ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 59(1): 113−120, 2017
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2017.59.1.11

EXPERIMENTAL AND THEORETICAL ANALYSIS OF IMPACT OF SHAPE SELECTED TYPE OF SELF-LOCKING JOINTS ON THEIR MECHANICAL PROPERTIES

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ABSTRACT

The main objective of this work is to determine the influence of the shape and dimensions of the tenon and mortise of self-locking frame joints on their mechanical properties. We studied three groups of joints. The basic joint has the tenon with a shaped head and straight arms. The other two joints were created by modifying the dimensions and shapes of arms of the joint. All joints were made from plywood with thickness of 18 mm; it is material which is suitable for production of these types of joints. The test specimens were loaded under the pressure caused by bending in the angular plane. The load carrying capacity and stiffness of the joint were evaluated. It has been found that the stiffness and deformation of the joint are influenced by the shape and dimensions of the joint. This statement is supplemented by numerical models created using the finite element method (FEM) for the purpose to optimise the joints. The results show that creating additional pins and changing dimension of the tenon can improve mechanical properties of the self-locking joint.

Key words: CNC technology, FEM, self-locking furniture joint, stiffness, strength.

INTRODUCTION

Traditional wooden joints and furniture structures typical for different historical periods and cultures always fill us with admiration. With the onset of industrialization and production efficiency, these connections were getting into the background. Development of new shapes of the traditional joints was suspended, and these connections were replaced by new types of mechanical connectors and adhesives. The incoming digitization and establishing CNC technology in furniture production provide a space to produce dimensionally precise and aesthetic joints. CNC routing is definitely a mainstay of future wood construction. Its reliability, speed and accuracy cannot be matched by traditional crafting techniques. In addition to facilitating new type of furniture construction, CNC routing extends the potential of timber (BAMFORD, 2003). A special group of joints produced by CNC technology are the self-locking joints; a principle of them was also used in old Japanese architecture. Self-locking joints allow creating aesthetic furniture structures easy to assemble. Furniture parts connected by self-locking joints contribute to the ecology of furniture, because it is not necessary to separate the connecting means and ecologically liquidate bonded joints. The potential using of these connections is a simple assembly process, without using any equipment and connecting materials.

The issue of investigation of mechanical properties of self-locking joints is given very limited attention. Investigation of mechanical properties of these connections is based on the thesis by ERDILE, ECKELMAN *et al* (2005) who dealt with glued joints, however the joints' shapes were formed on the principle of self-locking. They dealt with the impacts of wood species, adhesive type, width of the horizontal structural member, width of the tenon, and length of mortise on the bending strength of the central joints (created by the mortise and tenon). The analysis of finger joints from beech wood is reported in scientific work by FRANKE, *et al.* (2014). Another group of existing scientific work is mainly focused on the visual design of joints (GROS *et al*. 1998) or numerical processing of the problem (SEBERA *et al*. 2010).

To evaluate the numerical analysis used to determine the stress around the contact areas of self-locking joint, we have relied on the work concerning the problems of anisotropic materials (SAVIN 1968), (TIMOSHENKO *et al.* 1979), the problems of occurrence and spread of the stress around the holes (BODNÁR 2006) and connectors and fittings in wood (LANG, LANGOVÁ 1998) or in material composites (REZAEEPAZHAND, JAFAR 2010). Numerical analysis of the problem, the types of stress in joints in wooden structures, and their influence on the mechanical properties of the whole structure are described in works by AIRA *et al*. (2015), KHELIFA *et al*. (2016), SEBERA *et al*. (2010), and YAVARI *et al*. (2010).

The aim of our paper is to determine the strength characteristics of self-locking joints in structural nodes of furniture constructions, for the selected type of joint modified in its shape and dimensions, and to show possibilities of using of these connections. The way of shape and dimension modifications were proposed base on the work by KASAL *et al*. (2016); in the traditional tenon and mortise joint, the greatest stresses and deformation occurred in the point heel a tenon of the joint. Using finite element method (FEM), we have specified the places with the greatest stress concentration where failure may occur, compared the analysis with experimental tests, and determined the most suitable shapes among the designed joints.

