial suppliers (Yucel Kerestecilik, Mugla, Turkey). The average density value was 0.45 gr/cm^3. Specimens were conditioned to and held at 12% moisture content (MC) before and during testing. Some physical and mechanical properties of the wood were evaluated in accordance with the procedures described in ASTM D143-94 (2000) and ASTM D 4442-92 (2001).

An amount of 65% solids content polyvinylacetate (PVAc) adhesive (Polisan, İstanbul, Turkey) was utilized for assembling the chair frames.

Preparation of chair frames and individual joint specimens

Chairs were constructed and tested in which all of the chairs were identical except for the tenon dimensions in the back leg to side rail and front leg to side rail joints. Stretcher to back leg and stretcher to front leg joints had the same tenon size (30 mm width, 30 mm length by 7 mm thick) for all chairs. Tenon size effect were studied for just front leg to side rail and back leg to side rail joints.

Conventional manufacturing techniques were utilized in the material preparation and assembly. Cross-sections of all members of the chair frames were the same, 21-mm thick and 60-mm wide except for the stretcher. The stretcher member was 21-mm thick and 30-mm wide.

For the back leg to side rail and front leg to side rail joints, the tenons measured 30 mm, 40 mm, and 50 mm long by 30 mm, 40 mm, and 50 mm wide by 7 mm (1/3 of the member thickness) thick. A mortising machine and tenoning machine (Dinçmak, Bursa, Turkey) were utilized for opening the mortises and cutting the tenons. A snug fit (average mortise–tenon clearance of 0.076 mm ± 0.025 mm) was obtained between the tenons and mortises. The adhesive was liberally applied to all surfaces of the tenons and mortises. Adhesive was spread over approximately at 150 gr/cm^2 ± 10 gr/cm^2. Pieces of wax paper were placed between the mortise and tenon to prevent any possibility of the members adhering from the end grain of the tenon member. A typical chair dimensions are shown in Fig. 1 and tenon configurations are given in Fig. 2.

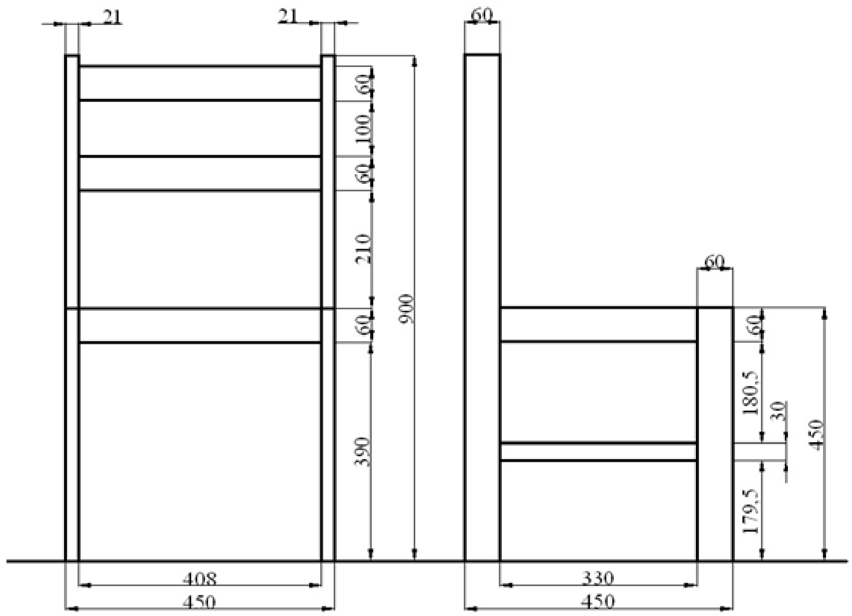


Fig. 1. Dimensions of the chair used in the tests (measurements in mm)

