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THE RELIABILITY OF JOINTS AND CABINET FURNITURE

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ABSTRACT

The objective of the study was to determine the distribution of strains and strength for some selected detachable and non-detachable furniture joints and to assess the probability of the damage-free operation of these joints and to determine probability of failure-free operation of case furniture constructions assembled with the assistance of these connections. Strength investigations were carried out on three populations of angle joints, 10 items each, in which two types of fasteners were used: a Confirmat type of bolt ø5x50 mm, beech dowels of ø6x32 mm dimensions and ø8x32 mm dowels. The joints were made from non-veneered particle boards. Strength and stresses of selected angle joints probability characteristics were elaborated. In the case 6 mm dowel joint, the probability of failure-free operation amounts to 0.927149, but the reliability of the furniture construction concerning this joints is equal 0.546004. For the ø8 mm dowel joint, this probability amounts to 0.999178, whereas for the bolt joint of the Confirmat type – to 0.999999. The reliability of the furniture concerning this joints is equal 0.993442 and 0.999992. Only the application of high reliability joints or systems employing additional safety precautions can improve significantly the reliability of furniture and prolong the period of their utilisation.

KEY WORDS: reliability, joints, cabinet furniture

INTRODUCTION

The European Union Directive No. 2001/95/EC concerning general safety of products also refers to furniture. The appropriate European standards define the requirements in the field of furniture safety; however they do not deal with the construction reliability during prolonged time of furniture utilisation. On the other hand, the application of traditional designing methods and assessment of strength requirements for furniture on the basis of subjectively adopted safety coefficients and a margin of safety fail to predict the time and probability of damage of a given piece of furniture or one of its elements. This point of view we can see in many papers. Dudas et al. (1999) appointed only stiffness characteristics of nail joints. Denizli-Tankut et al. (2003) described that performance of existing designs can by improved by attaching different furniture elements or joints but not by use joint with higher reliability. The Joscak's works (1999a, 2006) described characteristics of furniture joints and their influence on stiffness of furniture, but did not analysis of reliability this joints. It is, therefore, obvious that the deterministic approach to furniture design is not reliable and makes it difficult for furniture manufacturers to estimate warranty conditions which would be satisfactory for themselves and customers, including the period of repair free of charge. Therefore, it appears appropriate to introduce new designing methods which would take into account the random character of construction parameters which, in turn, would make it possible to determine the reliability of furniture already during the construction phase. Joscak (1999b) presented this kind of furniture design with use mathematical models of reliability with are friendly to use in practice. The durability of furniture, in the majority of cases, depends on the strength of its construction nodes (Bachmann and Hassler 1975, 1976; Chia-Lin and Eckelman 1994; Gozdecki and Smardzewski 2005; Kuhne and Kroppelin 1978; Ji-Lei-Zhang and Eckelman 1993; Smardzewski 2002a, 2002b; Smardzewski and Gozdecki 2007). Wan-Qian and Eckelman (1998) demonstrated that the ultimate bending strength oh fasteners used in corner joint construction decreases as their zones of influence being to overlap. In the case of the reliability analysis of furniture constructions, all construction parameters of systems must be determined by appropriate distributions of stresses and strengths or loads and carrying capacities, first and foremost, in relation to connections and elements. If these two distributions are determined, then we can determine the probability of connection damage and, later on, the probability of damage of the entire piece of furniture. The problems of reliability of furniture constructions were discussed in few publications (Smardzewski 2005, Smardzewski and Ożarska 2005) in which the main focus was on the studies of stiffness of dowel and bolt joints in furniture for storage. However, no investigations were carried out concerning the probability assessment of damage-free connections and failure-free operation of the entire furniture structure.

The objective of the study was to determine the deformation and strength for some selected detachable and non-detachable furniture joints and to assess the probability of the damage-free operation of these joints and to determine probability of failure-free operation of case furniture constructions assembled with the assistance of these connections.

MATERIAL AND METHODS

The probability of the excess of the limiting level of strength of furniture connections was adopted as the basis for the assessment of furniture joint reliability. From the point of view of reliability, the strength calculation can be reduced to the determination of the probability of exceeding a given level of limiting stresses Z of defined distribution area by random work stresses σ in a given time. In furniture utilisation practice, it is possible to find complex cases which require taking into consideration both the decreasing strength of the joint as well as increased internal stresses. Because Z and σ values are random variables, it was necessary to establish, on the basis of their characteristics, the destruction probability of the Φ(u) construction in the course of the planned period of utilisation. For random variable strengths Z and σ stresses characterising furniture joints, it was necessary to determine forms of distributions of f(Z) and f(σ) and, later on, on the basis of the sizes of the penetration surface areas (Fig. 1), to determine the probability of occurrence of a damage: ***F(Z< σ)***.

