ANALYSIS OF STRESS DISTRIBUTION AND PREDICTION OF FAILURES FOR T-SHAPED WOOD SCREW JOINTS USING THE FINITE ELEMENT METHOD (FEM)

Amir Lashgari [a],* and Seyyed Khalil Hosseini Hashemi [a]

In this study, finite element analysis was used to investigate the deflection, stiffness, and failure characteristics of case furniture. Tests were performed to evaluate the tensile stress distribution in screw joints under tensile load. To meet this objective, the effects of two screw diameters (4 and 5 mm) were studied using beech (*Fagus orientalis*), alder (*Alnus subcordata*), and white spruce (*Picea Abies*) wood species. The finite element analysis method (FEM) with ANSYS software was utilized to evaluate the distribution and concentration of stress in the joints, as well as variations of stress due to the mentioned variables. In order to perform the numerical computations, the T-shaped specimens had dimensions of 50 × 50 × 25 mm to meet EN 789 modified standard requirements, and the screw models had diameters of 4 and 5 mm, with a length of 50 mm. The results showed that stress concentration was between the screw threads. The stress in the joint model was less than that of the screw model. The larger screw diameter experienced a larger amount of stress but did not follow a constant trend, showing that screw diameter should be proportional to surface area. It was concluded that the finite element method is a suitable method with the use of exact numerical calculations to check the loads imposed on the structures. The FEM can be used as a suitable non-destructive technique for determining structural strength at various times.

Keywords: Tensile stress distribution; Screw joint; Beech; Alder; White spruce; Finite element method (FEM)

*Contact information: a: Department of Wood Science and Paper Technology, Karaj Branch, Islamic Azad University, Karaj, Iran; *Corresponding author: amir.lashgari@kiau.ac.ir*

INTRODUCTION

Many efforts have been put forth by furniture-making specialists in producing wood-based products to pay attention to both aesthetic value and the strength of the furniture. Generally, furniture resistance is related to the quality and the type of fasteners used. Therefore, strength and hardness properties of each joint member should also be evaluated. One of the most important stages in the design of the structure and furniture is the analysis of its mechanical performance in the total of designed structure. The purpose of such analyses is to characterize the commutative behavior and displacement of members and to determine stress values for each joint member.

In recent years, rapid development of computer techniques and their use during the design process has caused more attention to be placed on the cost and effectiveness of furniture manufacturing. Numerical computation is a suitable technique for studying the strength and hardness of furniture to create a suitable matrix in designing furniture. The finite element method is a numerical computation that is capable of determining the stress distribution in various structures. A finite element analysis (FEA) is conducted to investigate the stress distribution of joints in furniture. In order to perform the numerical simulation of the mechanical strength behavior of the joints, each joint was modeled using the ANSYS finite element software (ANSYS 2003).

Some authors have compared the numerical finite element method (FEM) with experimental models for the analysis of metal-plate-connected wood truss joints (Gupta and Gebremedhin 1990; Vatovec *et al.* 1996a; Hussein 2000). These authors modeled trusses with beam elements and semi-rigid joints, but not traditional joints (Gupta and Gebremedhin 1992; Gupta *et al.* 1992; Vatovec *et al.* 1996b, 1997).

Many studies have been performed to develop a comprehensive methodology that integrates rational structural design methods with performance testing to provide an effective and economical means of assuring that furniture can fulfill its intended purposes in terms of structural durability, safety, and overall quality (Erdil and Eckelman 2003). The rational design of case furniture, for example, requires that methods of analysis be available that can be used to determine the deflection and stiffness of the case, along with the forces at the various joints. The methods required for such analyses, however, have been slow to evolve. Based on extensive investigation, the first published analysis of a case was carried out by Kotas (1957, 1958a) on an open-faced, five-sided box. Results of this research were later incorporated into a small design manual (1958b).