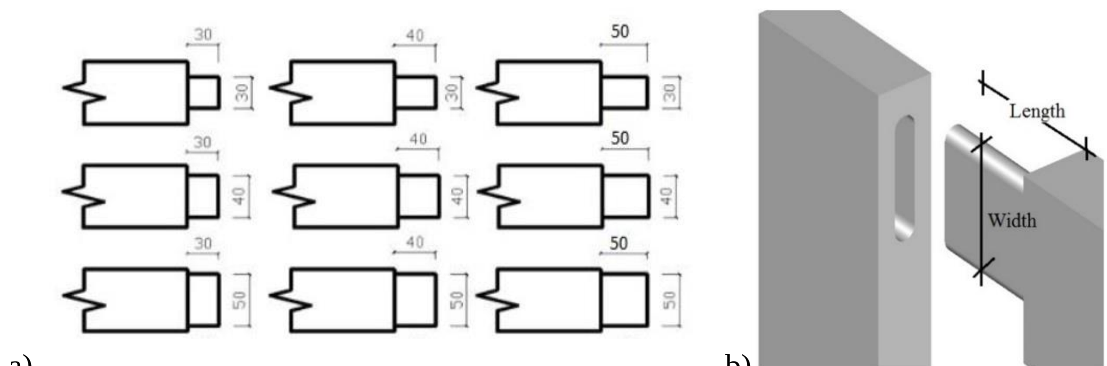


Fig. 2. Geometries of the various sizes of mortise and tenon joints (a) and detail of round edge (b) of the mortise and tenon joint; measurements in mm

First, the side frames were constructed. Then, the assembly of two side frames was provided by means of top, back, and front rails with two beech (*Fagus orientalis* L.) dowels measuring 8 mm in diameter and 35 mm in length. Dowels were placed to the center of the thickness of the members. The depth of the embedment of the dowels in the edge was 30 mm, and the depth of the embedment of the dowels in the face was 5 mm. The distance between the centerlines of the two dowels and screws was 32 mm. The mortises, tenons, dowels, and dowel holes were coated with an adhesive during the assembling process.

Not only chair frames were constructed but also 100 T-type individual joint specimens (90 representing the back leg to side rail joints and 10 representing the back or front leg to stretcher joints) and 90 L-type individual joint specimens for representing the front leg to side rail joints (3 tenon widths, 3 tenon lengths, and 10 replications for each) with cross-sections and tenon sizes identical to those used in the chair frames were prepared of the same wood species for obtaining the spring constant values for each size of mortise and tenon joints in order to treat the joints as semi-rigid connections in the structural analyses of chair frames and their moment rotation characteristics were determined. The T-type and L-type individual joint specimens are shown in Figs. 3a, b, and c.

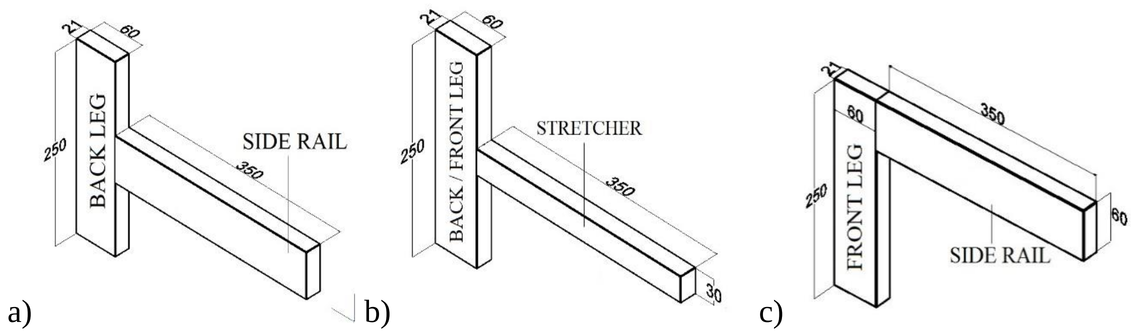


Fig. 3. T-type (a, b) and L-type (c) specimens; measurements in *mm*

Before testing, to eliminate moisture content variations, the joint specimens and chair frames were allowed to cure for at least one month after assembly in an environmentally controlled conditioning room that was set to produce an average equilibrium moisture content of 12%.

Methods

Static front to back loading tests of chairs and moment-rotation characteristics of joints

Static front to back loading tests of the chair frames were performed on a 50 kN capacity universal-testing machine (Mares, İstanbul, Turkey) in the mechanical test laboratory of Wood Science and Industrial Engineering Department of Muğla Sıtkı Koçman University with a 6 mm/min loading rate under the static loading. Chair frames were tested according to the principles of ALA specification by applying front to back loads that the chair was likely to be exposed to during service. Front to back loading tests of the chair frames were conducted using the test set up shown in Fig. 4.