MATERIAL AND METHODS

The methodology of work was divided into three basic steps: to design a shape of the tenon and mortise of the joint, to determine mechanical properties experimentally, and to analyse it numerically to validate the experiment.

Experimental method

To compare joints with different dimensions and the shape of tenon and arm of tenon mutually, three groups of joints were tested. The joints were made of plywood (thickness of 18 mm). The basic terminology of the joint is shown in Fig. 1.

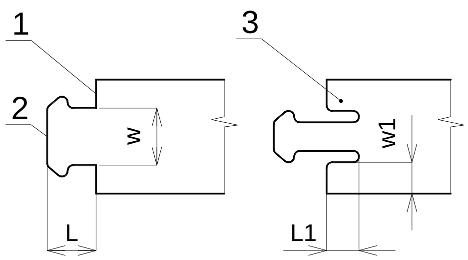
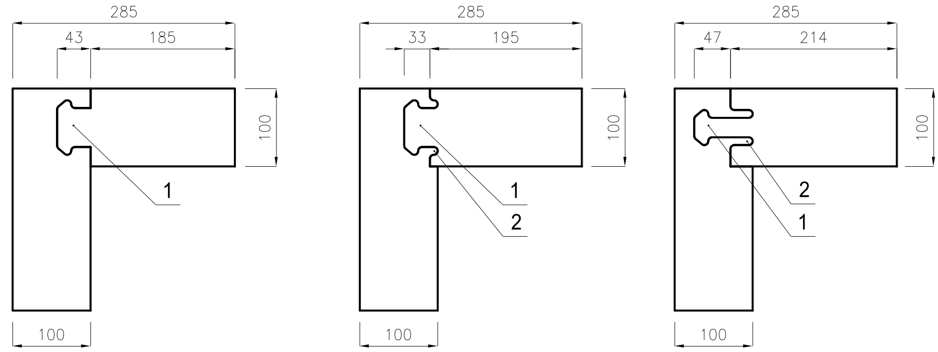


Fig. 1 Basic terminology of joints: 1 – arm of tenon, 2 – tenon with shaped head, 3 – pin on the arm, L – the length of the tenon, L1 – the length of the pin, w – width of the tenon, w1 – width of the tenon pin.

In the first step, we designed a basic shape of the joint (reference Z). It consisted from tenon with shaped head and the straight arm (Fig. 2a). The other two types of joints (MK and MD) were designed with changed dimensions and changed shape of the contact surface of the arm of joint. Modification of the contact surface of the arm was achieved by creating a pin on both sides of the connected element; by their location we expected an increased stiffness of the joint. The joints MK and MD (Fig. 2b, c) had the same shape, but different size. The joint MD had the pin and tenon width modified, unlike the joint MK. The tenon and arm of joint on one element and the shape corresponding hole (mortise) in the second element were forming a contact surface of connected parts.



a) b) c)

Fig. 2 The shapes tested joints: 1 - tenon, 2 – pin, a) Z - basic joint, b) MK - modified short joint, c) MD - modified long joint.

In the experimental determination of mechanical properties of the joints, the impact of changes in shape and in size of contact surface of conected elements was examined.

The test specimens were made from beech plywood with thickness of 18 mm (13 layers). The average moisture content was about 12 % after controlled conditioning in standard climate of 20 °C and 65 % relative humidity. The average density was about 670 kg/m³.