Eckelman (1967, 1978) subsequently developed a method of analysis for cases based on the inter-related deflections of the various corners and the stiffness of the individual panels. Eckelman and Resheidat (1983) elaborated upon all of the analyses cited above also dealt with simple five-sided cases. Ganowicz and Rogozinski (1978) applied the principles of internal work to the analysis of case furniture, and Ganowicz *et al.* (1978) and Ganowicz and Kwiatkowski (1978) subsequently developed this analysis further and evaluated the forces acting on the corners of a case under two loading conditions. Chen *et al.* (2003) presented the numerical simulation of the performance of a dowel joint. Additionally, Moses and Prion (2003) and Sawata and Yasumura (2003) studied bolted or dowel joints, while Williams *et al.* (2000) suggested a finite element-based failure model for bolted joints.

Guan and Rodd (2000) studied contact problems in timber joints and showed that these affected the convergence, the deformation, and the failure mode of the joint. They also investigated the stress distribution in metal dowels used in plywood panel joints with the finite element method. The results showed that by increasing the number of dowels from four to eight, the dowels used in the bottom joint experienced minimum deformation. Their stress distribution was decreased, and with an increase of space around the dowels, failure and deformation occurred.

The investigations of Smardzewski and Prekrad (2002) and Smardzewski and Papuga (2004), who considered the stress distribution in three different joints of furniture made of wood, metal, and plastic, showed that the amount of movement is greater in a metal joint, inducing failure, whereas a dowel joint is able to bear greater force, but breaks more quickly.

Samardzewski *et al.* (2004) studied the stress distribution in two joints in a furniture frame: one with a dowel, and one with a mortise and tenon, using the finite element method and ANSYS software for analysis. In the cited study, the joints within the simple chair structure were compared using static loads. The type of mesh scheme presented in this study was rectangular. The results showed that the stress was concentrated on the upper side of the vertical joint and in the horizontal and vertical member of joint for dowel and mortise and tenon joints, respectively. Maximum stress was located in the mid part of the dowel.

The objective of the present work was to evaluate the joint strength, the results of experimental and finite element methods. Also, the purpose was to evaluate the potential of using a screw joint to produce experimental T-shaped joints made of beech (*Fagus orientalis*), alder (*Alnus subcordata*), and white spruce (*Picea Abies*) and to predict their tensile stress distribution, bending moment, and failure. Finite element analysis and ANSYS software were used to assess of mechanical strength of T-joints.

EXPERIMENTAL

Test Materials and Preparation of the Specimens

Beech, alder, and white spruce woods were randomly selected from a joinery workshop, based on board straightness and the absence of obvious decay. The samples were selected to be defect-free, clear, and normally grown (without zone lines, reaction wood, decay, insect damage, or fungal infection). For each wood species, 1 m-long samples without defect were obtained from the center of the logs, were tangentially sawn at 30 mm thickness, and stored at 20 ºC and 65% relative humidity for 2 months, until constant moisture content was achieved. The model used to assess the stress distribution in the screw joint under a tensile load was T-shaped. Test specimens were cut from these boards with dimensions of 50 x 50 x 25 mm (longitudinal x tangential x radial) for the T-shaped model joints (Fig. 1). Four joints, with dimensions 50 x 50 x 25 mm, from beech (*Fagus orientalis*), alder (*Alnus subcordata*), and white spruce (*Picea abies*) with densities of 0.56 g/cm^3, 0.45 g/cm^3, and 0.40 g/cm^3, respectively, were used in laboratory conditions.

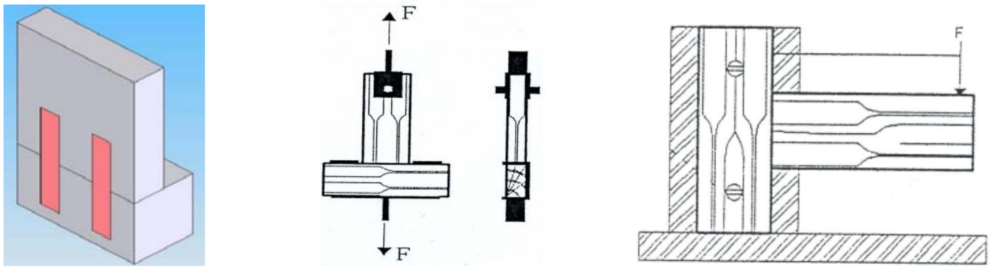

Fig. 1. T-shaped joint specimen in the fitting screw (cutting out the middle joint). The dimensions of specimens (50 × 50 × 25 mm) and load directions for both tensile and bending tests.