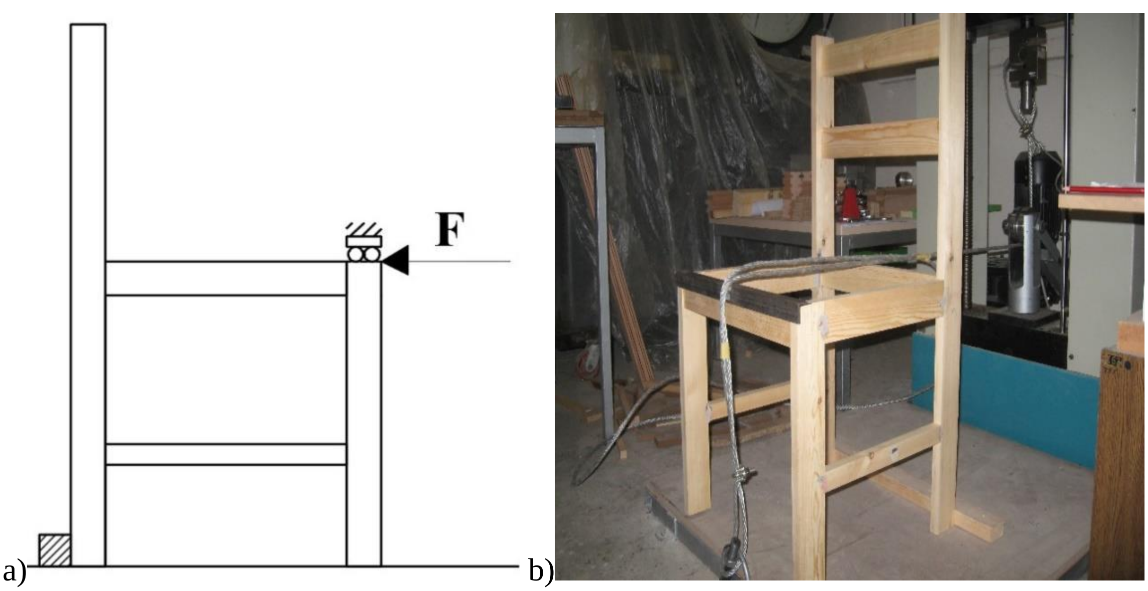


Fig. 4. Side view illustration of front to back loading of chair (a), and loading configurations of real chair tests (b)

Horizontal front to back loads were applied from the point that is 420 mm far from the supports. An L-shape steel angle was utilized for transferring the horizontal front to back loads to the two side frames directly. In the tests, reaction brackets were placed behind each of the back legs to prevent the chair from sliding backwards. A steel rope then passed over the seat from front to back and attached to the load head of the universal testing machine with a roller that was used to apply the horizontal loads to the chair. The other end of the steel rope was dropped over the front edge of the seat, allowed to hang vertically, and attached to the floor located directly below the front edge of the seat. This steel rope provided the reactive force required to keep the chair from overturning; it was placed in a perfectly vertical position and it was free to move slightly forward free of restraint. Loading was continued until the chairs suffered catastrophic failure. The ultimate failure loads were recorded in Newtons.

The moment rotation characteristics of joints were determined according to each tenon size. Any size of mortise and tenon joint has a unique relative degree of rigidity. The relationship between the internal angle change in a joint and applied moment is the moment rotation characteristic of the joint. The moment rotation characteristics could be considered as the "spring constant" of joints and were calculated by means of Eq. 2,

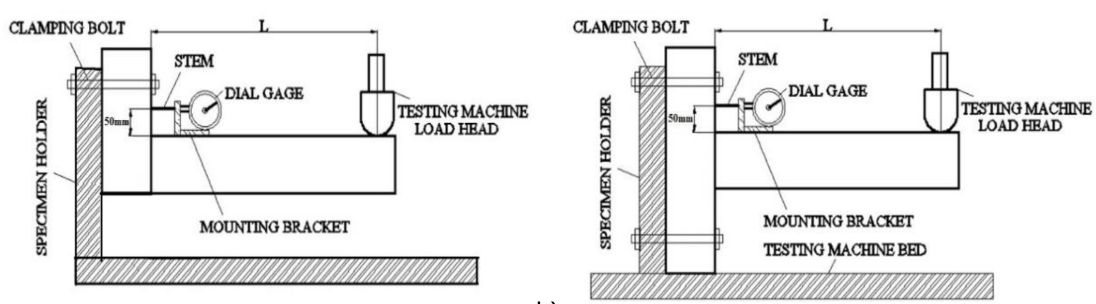
$$k = \frac{M}{\phi} \tag{2}$$

where k refers to the spring constant (Nm/rad), M refers to the bending moment (Nm), and $ø$ refers to the angle change in a joint (rad).

