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Strength properties of self-locking furniture joints with shape adapted for the production by CNC technology

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Abstract: *Strength properties of self-locking furniture joints with shape adapted for the production by CNC technology*. This work deals with strength characteristics of self - locking furniture joints. The basis of these connections is created using the tenon and mortise. However, we are modifying their shape so as to ensure self-locking joint, without glue or other connecting element. For the construction of joints was used plywood for its good mechanical properties and aesthetic properties especially in the transverse direction. The results of experiments and calculations are compared with traditional joints which are made of wood-based materials.

Keywords: furniture joints, self-lock joints, strength properties of joints, plywood, CNC technology

INTRODUCTION:

Self-locking connections are mainly produced with the support of CNC technology which allows creating precision and aesthetic connections. The potential use of these joints consists in simple assembly procedures, without the use of plant materials and fasteners. Therefore, this furniture can be just considered as ecological because there is no necessary to separate fasteners or ecologically dispose of bonded joints. Use of these joints we expect an increase in the competitiveness of small and medium-sized furniture manufacturers.

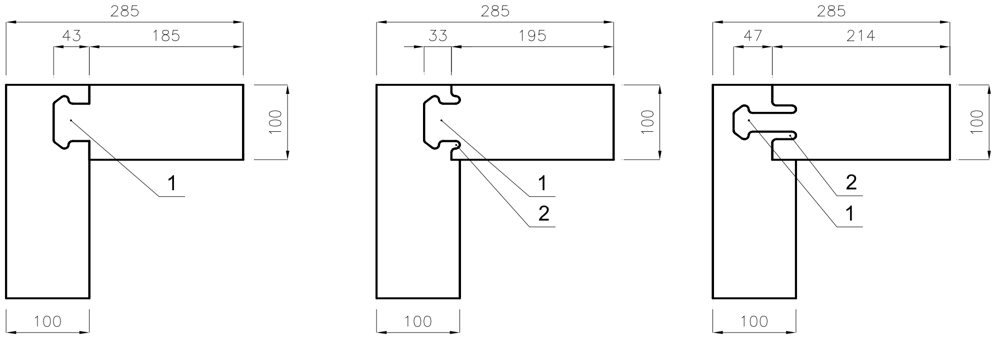
The issue of investigation mechanical properties self-locking joints is given very little attention. Monitoring the mechanical properties these connections is based on the works of authors (Erdil, Kasal, Eckelman 2005), who devoted glued joints, shapes, joints, however, are created on the principle of self-locking. The authors deal with influence of wood species, adhesive type, the width of the horizontal structural element, the width and length of the tenon on the bending strength of joints made using the tenon and mortise. Another group of existing work is mainly focused on the aesthetic design of joints (Gros, 1998) or numerical treatment of the problem (Sebera, Simek, 2010).

Our paper is devoted to identifying the impact of the shape and dimensions of the contact surfaces of self-locking joints on their mechanical properties. The joints were created using the tenon and a corresponding mortise. By modifying the dimensions of the contact area, we created three groups of joints made of beech plywood thickness 18 mm.

MATERIALS AND METHODS:

The joints were made of beech plywood 18 mm thick (13 layers). We chose plywood on the basis of its strength properties. Importance is also the aesthetic properties in the transverse direction, which proves precisely at times those types of joints. Aesthetic properties of plywood in the transverse direction are important to show just for these types of connections.

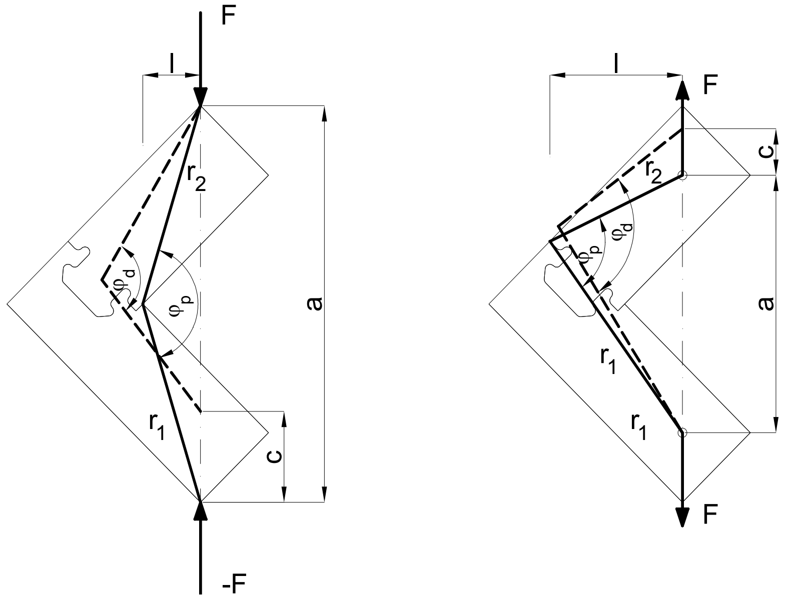
We created three groups of joints. The basis for these joints represented shaped tenon, modifying its size and contact surface we created other two shapes of joints. Tested joints are shown in Fig. 1, the designation is as follows: Z - basic joint, MK - modified short joint, MD - modified long joint. For determining the mechanical properties of the investigated joints, we investigated the effect of the shape of the contact surface and the influence of the shape and dimensions of the tenon. The basic joint has a smooth, untreated contact surface. Modified joints have the contact area with the pins; their size is adapted to the shape and dimension of the tenon.