Method of Loading and Testing

Analysis process of joints using the finite element method

In this study, ANSYS software (version 2003) was utilized, which is simulator software used in mechanical sciences. The joints were designed virtually and experienced tensile load.

The T-shaped joint is one of more important joint in the structure of furniture. In the application of tensile load, the cross-section of the T-shaped joint was divided into equal proportions (meshes), and the necessary load was applied on each proportion. In this work the cross section of the joint was divided into 70 meshes, while the joint was divided into 700 meshes in total. First, the modes of deflection were attained experientially, and then, according to those values, an ANSYS analysis was done. To analyze the deflection of the joint, the material properties and element type were defined. The longitudinal (L) Young's modulus values of the joints were the experimental values obtained. Other values, including elastic constants in radial (R) and tangential (T) directions and the Poisson's ratio of the T-shaped wood specimens, were approximated and are listed in Table 1.

Table 1. Selected Elastic Properties of Clear Wood Specimens

Elastic properties	E_L (MPa)	E_R (MPa)	E_T (MPa)	G_{LR} (MPa)	G_{LT} (MPa)	G_{RT} (MPa)	v_{LR}	v_{LT}	v_{RT}
Beech	13065	1311	678	1007	754	271	0.5	0.37	0.25
Alder	10425	809	356	632	452	199	0.4	0.31	0.21
White spruce	10163	830	494	699	663	659	0.35	0.17	0.16

E_L, E_T, and E_R, are the MOE of L, T, and R; G_{LR}, G_{LT}, and G_{RT}, are the shear moduli in the directions L, T, and R; ν_{LR}, ν_{LT}, and ν_{RT}, are the Poisson's ratios

In order to analyze joints using a numerical computation method, two material engineering constants were calculated using the following equations,

$$\sigma_i = E_i \varepsilon_i \tag{1}$$

$$\tau_{ij} = G_{ij} \gamma_{ij} \tag{2}$$

where σ_i, E_i, ε_i, τ_{ij}, G_{ij}, and γ_{ij} are the stress, modulus of elasticity (MOE), strain, shear stress, shear modulus, and shear strain, respectively.

$$E_L = \frac{1}{E_L}\sigma_L - \frac{\nu_{TL}}{E_T}\sigma_T - \frac{\nu_{RL}}{E_R}\sigma_R \tag{3}$$

$$E_L = \frac{\nu_{LT}}{E_L}\sigma_L - \frac{1}{E_T}\sigma_T - \frac{\nu_{RL}}{E_R}\sigma_R \tag{4}$$

$$E_L = \frac{\nu_{LT}}{E_L}\sigma_L - \frac{\nu_{TR}}{E_T}\sigma_T - \frac{1}{E_R}\sigma_R \tag{5}$$

where E_L, E_T, and E_R, are the L (longitudinal), T (tangential), and R (radial) MOE. σ_L, σ_T, and σ_R, are the stress in the directions L, T, and R. ν_{ij} is the Poisson's ratio (i, j = L, T, R).

In the application of bending load, the concentration load was also applied on the top section of the joint bond. The loading rate was 12 mm min^{-1}. The bending moment (M) was calculated using the following equation,

$$M = d \times F \tag{6}$$

where d and F are the distance and force, respectively.

Statistical Procedure

Statistical analysis was conducted using the SPSS program in conjunction with a general linear model (univariate). Duncan's multiple range test (DMRT) was used to test the statistical significance at $\alpha = 0.01$ confidence level.

RESULTS AND DISCUSSION

Experimental Results

The experimental results of the mean tensile strength (TS) and bending moment (BM) tests for T-shaped screw joints are summarized in Table 3. The averages and standard deviations for the TS and BM of screw joints for beech, alder, and white spruce wood samples are summarized in Table 3.

The significant mean values of the variation sources were compared using the Duncan test, and the results are summarized in Table 2.