This value is unique for each size of mortise and tenon joint. In practice, semi-rigid connection factors may be estimated through the measurement of individual member rotations.

L-type specimens were tested under the tension loads, while the T-type specimens were tested under compression loads to simulate the condition in which they are exposed to these loads in the side frame of a full scale chair under front to back loading (Fig. 5). Tests of the L-shaped and T-shaped joints were also carried out on the universal-testing machine with the same loading rate under static loading. A concentrated load was applied to the rail member of each specimen at a point 300 mm from the front edge of the leg; *i.e.*, the moment arm was 300 mm according to the literature (Kuşkun 2013; Kasal *et al.* 2016).

The measurements of the joint moment rotation characteristics (rigidity) were obtained by means of a dial gage clamped to the top edge of the rail for both the L-shaped and T-shaped joint specimens. Dial gage readings were taken at regular intervals as the specimens were loaded.



a) b)

Fig. 5. Diagrams showing the bending loading forms and attachments of (a) L- and (b) T-shaped joint specimens to the test rig

Structural analysis and modeling of chair frames

Each chair frame was structurally analyzed to obtain the moment acting on each joint in the side frames under the action of a front to back load. Analyses of the chair frames were performed with commercially available finite element analysis software (RISA-3D, RISA Technologies, Inc., Version 4.1., Foothill Ranch, CA, USA). RISA-3D is one of the most widely used structural analysis software by engineers in terms of its ease of use. The software enables engineers to analyze and optimize all types of structures and structural materials including steel, concrete, wood, aluminum, and masonry.

The chair frames were modelled as three–dimensional frames with wood members. All structural members were treated as linear elastic beams. Some necessary physical and mechanical properties (Table 1) of the wood were then entered into the software. Each member of the chair frame was modelled individually, and then attached (merged) to each other, so that the frame system was integrated.

According to Eckelman (1968), the accuracy of any structural analysis depends upon how well the behavioral characteristics of the structure conform to those postulated for it. If the joints in a frame are assumed to be rigid, the joint does not deform under load. More formally, a rigid joint is defined as one in which the angles between the tangents to the elastic curves of the members framing into the joint at their point of intersection do not change under the load. This concept of a rigid joint as applied to furniture is a confusing one and merits further explanation. In a semi-rigid joint, the angle between the elastic tangents changes so that the loaded beam end rotates slightly more than the rest of the joint. The internal angle change has an effect on the distribution of the bending moment (Eckelman 1968). Therefore, the joints in a frame cannot be considered rigid in a structural sense.

The software used allows the user to assign semi-rigid connections by adding springs which are predefined by spring constant value (k). The joints in the side frame of chair were considered as a “spring” where the rotation around the (Z) direction, and spring constant (Nm/rad) values were entered into the structural analysis program for these joints so that the connections at these points could simulate the semi-rigid joints as close to real-time conditions.

These spring joints had to be included in the model to provide the means of distributing the bending moments to the nodes of the model according to their respective positions. Therefore, the bending moments were transferred to the nodes more realistically.

Next, some required physical (density) and mechanical (modulus of rupture (MOR), modulus of elasticity (MOE), Poisson ratio: 0.3) properties of Scotch pine were entered into the analysis program to calculate the bending moments at the end of members. Afterwards, sectional properties of members, such as cross-sectional area, moment of inertia around (Y) and (Z) axes, and torsional constant values, were entered into the program. Although cross-sections of all of the members except for the stretcher were the same, their orientations were different resulting in different inertial values.

Before attempting to obtain a solution, the loads and boundary conditions were applied to the model. The front legs of the chair frame were supported by movable support (roller), whereas the back legs were supported as a pin connection to the floor. In other words, it was considered that there were reaction forces in (X), (Y), and (Z) translations, while the rotations around each direction were free for the back legs; in the case of the front leg, there was only a reaction force in the (Y) translation, whereas the (X) and (Z) translations and the rotations around each direction were free.