Mechanical properties of the tested self-locking joints were examined under the pressure caused by bending in the angular plane; tested using a universal testing machine. In the tests, maximal force F_{max} (N) and displacement of arms c (mm) were recorded. This data were used to determine the load capacity $M_{u,max}$ (N.mm) and the stiffness T (N.m/rad) for each type of the tested joints. The loading scheme is shown in Fig. 3

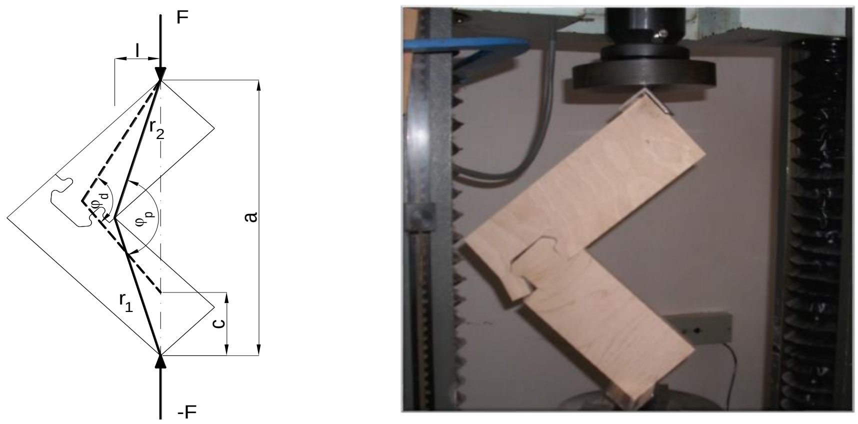


Fig. 3 Diagram of load with parameters for calculation; realisation of experiment under the pressure test, F - press force (N), $r_{1,2}$ - length of the joint shoulder (the distance between the point of force and the point of rotation) (m), φ_p - the angle between the arms before loading (original shape joint) (rad), φ_d - the angle between the arms after loading (deformed shape of the joint) (rad), a - the span joint arms (m), l - length of the force arm (m), c - shoulder joint displacement (m).

On the basis of dimensional parameters of the joint and the load scheme, the strength characteristics of joints were determined (JOŠČÁK *et al.* 2011):

Load carrying capacity: $M_{u,max} = F_{max}.l$

Stiffness of joints: $t = \frac{\Delta M}{\Delta \varphi}$

the following applies: $\Delta M = 0{,}3 M_{u,max}$;

$$\Delta\varphi = \arccos \frac{r_1^2 + r_2^2 - (a - \Delta c)^2}{2.r_1.r_2};$$

$$\Delta c = c_{40} - c_{10}$$

c_{40}, c_{10} – the joint shoulder displacement at 40 % and at 10 % of the maximum load.

Numerical method

Finite element analyses (FEA) were also conducted in order to complement the experimental observations. FEA were performed using commercial software ANSYS in cooperation with Mendel University in Brno. Comprehensive parameter studies were carried out to optimize the geometry of self-locking joints according to the resulting stress distribution and the mechanical properties of plywood.

During the finite element analysis, we considered with the forces only in the linear area for which Hooke's law is valid. The linear elastic material behaviour was assumed. The used material constants are listed in Table 1. In creating a numerical model, we have assumed that the plywood is homogeneous material through its thickness.

Tab. 1 The material constants for plywood (SEBERA *et al.* 2010).

Young's modulus	E_x = 6.97 (GPa)	E_y = 7.25 (GPa)	E_z = 0.65 (GPa)
Shear modulus	G_{xy} = 0.545 (GPa)	G_{yz} = 0.397 (GPa)	G_{zx} = 0.286 (GPa)
Poisson's ratio	μ_{xy} = 0.400 (-)	μ_{yz} = 0.320 (-)	μ_{zx} = 0.310 (-)

The simulation analysis of self-locking frame joint was carried out using ANSYS software. The Finite Element model was built by Solid Brick 8 node 185 element and meshed in triangle element. In numerical model, the plane of joints is created in X-Y plane, the thickness of the joint is modelled along the Z axis. The vertical static load along the Y axis direction was applied to the end of arm of the joint as shown in Fig. 4. The degree of freedom UX, UY, and UZ at the bottom of the joint was totally constrained

RESULTS AND DISCUSSION

The tested joints were loaded under compression force in angular plane. Working diagrams of the experimental measurements for all types of joints showed "non-linear" behaviour at the beginning of the load. It is typical behaviour for all types of investigated self-locking joints for the given type of load. It is caused by the abutment of contact surfaces of the joint and involvement of all shaped parts while transferring the load. In the next phase, linear behaviour continues up to the sudden failure of the joint.