Table 2. Univariate Test Results for TS and BM Test Results of the Screw Joint in Beech, Alder, and White Spruce Wood Samples

Test	Source	DF	F	*P* value
Tensile strength	Between groups or SD	1	24.236	< 0.000
	Within groups or WS	2	254.435	< 0.000
	Interaction between groups and within groups or SD * WS	2	0.932	< 0.412
Bending moment	Between groups or SD	1	13.903	< 0.002
	Within groups or WS	2	71.342	< 0.000
	Interaction between groups and within groups or SD * WS	2	5.145	< 0.017

DF: degree of freedom; SD: screw diameter; WS: wood species

Table 3. Average and Standard Deviation Values for TS and BM of T-shaped Screw Joints

Test	Screw diameter (SD) (mm)	Wood species (WS)		
		Beech	Alder	White spruce
Tensile strength (N)	4 ^{a}	3486 ± 7.4 ^{b}	3237 ± 16.2 ^{b}	1956 ± 9.6 ^{a}
	5 ^{b}	3743 ± 3.4 ^{b}	3434 ± 27.5 ^{b}	2337 ± 3.3 ^{a}
Bending moment (N m)	4 ^{a}	1821 ± 5.6 ^{b}	1754 ± 16.3 ^{b}	1229 ± 6.9 ^{a}
	5 ^{b}	1714 ± 7.8 ^{c}	1447 ± 8.5 ^{b}	1215 ± 8.2 ^{a}

*Values are mean and standard deviation. Results with different letters are significantly different (Duncan test)

The mean tensile strength values were 3486 N, 3237 N, and 1956 N for the 4 mm-diameter screw in the beech, alder, and white spruce wood samples, respectively, and 3743 N, 3434 N, and 2337 N for the 5 mm-diameter screws from the beech, alder, and white spruce wood samples, respectively (Table 3). The mean bending moment values obtained from the strength test were 1821 N m, 1754 N m, and 1229 N m for the 4 mm-diameter screws from the beech, alder, and white spruce wood samples, respectively, and 1714 N m, 1447 N m, and 1215 N m for the 5 mm-diameter screws (Table 3). The patterns of variation in tensile strength of the screw joints in the beech, alder, and white spruce wood samples, as a function of screw diameter and wood species, are also summarized in Table 3.

The results of the univariate test (Table 2) indicated that wood species and screw diameter had a significant effect on the tensile strength of the screw joint in the different wood samples ($P < 0.01$), but interaction between wood species and screw diameter had no significant effect on the tensile strength of the screw joint in the different wood samples ($P < 0.01$). Wood species and screw diameter also had a significant effect on the bending moment of the screw joint in the different wood samples ($P < 0.01$), but interaction between wood species and screw diameter had no significant effect on the bending moment of the screw joint in the different wood samples ($P < 0.01$).

Structural Analysis Results Using FEM

The variations of stress distribution, meshing screw, and nebulosity showing tensile strength in the screw joint are shown in Fig. 2. The nebulosity for variations of stress distribution, the mode of failure, and segregation in the screw joints for study of the bending moment are shown in Fig. 3.

The tensile strength in the screw joints with diameters of 4 and 5 mm was greater in beech wood than the alder and white spruce wood species. The larger screw diameter resulted in a greater tensile strength, agreeing with Erdil's (2004) conclusions. An increase in screw circumference results in the end of the screw acting as a barrier, preventing movement of the screw in the joint member. However, the screw with a diameter of 4 mm can be moved in the joint member. The distribution of stress in the screw joint was caused by the created grooves with screw threads into the wood and also the escape of the screw into the wood; then failure of joint occurred at this location. Generally, in the screw joints and in both the study of tensile strength and bending moment, the maximum stress is concentrated in the around of screw hole, and stress is dispersed in the connection members.