There were six degrees of freedom (DOF) at each node. The maximum load level achieved during static testing of the chair frame was taken as the load to be applied at the nodes in the model. Half of the maximum loads were symmetrically applied at corresponding nodes that were on the two side frames (Fig. 6).

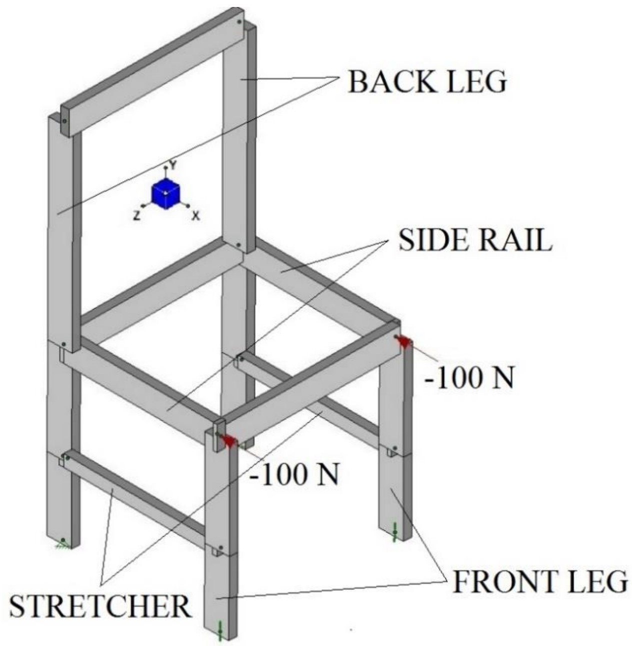


Fig. 6. Graphical representation of load application and constraints of DOF on a typical chair frame loaded under front to back direction

Three-dimensional static structural analyses of each sofa frame were performed for 9 chair frame groups. The bending moments acting on each joint were taken from the analyses.

RESULTS AND DISCUSSION

Static Front to Back Loading Performance of Chair Frames

The chair frames failed completely without tilting in approximately 5 min. The joints of the chair opened up suddenly, but they kept holding the loads for 60 s to 90 s more. Generally, front leg to side rail joints of the chair frame failed first (Fig. 7).

The chair frames were constructed with small width and longer tenons; failures occurred due to the fracture of the tenons on the side rails and stretchers at their point of entry into the walls of the back and front legs. In the case of shorter tenons; joints of the frame failed with modes of glue line fracture. In other words, the short tenons withdrew entirely from the front or back leg, generally back leg members, which resulted in the chair frames being broken into pieces. For the large width and long tenons, the common mode of failure was the pull-out of tenons from the front and back leg member with some core wood materials attached to the tenon. Opening failures started at the edge of the joint section and then propagated toward the other edge of the joint with increased load for the joints. As the glue lost its strength, the tenons started to take the load. Some splits occurred on top of the front leg, due to the forcing of the tenons under shear parallel to the grain.

Fig. 7. Typical failure modes of the chair frames including the first failed joint

The MANOVA results indicated that the main factors (tenon width and tenon length) and two-factor interaction for ultimate front to back loading performance values were statistically significant at the 95% confidence level. Therefore, the two-factor interaction was further investigated. The analysis of variance results is given in Table 1.

Table 1. Summary of the ANOVA Results for Front to Back Loading Tests

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F Value	Prob. (Sig)
Width	2	1373633.200	686816.600	17.4885	0.0000
Length	2	8193561.600	4096780.800	104.3170	0.0000
Width × Length	4	2541022.000	635255.500	16.1756	0.0000
Error	36	1413806.400	39272.400		
Total	44	13522023.200			

Results of the ultimate front to back loading performance of whole chair frames with their coefficients of variation values, along with LSD comparison test results for two-way interactions are given in Table 2. The single LSD values were 254.2 N.