Characteristics properties of self-locking joints under compressive stress are shown in Tab. 2.

The largest load carrying capacity was reached by the modified joint MD (372.36 N·m). The lowest value of load capacity was measured for the Z joint (260.54 N·m). The difference is 42.9 %; the large difference is due to absence of pin on the arm of the basic joint. Comparing the load carrying capacity of the two modified joints MK (356.65 N·m) and MD (372.36 N·m), the difference in the load capacity is low (4.4 %). It should be noted that despite the dimensional differences (width and length of the tenon, width and length of the pin) between modified joints MD and MK, the difference in load capacity of these joints is small.

Tab. 2 The average values of measured and calculated values necessary for assessing the mechanical properties of self-locking joints - compressive force in angular plane.

Type of joint	The number of samples	M_u (N.m)	T (N.m/rad)	Coefficient of variation M_u	Coefficient of variation T
Z	10	260.54	512.45	14.70	14.73
MK	10	356.65	701.38	5.100	5.175
MD	10	372.36	735.49	2.980	3.010

The highest stiffness value was calculated for the MD joint (735.49 N·m/rad), whereas in the case of the Z joint the stiffness reached the lowest value (512.45 N·m/rad). The difference is 43.5 %, which is similar to the difference if comparing the load capacity of the two joints. The difference between the stiffness of MK joint (701.38 N·m/rad) is lower by only 4.9 % if compared to the highest value of stiffness at MD joint (735.49 N·m/rad).

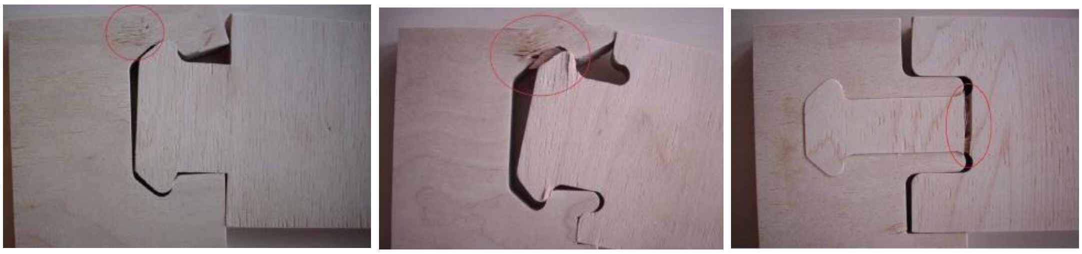
In Tab. 3 there is a statistical evaluation by ANOVA. The load capacity and stiffness of joint are evaluated on the basis of joint's shape on the significance level $p = 0.000002$ (< 0.5)

Tab. 3 The significance level by Duncan's test.

	Type of joints	Thickness of material	{1} M_u=260.50	{2} M_u=356.68	{3} M_u=372.40	{1} T=260.50	{2} T=356.68	{3} T=372.40
1	**Z**	**18**		**0.000172**	**0.000090**		**0.000172**	**0.000090**
2	**MK**	**18**	**0.000172**		**0.298634**	**0.000172**		**0.256372**
3	**MD**	**18**	**0.000090**	**0.298634**		**0.000090**	**0.256372**	

It follows, that the differences between the mechanical properties of the modified joints, e.g. joints with additional pins on the arm of tenon (joints MK and MD) and the basic joint Z are statistically significant.

The possible types of failures of the joints loaded by compressive force are shown in Fig. 4. In the basic joint Z and the modified joint MK, the failure element arose on the inner part of the mortise. It is at this place, the modified head of tenon is causing the stress concentration which exceeds the strength value of plywood. The failure of modified joint MD was visible at the point of heel pin of a structural element; it is justified by the concentration of shear stress in the heel of tenon. However, the reduced width of the tenon contributed to the fact that the joint did not fail in the inner circumference of the mortise, as in the cases of Z and MK joints.



a) b) c)

Fig. 4 Typical breaches of joints loaded by compressive stress in angular plane. a) basic joint (Z), b) modified joint, short (MK), c) modified joint, long (MD).