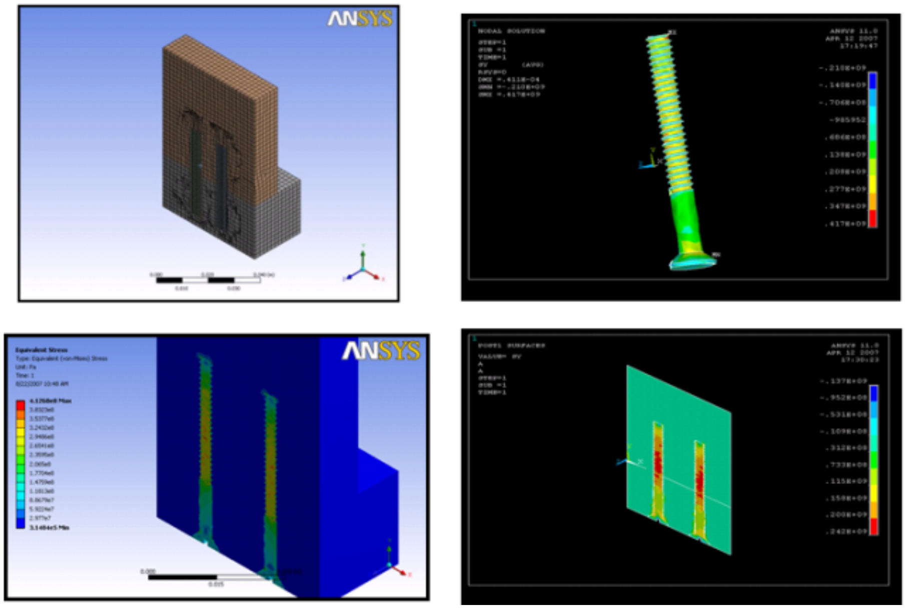

Fig. 2. The variations in stress distribution, meshing screw, and nebulosity showing tensile strength in the screw joint

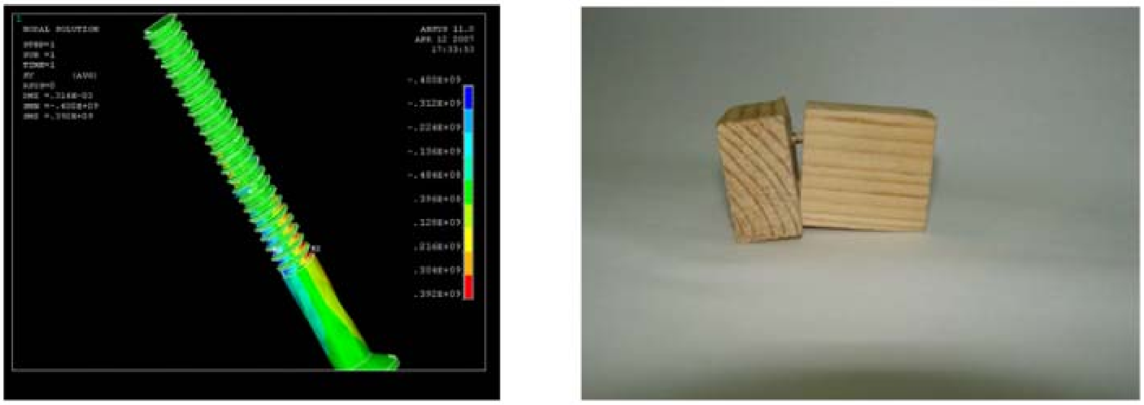

Fig. 3. The nebulosity showing variations of stress distribution, the mode of failure, and segregation in the screw joints for studying bending moment strength

According to the study of screw joints, there was a decreased in bending moment with increasing screw diameter (this does not agree with Erdil's (2004) conclusions). Thus, the cavity diameter created by the screw increased and in this case weakened the screw member and joints to bending load. In the bending moment, the distribution of stress in the screw joint was affected by the screw member and the grooves it created in the wood.

Screws are used to carry tension and compression loads parallel to the grain as well as shear forces diagonal to the grain. The reinforcement screws can be applied both locally in areas of load concentrations and generally to increase the strength and stiffness of the whole element (Trautz and Koj 2009). It was found that the screw joint for negative bending moment could bear almost 90% of the calculated ultimate load and in the load test this configuration reached failure by a bending fracture of the vertical leg of the test specimen. For wood fasteners, the withdrawal strength of the screw depends on the length and width of the screw, and on the density of the wood material (Özcifci 2008).