Table 2. Mean Front to Back Loading Capacities of Whole Chair Frames with their Coefficients of Variation

Tenon Size (width × length) (mm)	Front to Back Loading Performance (N)	
	Mean	COV* (%)
30 × 30	1409 (F)	10.99
30 × 40	1829 (D)	9.59
30 × 50	1934 (CD)	17.63
40 × 30	1530 (EF)	4.62
40 × 40	2097 (C)	9.47
40 × 50	2496 (B)	6.46
50 × 30	1503 (F)	10.23
50 × 40	1764 (DE)	8.32
50 × 50	3127 (A)	7.64

*Values in parenthesis followed by the same capital letter are not significantly different

As shown in Table 2, the chair frames constructed with 50 mm × 50 mm tenons had the highest front to back loading performance, whereas the chair frames constructed with 30 mm × 30 mm tenons had the lowest. Generally, results indicated that the front to back loading performance of chair frames increased as either the tenon width or tenon length increased. However, tenon length had a greater effect than the tenon width.

The left side of Table 3 gives the mean comparisons of front to back loading performance values of chair frames for tenon length effect within each of three tenon widths. The right side shows the tenon width effect within each of three tenon lengths. The single LSD values were 146.8 N for both tenon length and tenon width.

Table 3. Mean Comparisons for Tenon Length and Tenon Width on Front to Back Loading Performance

Tenon length effect within each tenon width				Tenon width effect within each tenon length			
Tenon Width (mm)	Front to Back Loading Performance (N)			Tenon Length (mm)	Front to Back Loading Performance (N)		
	Tenon Length (mm)				Tenon Width (mm)		
	30	40	50		30	40	50
30	1409 (B)	1829 (A)	1934 (A)	30	1409 (A)	1530 (A)	1503 (A)
40	1530 (C)	2097 (B)	2496 (A)	40	1829 (B)	2097 (A)	1764 (B)
50	1503 (C)	1764 (B)	3127 (A)	50	1934 (C)	2496 (B)	3127 (A)

An increase in the tenon length significantly increased the performance. For the chair frames constructed with 30 mm tenon width, increasing the tenon length from 30 mm to 40 mm increased the performance by 30%, whereas increasing the tenon length from 40 mm to 50 mm increased the performance by only 6%. In the case of 40 mm tenon width, increasing the tenon length from 30 mm to 40 mm increased the performance by 37%, whereas from 40 mm to 50 mm increased the performance by 19%. In the case of 50 mm tenon width, increasing the tenon length from 30 mm to 40 mm increased the performance by 17%, whereas from 40 mm to 50 mm increased the performance by 77%. The utmost tenon length effect was obtained with 50 mm width tenons.

For the chair frames constructed with 30 mm and 40 mm tenon length, increasing the tenon width from 30 mm to 40 mm increased the performance by 9% and 15%, respectively. In contrast, increasing the tenon length from 40 mm to 50 mm decreased the performance by 2% and 16%, respectively. In the case of 50 mm tenon length, increasing the tenon length from 30 mm to 40 mm or 40 mm to 50 mm increased the performance by an average of 27%. The most tenon width effect was obtained with 50 mm long tenons.

Structural Analyses Results

Some of the necessary physical and mechanical properties determined with the tests and used in the structural analyses in this study are given in Table 4.

Table 4. Physical and Mechanical Properties of Scots Pine Specimens used in the Study

Wood Species	MOE* (N/mm^2)	Tension Strength Parallel to Grain (N/mm^2)	Compression Strength Parallel to Grain (N/mm^2)	Shear Strength (N/mm^2)	Modulus of Rigidity (N/mm^2)	MOR* (N/mm^2)	Density (g/cm^3)	MC* (%)
Scots Pine	10289	65.5	57.2	6.2	3957	88.3	0.45	11.2
COV*	12.35	9.85	5.87	3.75	5.87	9.04	2.54	3.75

*MOE: modulus of elasticity; MOR: modulus of rupture, MC: moisture content, COV: Coefficients of variation

In the structural analyses of chair frames, the joints were treated as semi-rigid connections rather than rigid. The spring constant values of each size of tenon joints are listed in Table 5.

Table 5. Spring Constant Values Obtained for Each Tenon Size of Joints

Joint Type	Spring Constant (*k*) Values (Nm/rad)								
	Tenon Size (width × length) (mm)								
	30 × 30	30 × 40	30 × 50	40 × 30	40 × 40	40 × 50	50 × 30	50 × 40	50 × 50
T-type (Back leg to side rail)	2006	2628	2088	2021	3000	3214	3112	3485	4614
T-type (Front/back leg to stretcher)	1325	1325	1325	1325	1325	1325	1325	1325	1325
L-type (Front leg to side rail)	1286	1147	1167	1341	1384	1588	2997	2605	2913

The bending moments carried by each joint around the (*Z*) direction in the side frame of chairs were obtained from the results of structural analyses (Table 6).