To evaluate the state of stress, the von Mises criterion was used. In view of the relatively small difference in the values of modulus of elasticity and Poisson's ratio, as shown in Tab. 1, it comes to a weakly anisotropic ductile material, for which even the Mises criterion has sufficient explanatory power. Numerical analysis showed that the damages and a potential places for creation of cracks are just in the points of stress concentration. The forces F_{max} under which the joints were loaded in numerical analysis were based on experimental measurements, as shown in Tab. 2. The values of stress (Fig. 5) for these forces have confirmed the assumption of increasing load capacity of joint by changing the shape design. In the experiments, the joint Z showed the lowest load capacity (Z; M_u = 260.54 N·m), which was reflected also in the value of stress 299.17 MPa at a force of 4390 N. The joint MD with the highest load capacity (MD; M_u = 372.30 N·m) achieved the highest stress of 157.45 MPa at a force of 6110 N.

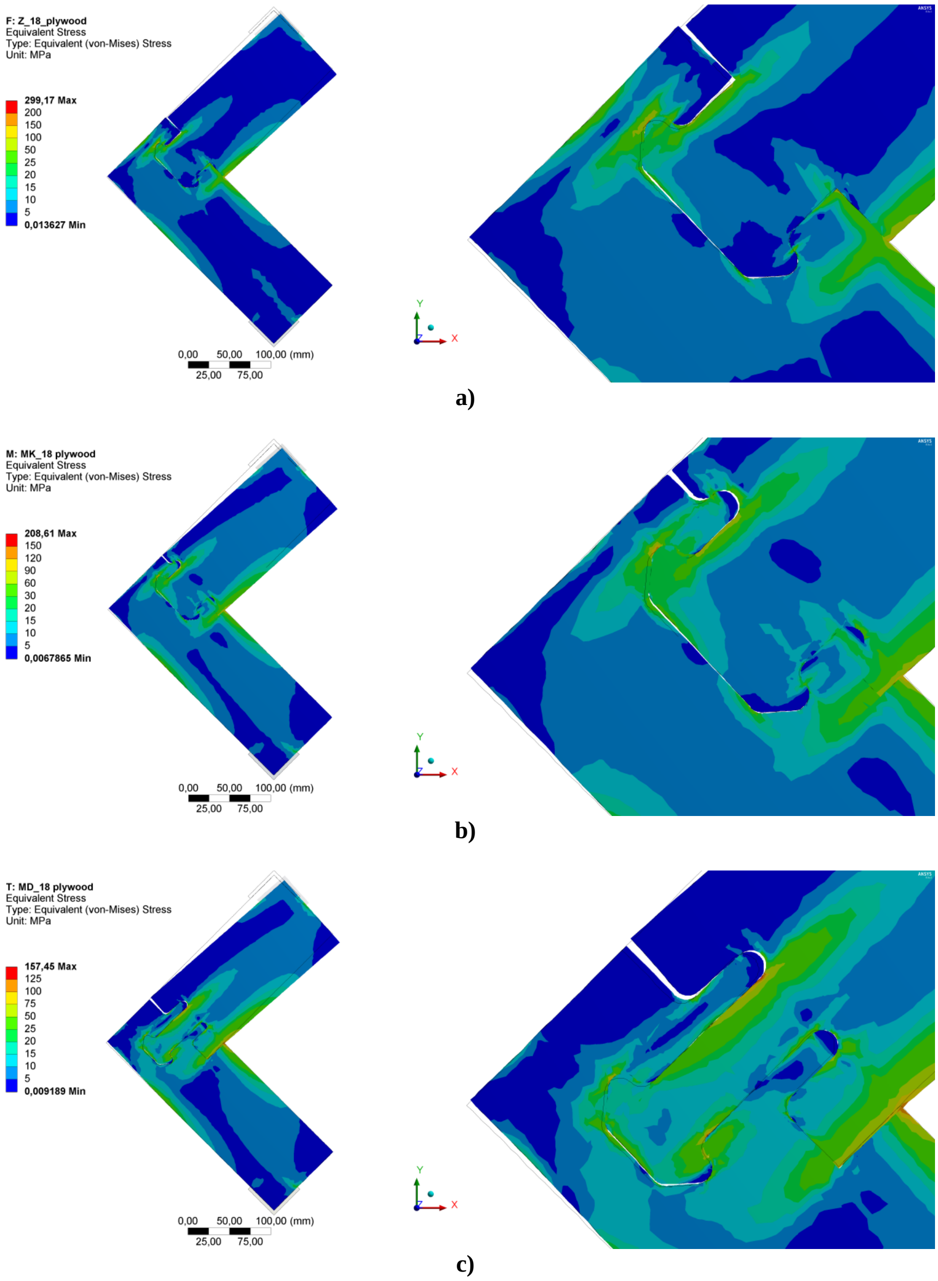
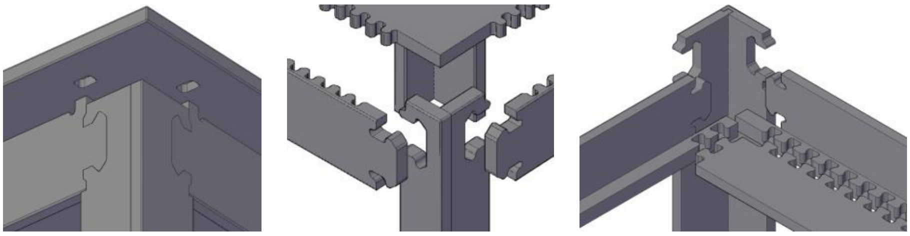