Gaunt *et al.* (1997) reported that a screw in the end-grain of radiata pine with an applied end-grain crushing stress of 10 MPa and steel yield strength of 275 MPa gives a thread ratio (*d/r*) of three. They also noted that a maximum withdrawal load of 113.5 kN represented a stress in the shank of the screw of 560 N/mm^2. At this stress no signs of steel yield were evident.

The failure modes in the timber around the screw are brittle and with small ultimate deformation and there is therefore a limited possibility for stress redistribution (BS EN 1995). According to the results from research conducted by Daudeville and Yasumura (1996) on failure analysis of timber bolted joints by fracture mechanics, the mean experimental fracture energy of spruce under tension perpendicular to the grain with a density of 460 kg/m^3 is 180 N/m.

Normally, bolted joints are designed with the intent of avoiding brittle failure modes associated with catastrophic crack growth parallel to the grain. The main function of the screw thread is to prevent the screw from being moved along its axial direction, but not from being rotated. In screw connections, as long as failure does not take place in the screw itself, the screw rigidity is always much greater than the other materials. Because the screw is regarded as linear elastic material with, more or less, the same Young's modulus as connected steel sheets, the deformation of the screw would be much less than that of the other materials (Fan *et al.* 1997).

Also, Yasumura and Daudeville (2000) presented a finite element model to analyze the fracture of multiple-bolted joints under lateral force perpendicular to wood joints and calculated the maximum loads and the crack initiating loads by linear elastic fracture mechanics (LEFM) and the average stress method (ASM). Usually, the assumption of elastic bodies is adopted in the LEFM models. According to their experimental observations, this assumption seems valid for the brittle failure of a timber joint with rigid fasteners. For dowel joints with a ductile failure mode, the behavior is characterized by the bending of the fasteners and/or the embedding of the fastener into the wood. In this case, failure is the result of a complex stress interaction.

CONCLUSIONS

1. The method of algorithms can be a suitable and an accurate method to evaluate the stress distribution in the different joints of structures under different loads.
2. Screw diameter increases the amount of stress, but it does not follow a constant trend and shows that an increase in screw diameter should be proportional to surface area connection.
3. The finite element method was determined to be a general and suitable method. When exact numerical calculations are used to check the loads imposed on structures, it can be used as a suitable, non-destructive technique for calculating structural strength at various times.

REFERENCES CITED

ANSYS (2003). "Theory manual version 8.1," Ansys, Inc., Canonsburg, USA.

British Standard EN (1995). "Design of timber structures: Part 1.1. General rules and rules for buildings," BSI, London, UK.

Chen, C. J., Lee, T. L., and Jeng, D. S. (2003). "Finite element modeling for the mechanical behavior of dowel-type timber joints," *Comput. Struct.* 81(30-31), 2731-2738.

Daudeville, L., and Yasumura, M. (1996). "Failure analysis of timber bolted joints by fracture mechanics," *Materials and Structures* 29(7), 418-425.

Eckelman, C. A. (1967). "Furniture mechanics: The analysis of paneled case and carcass furniture," *Research Progress Report 274*, Purdue University Agricultural Experiment Station, West Lafayette, IN, USA.

Eckelman, C, A. (1978). *Strength Design of Furniture*, Tim-Tech., Inc., West Lafayette, IN, USA.

Eckelman, C. A., and Resheidat, M. (1985). "The analysis of five-side furniture cases," *Purdue Univ. Agr. Res. Bul. No. 981*, West Lafayette, IN, USA.

Erdil, Y. Z. (2003). "Integrated product engineering and performance testing of furniture," PhD Dissertation, Purdue University, West Lafayette, IN, USA.

Fan, L., Rondal, J., and Cescotto, S. (1997). "Finite element modeling of single lap screw connections in steel sheeting under static shear," *Thin-Walled Structures* 27(2), 165-185.

Ganovicz, R., Dziuba, T., and Ozarska-Bergandy, B. (1978). "Theory of deformation of case design," *Holztechnologie* 19(2), 100-102.