Table 6. Moment Distributions of Side Frame of Chairs According to Tenon Size

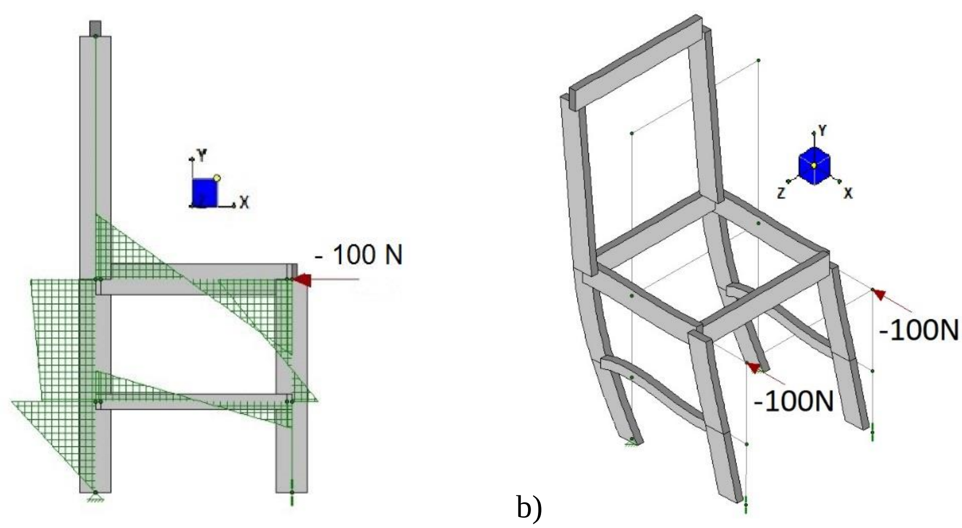
Tenon Size (width × length) (mm)	Front to Back Load Carried by a Side Frame (F/2) (N)	Theoretical Total Moment Occurred in the Side Frame (F/2*0.42) (Nm)	Total Moments Carried by the 4 Joints According to Structural Analyses (Nm)	Bending moments carried by each joint according to structural analyses results			
				Back Leg to Side Rail Joint (Nm)	Front Leg to Side Rail Joint (Nm)	Back Leg to Stretcher Joint (Nm)	Front Leg to Stretcher Joint (Nm)
30 × 30	705	296	271	94.03 (34.74*)	104.50 (38.61)	38.95 (14.39)	33.21 (12.27)
30 × 40	915	384	350	121.46 (34.65)	135.46 (38.65)	50.52 (14.41)	43.06 (12.29)
30 × 50	967	406	372	129.07 (34.72)	143.58 (38.63)	53.47 (14.38)	45.59 (12.27)
40 × 30	765	321	294	102.08 (34.74)	113.43 (38.60)	42.29 (14.39)	36.07 (12.27)
40 × 40	1049	440	400	138.56 (34.61)	154.64 (38.63)	57.86 (14.45)	49.30 (12.32)
40 × 50	1248	524	476	164.45 (34.58)	183.56 (38.60)	68.84 (14.48)	58.66 (12.34)
50 × 30	752	316	284	98.22 (34.62)	108.90 (38.39)	41.33 (14.57)	35.23 (12.42)
50 × 40	882	370	333	115.16 (34.57)	128.13 (38.46)	48.52 (14.56)	41.34 (12.41)
50 × 50	1564	657	586	201.65 (34.43)	225.21 (38.45)	85.79 (14.65)	73.06 (12.47)

* Values in parenthesis are percentages of bending moments carried by each joint with respect to total moment

Generally, front leg to side rail and back leg to side rail joints carried approximately 73% of the total moment occurred in the side frame under front to back loading, and the remaining 27% of the total moment carried by the back leg to stretcher and front leg to stretcher joints.

It should be noted that according to the results of structural analyses, the total moment appears to add up to 100%, if all 4 joints are fictitiously given as fixed; whereas, more realistically, if the joints are assumed to be semi-rigid, the total moment adds up to nearly 90% in joints on the side frame. The remaining 10% is stored as strain energy in the spring definitions of semi-rigid joints until the spring constant is surpassed.