Fig. 5 Distribution and locations of stress concentration in self-locking joints. a) the base joint (Z), b) the modified joint, short (MK), c) the modified joint, long (MD).

A breach can be evaluated according to the places with the highest stress concentration. In the joints Z and MK, the maximum stress concentration is in that point of a joint, where the modified head of tenon is leaning into the mortise of the opposite member. The tenon width is large enough to be able to transfer the required load. In the joint MD the highest stress concentration is created in the point of the heel of the extended tenon; from there the damage is spreading to the entire width of the tenon. This type of damage was developed in experimental test as well (Fig. 4c). Follows from the above that the load capacity of this joint is limited by the width of tenon.
Possibilities of using the studied joints are shown in Fig. 6.



a) b) c)

Fig. 6 Examples of application of the tested self-locking joints in furniture constructions (GRIČ 2014). a) connection of structural parts of the table, b) connection of structural parts of the chair, c) support frame of the bed.

CONCLUSIONS

The assumption to increase the mechanical properties of the joint by changing the shape and dimensions of the contact surfaces of assembly elements has been confirmed. Mainly pin created on the shoulder of tenon contributed to increased mechanical properties. The mutual comparison of mechanical properties of all the joints with pin showed the modest increase even if the length of tenon was enlarged and width of the tenon was reduced (MD).

Based on analysis of failures of self-locking joints, we can conclude that for each type of designed joint the specific failure was observed that is described and theoretically confirmed. From failures of individual types of joints, which showed very little variability in the experiments, the relationships can be designed to optimize the shape and dimensions of self-locking joints.

If comparing the experimental measurements and numerical analysis by FEM, we can conclude that the mechanical properties of self-locking tenon joints depend on the width of the tenon and dimensions of the additional pins. With an enlarged pin width the mechanical properties of the joints will increase; the joints are deformed or damaged at higher forces. The research results presented are good basis to continue the research on high performing self-locking joints in plywood created by CNC technology.

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ACKNOWLEDGEMENT

This work was supported by the grant agency VEGA under the project No. 1/0626/16.

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