Ganovicz, R., and Kwiatkowski, K. (1978). "Experimental testing of the theory of deformation of cabinet designs," *Holztechnologie* 19(4), 202-206.

Gaunt, D. (1997). "A structural end-grain screw for heavy timber construction," *IPENZ Transactions* 24(1) 18-26.

Guan, Z. W., and Rodd, P. D. (2000). "Three-dimensional finite element model for locally reinforced timber joints made with hollow dowel fasteners," *Canad J Civil Eng* 27(4) 785-797.

Gupta, R., and Gebremedhin, K. G. (1990). "Destructive testing of metal-plate-connected wood truss joints," *J. Struct. Eng.* 116 (7), 1971-1982.

Gupta, R., and Gebremedhin, K. G. (1992). "Resistance distributions of a metal-plate-connected wood truss," *Forest Prod. J.* 42(7-8), 11-16.

Gupta, R., Gebremedhin, K. G., and Cooke, R. J. (1992). "Analysis of metal-plate-connected wood trusses with semirigid joints," *T. ASAE* 35(3), 1011-1018.

Hussein, R., (2000). "Parametric investigation of the buckling performance of metal-plate-connected joints," *Adv. Eng. Softw.* 31(1), 45-56.

Kovats, T. (1957). "The theoretical and experimental analysis of cabinet structures," *Furniture Development Council Research Rep. No. 6.*, London, UK.

Kovats, T. (1958a). "Steifigkeit der Korpusmöbel," *Przem. Drzweney* 9(10), 15-18.

Kovats, T. (1958b). *A Design Manual for Cabinet Furniture*, Furniture Development Council, Pergamon Press, New York, USA.

Moses, D. M., and Prion, H. G. L. (2003). "A three-dimensional model for bolted connections in wood," *Canadian Journal of Civil Engineering* 30(3), 555-567.

Özcifci, A. (2008). "The effects of pilot hole, screw types and layer thickness on the withdrawal strength of screws in laminated veneer lumber," *Materials and Design* 30, 2355-2358.

Sawata, K., and Yasumura, M. (2003). "Estimation of yield and ultimate strengths of bolted timber joints by nonlinear analysis and yield theory," *J. Wood Sci.* 49(5), 383-391.

Smardzewki, J., and Prekrad, S. (2002). "Stress distribution in disconnected furniture joints," *Electronic Journal of Polish Agricultural Univ.* 5(2), 1-7.

Smardzewski, J., and Papuga, T. (2004). "Stress distribution in angle joints of skeleton furniture," *Electronic Journal of Polish Agricultural Univ.* 7(1), 11 http://www.ejpau.media.pl/series/volume7/issue1/wood/art-05.html.

Trautz, M., and Koj, C. (2009). "Self-tapping screws as reinforcement for timber structure," A. Domingo and C. Lazaro (eds.), *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium*, Sept. 28- Oct. 2, Valencia, Spain.

Vatovec, M., Gupta, R., and Miller, T. H. (1996a). "Testing and evaluation of metal-plate-connected wood truss joints," *J. Test Eval.* 24(2), 63-72.

Vatovec, M., Miller, T. H., and Gupta. R. (1996b). "Modeling of metal-plate-connected wood truss joints," *T. ASAE* 39(3), 1101-1111.

Vatovec, M., Gupta, R., Miller, T. H., and Lewis, S. (1997). "Modeling of metal-plate-connected wood truss joints: Part II- Application to overall truss model," *T. ASAE* 40(6), 1667-1675.

Williams, J. M., Fridley, K. J., and Cofer, W. F. (2000). "Falk failure modelling of sawn lumber with a fastener hole," *Finite Elem. Anal. Des.* 36(1), 83-98.

Yasumura, M., and Daudeville, L. (2000). "Fracture of multiply-bolted joints under lateral force perpendicular to wood grain," *J. Wood Sci.* 46(1), 87-92.

Article submitted: May 23, 2012; Peer review completed: June 30, 2012; Revised version received and accepted: July 30, 2012; Published: August 20, 2012.