In most cases, the ultimate bending moments calculated by the software consistently corresponded to the front leg to side rail joints at which the actual failures started to occur. Bending moment diagrams and the exaggerated deflected shape of the chair frames are given in Figs. 8a and b.



a) b)

Fig. 8. Bending moment diagram (a) and exaggerated deflected shape (b) of the chair frames

According to the results of structural analyses, it is confirmed that front or back leg to side rail joints were the critical joints in the side frame for resisting the front to back loading. Therefore, the tenon size at these joints affected the front to back loading performance of the whole chair frame.

Comparison of Strength Values with Acceptable Design Loads

The cyclic front to back loading performances of chair frames were estimated from static front to back loading performances, according to various studies in previous literature. It was recommended from the literature that the cyclic strength of the furniture frames could be taken as nearly 50% of the static strength (Kuşkun 2013; Likos *et al.* 2013). Accordingly, the cyclic front to back performances were taken as 56% of the static front to back loading performances. Then, the estimated cyclic front to back loading performances of chair frames for each tenon size were compared to the acceptable light, medium, and heavy design load levels that are given in the ALA specifications (ALA 1982). The specified acceptable cyclic front to back loading performance levels are 1335 N, 1557 N, and 2002 N for light, medium, and heavy service, respectively. The acceptable light design load represents the domestic use in practice. The comparison results of the chair frames are given in Table 7.

Table 7. Comparison of the Estimated Cyclic Front to Back Loading Performance Values of Chairs with the Acceptable Design Loads in ALA Specifications

Tenon Size (width × length) (mm)	Static Strength (N)	Estimated Cyclic Strength* (N)	Acceptable Light Design Load (N)	Result	Acceptable Medium Design Load (N)	Result	Acceptable Heavy Design Load (N)	Result
30 × 30	1409	789	1335	Fail	1557	Fail	2002	Fail
30 × 40	1829	1024		Fail		Fail		Fail
30 × 50	1934	1083		Fail		Fail		Fail
40 × 30	1530	857		Fail		Fail		Fail
40 × 40	2097	1174		Fail		Fail		Fail
40 × 50	2496	1398		***Pass***		Fail		Fail
50 × 30	1503	842		Fail		Fail		Fail
50 × 40	1764	988		Fail		Fail		Fail
50 × 50	3127	1751		***Pass***		***Pass***		Fail

*: Cyclic strength values were taken as 56% of the static strength (Likos *et al.* 2013; Kuşkun 2013)

According to the comparison results, the chairs constructed with 40 mm × 50 mm tenons could meet the light acceptable design load level (domestic use); whereas the chairs constructed with 50 mm × 50 mm tenons could satisfy the medium acceptable design load levels. Chairs constructed with other sizes of tenons could not resist any acceptable levels and need to be reinforced or redesigned.

CONCLUSIONS

This study was conducted to obtain quantitative information related to the front to back loading performances of chair frames constructed of Scots pine. Another purpose was to compare the front to back loading performance of chair frames with the acceptable design loads that are given in ALA specifications. At the end of the study, the following deductions were achieved:

1. According to the structural analyses results, the front leg to side rail and back leg to side rail joints carried approximately 73% of the total moment induced under the front to back loading. The tenon size of these joints influenced the overall strength performance of the chair frames.
2. Tenon width and tenon length significantly affected the ultimate front to back loading performance at the 5% significance level.
3. Chair frames constructed with 50 mm × 50 mm tenons had the highest front to back loading performance, whereas the chair frames constructed with 30 mm × 30 mm tenons had the lowest front to back loading performance.
4. The front to back loading performance of a chair increased as either the tenon width or tenon length increased, but was more affected by the tenon length.

5. The chairs constructed with any size of tenon tested in this study could not meet the acceptable heavy service load levels.
6. The chairs constructed with any size of tenon could not meet the light service (domestic usage) except for the chairs constructed with 40 mm × 50 mm and 50 mm × 50 mm tenons.
7. Chairs constructed with 50 mm × 50 mm tenons could satisfy the medium acceptable design load levels.

In conclusion, it was clearly seen that the performance tests allowed for discovery and observation of unexpected failures and provided useful insight into actual usage and failure conditions. The results of this study provide fundamental information on the strength properties of Scots pine chair frames constructed with mortise and tenon joints, which will in turn help optimize furniture engineering design and construction of similar chairs.

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