a) **b)** **c)**

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

Mechanical properties of the tested self-locking joints were investigated under pressure and tension load in the angular plane on a universal test machine. We have determined the size of the maximum force in breach the joint F_{max} (N) and displacement joint shoulder c (mm). These data are used to determine the load carrying capacity of the joint M_u (N.mm), the deformation on limit load carrying capacity φ_{max} (rad) and stiffness T (Nm/rad) each types of joints. Schemes for different types of load are shown in Fig. 2 Samples were conditioned at 21° C and a relative air humidity of 65%, on the following conditions was also tested.



a) **b)**

Fig. 2 Schemes for each type loads with calculation parameters:
a) pressure test, b) tensile test
F-tensile / press force (N), r1, 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 the force arm (m), c - shoulder joint displacement (m)

On the basis of dimensional parameters joint and load diagram was determined joints strength properties:

Load carrying capacity: $M_u = F_{max} . l$

Deformation at maximum load carrying capacity of joint: $\varphi_{max} = \varphi_p - \varphi_{d,max}$

To apply the pressure:

$$\varphi_{d,max} = \frac{\arccos(r_1^2 + r_2^2 - (a - c)^2)}{2 . r_1 . r_2}$$

To apply the tensile:

$$\varphi_{d,max} - \frac{\arccos(r_1^2 + r_2^2 - (a + c)^2)}{2 . r_1 . r_2}$$

Stiffness of joints:

$$T = \frac{\Delta M}{\Delta \varphi}$$

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

Pressure stress:

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

Tensile stress:

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

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

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

RESULT

Pressure load:

The characteristics properties of self-locking joints loaded pressure are shown in Table 1. The greatest load carrying capacity was achieved in the modified joint MD (372, 36 Nm). The lowest value of load carrying capacity was measured in the case basic joint Z (260,54 Nm). The high difference 42, 9% is caused to the absence of pins and mortise in the base joint Z. When we compare load carrying capacity modified joints MK (356, 65 Nm) and MD (372, 36Nm) difference between the carrying capacity of these joints is low (4.4%). It is necessary to note that in spite of differences dimensional (tenon width, tenon length, length of pin) difference between the load carrying capacity modified joints MK and MD is very low.

The highest value stiffness in bending stress joints in the angular plane of pressure was measured in joint MD (735, 49 Nm/rad), while in the case of base joint Z stiffness is lowest (512.45 Nm/rad). Differences represent 43, 5%, which is similar to difference in the comparison of the two load capacity joints. The difference between joint stiffness M (701, 38 Nm / rad) is compared to the highest value of joint stiffness D (735.49 Nm / rad) is lower by only 4.9%.

Tab. 1: Average values of measured and calculated values necessary for assessing mechanical properties self-locking joints - the pressure in angle plane

Loads method	**Type of joint**	**Plywood thickness (mm)**	**F_{max} (N)**	**M_u (N.m)**	**C_{max} (mm)**	**$\Delta\varphi_{max}$ (rad)**	**T (Nm/rad)**
Stress	Z (basic j.)	18	4342	260,54	4,97	0,0776	512,45
	MK (short j.)	18	5943	356,65	6,21	0,0957	701,38
	MD (long j.)	18	6205	372,36	8,19	0,1232	735,49

Characteristic force-deformation diagram joints pressure loaded in the angular plane shown in Fig. 3.

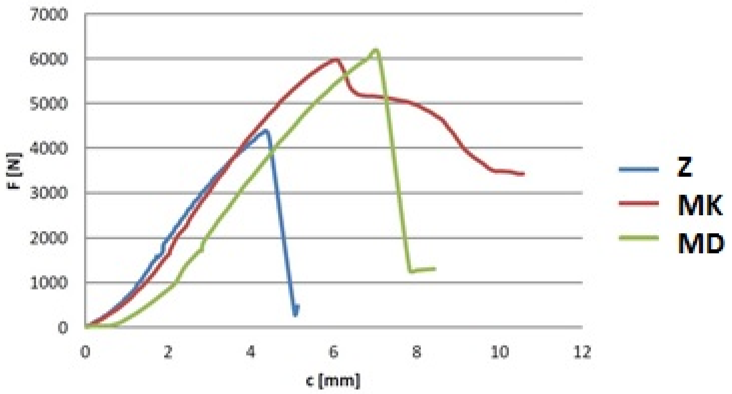


Fig. 3 Load-deformation diagram for joints loaded by pressure in the angular plane

Mode of failure joints loaded by stress shown in Fig. 4 In the basic joints Z and modified joints MK are being infringed outside of the element with the notch. Precisely in this point pin causes stress concentration. This value exceeds the strength of plywood. A modified joint MD was broken in heel of pin. Breach is caused by the concentration of shear stresses in the heel pin. Damage to the outside of the element with the mortise occurred due to the increase in the size, compared with joint Z.

Fig. 4: Characteristic breach of joints under pressure load in the angular plane

Tensile load:

Characteristics mechanical properties self-locking joints under tension loading are shown in Table 2. The greatest load carrying capacity was achieved in the modified short joint MK (362,71 Nm) while in the case of modified long joint MD is this lowest value (216,89 Nm). The achieved difference in load carrying capacity between these joints is reasoned by different width pins both joints. The results obtained shows that the pin width significantly influences the load carrying capacity of joints which are loaded in the angular plane. When comparing the load carrying capacity the basic joint Z (300,20 Nm) with modified joint MK (362.71 Nm) difference represents a 17.3% in favour of joint MK. On the basis of this finding, we can say that the presence of the pins, resp. their absence, has a relatively large impact on the load carrying capacity of joints.

Within the comparison of stiffness, the highest value was reached in the case of joint MK (561,23 Nm/rad), while in the case of joint MD (335,45 Nm/rad) was reached lowest stiffness. The reached difference between the joints stiffness has 40,22%, which can be attributed to the difference width of the tenon compared joints. The stiffness difference between the basic joints Z (463,62 Nm / rad) and joint MK (561,23 Nm/rad) is 17,40%. Difference is caused by the absence (Z joint) respectively presence (M joint) pins.

Tab. 2 Average values of measured and calculated values necessary for assessing mechanical properties self-locking joints - the tensile in angle plane

Loads method	**Type of joint**	**Plywood thickness (mm)**	**F_{max} (N)**	**M_u (N.m)**	**C_{max} (mm)**	**$\Delta\varphi_{max}$ (rad)**	**T (Nm/rad)**
Tensile	Z (basic j.)	18	2175	300,2	8,5	0,3046	463,62
	MK (short j.)	18	2628	362,71	6,73	0,2916	561,23
	MD (long j.)	18	1572	216,89	7,66	0,2984	335,45

The force-deformation diagram joints tensile loaded in the angular plane shown in Fig. 3.

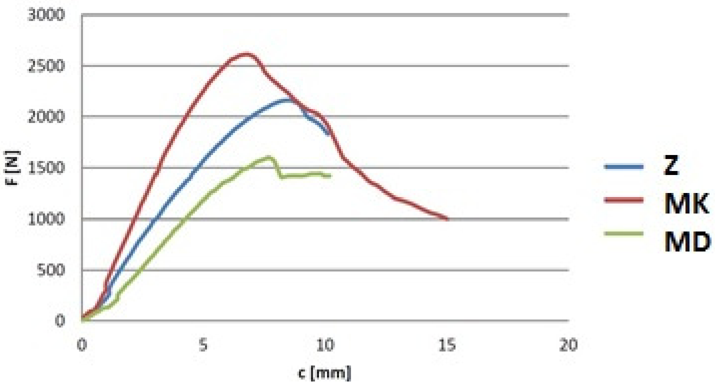


Fig. 5 Load-deformation diagram for joints loaded by tensile in the angular plane

Modes of failure joints under tension loading are shown in Fig. 6. In the case of basic and modified joint M was breach created in the place protrusion a pin. Breach is clearer in the modified short joint MK, which is caused by a better stabilization of the pin through the mortise in the vertical structural elements. The joint is able to bear the larger loads, which led to larger deformation at the bottom of the pin, as well as larger load capacity to deformation of the joint. Breach of D joint is different than other damage. The damage has occurred in pin the structural element due to the downsizing

Fig. 6 Characteristic breach of joints under pressure load in the angular plane

CONCLUSIONS

1. Increase the mechanical properties of joints by increasing the contact area, this means creating mortises and pins in the contact area was confirmed. This was most reflected in the modified joints. The highest average values were obtained in the modified short joints MK: load carrying capacity 359 N.m, stiffness 631 Nm/rad. This joint has sufficient tenon width and optimal length for pin, against modified long joints MD.
2. On the basis of the breach of each type of joints, that exhibit very little variability, we can suggest relationships to optimize the shape and dimensions of self-locking joints.

3. Our next research will focus on other shapes of the self-locking of joints. We will examine the interaction between shape and size of joints, thickness and type of material. Experimental results will be compared with the calculation method (FEM) and optical methods for detecting deformations which we achieve mutual authentication and validation of the results.

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Streszczenie: *Wytrzymałość samoblokujących połączeń meblowych o kształcie dostosowanym produkcji na centrach obróbkowych.* Praca dotyczy parametrów wytrzymałościowych samoblokujących połączeń meblowych. Podwalinę stanowiły zwykłe połączenia czopowe, o zmodyfikowanej konstrukcji nie wymagającej kleju ani innych elementów pomocniczych. Do wykonania połączeń użyto sklejki, zapewniającej wytrzymałość oraz estetykę, zwłaszcza w przekroju poprzecznym. Rezultaty eksperymentów zostały porównane z tradycyjnymi połączeniami.

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