According to Murzewski (1989), the probability that a certain value of strength Z is situated in a narrow interval dZ (Fig. 2) and that the σ stress does not exceed Z_0 can be expressed as follows:

$$R(\sigma \le Z) = f_Z(Z_0)dZ\int_{-\infty}^{Z_0} f_\sigma(\sigma)d\sigma . \tag{1}$$

The non-reliability, or the probability of damage of the construction will thus amount to:

$$F = F(Z \le \sigma) = 1 - \int_{-\infty}^{\infty} f_\sigma(\sigma)(1 - F_Z(\sigma))d\sigma = \int_{-\infty}^{\infty} F_Z(\sigma) f_\sigma(\sigma)d\sigma , \tag{2}$$

or for,

$$R = \int_{-\infty}^{\infty} f_Z(Z)\left(\int_{-\infty}^{Z} f_\sigma(\sigma)d\sigma\right)dZ, \tag{3}$$

$$F = F(Z \le \sigma) = 1 - \int_{-\infty}^{\infty} f_Z(Z)F_\sigma(Z)dZ = \int_{-\infty}^{\infty}\left(1 - F_\sigma(Z)\right)f_Z(Z)dZ. \tag{4}$$

Strength investigations were carried out on three populations of angle joints, 10 items each, in which two types of fasteners were used: a Confirmat type of bolt ø5x50 mm, beech dowels of ø6x32 mm dimensions and ø8x32 mm dowels. The joints were made from non-veneered particle boards characterised by the following parameters: thickness h_p=18 mm, density ρ=660 kg/m^3, bending strength k_G=16MPa, interlaminar strength k_R=0.35 MPa, absolute moisture content 8%, and glue shear strength k_S=9MPa and beech shear strength k_B=17MPa. Compression loads were applied on a ZWICK 1445 test machine which recorded simultaneously the load value P and the translocation ΔP at the point of force application (Fig. 3). These results were used to determine values of breaking forces and the most significant strength indices of joints.

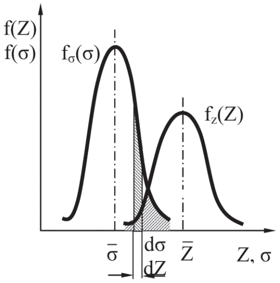

Fig. 1: Distribution penetration of stress $f_\sigma(\sigma)$ *and strength* $f_Z(Z)$

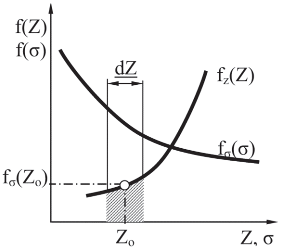

Fig. 2: Determination of the probability of failure-free operation

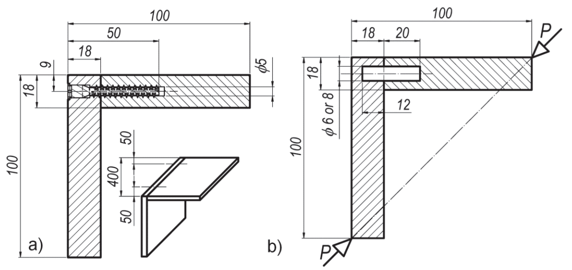

Fig. 3: Joint construction and the method of their loading: a) bolt joints of Confirmat type, b) dowel joints

The following were adopted as indices of joint strength:
the shear strength of the fastener:

$$Z_B = \frac{4P\ \sin\left(45^\circ\right)}{\pi d^2} \le k_B \tag{5}$$

the glueline shear strength

$$Z_S = \frac{3\left(P\cos\left(45^\circ\right) + 2M_i/h_p\right)}{2\pi d h_p} \le k_S \tag{6}$$

and the interlaminar strength of the particle board

$$Z_R = \frac{P\sin\left(45^\circ\right)}{\left(L - 2/3h_p\right)^2} \le k_R \tag{7}$$

The value of the bending moment M_i in the joint was determined from the following equation:

$$M_i = P\cos\left(\Delta\varepsilon_2\right)\left(\left(L - h_p\right)^2 + h_p^2\right)^{0,5}, \tag{8}$$

where:

$$\Delta\varepsilon_2 = 45^o + ar\sin\frac{h_p}{\left(\left(L - h_p\right)^2 + h_p^2\right)^{0,5}} - \varphi_2,$$

$$\varphi_2 = \gamma_3 - \beta_2$$

$$\gamma_3 = ar\cos\frac{\frac{1}{2}\left(a - \delta_p\right)\left(\left(L - h_p\right)^2 + h_p^2\right)^{0,5}}{\left(L - h_p\right)^2 + h_p^2},$$

$$\beta_2 = ar\cos\frac{\frac{1}{2}a\left(\left(L - h_p\right)^2 + h_p^2\right)^{0,5}}{\left(L - h_p\right)^2 + h_p^2},$$

determined on the basis of a geometric dependence in the deformed joint (Fig. 4).

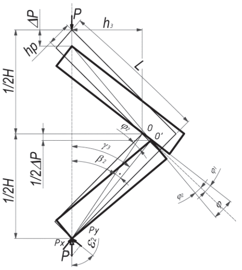

Fig. 4: Geometric dependence in the deformed joint

The strength coefficient values of the examined joints are presented in Tab. 1. It is evident from this Table that the low interlaminar strength of particle boards could have posed a serious hazard to the failure-free work of the furniture construction. That is why further investigations on the character of random variable strength f(Z) and stresses f(σ) were limited only to the results of determination of the particle board interlaminar strength.

Tab. 1: Indices of joint

Type of joint	Symbol	Strength [MPa]					
		Of fastener to shear		Of glue line to shear		Particle board to delamination	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Dowels 6	Z6	7.03	0.59	8.64	0.72	0.501	0.044
Dowels 8	Z8	5.22	0.27	8.87	0.41	0.662	0.033
Confirmat	ZK	19.86	1.84			0.272	0.025

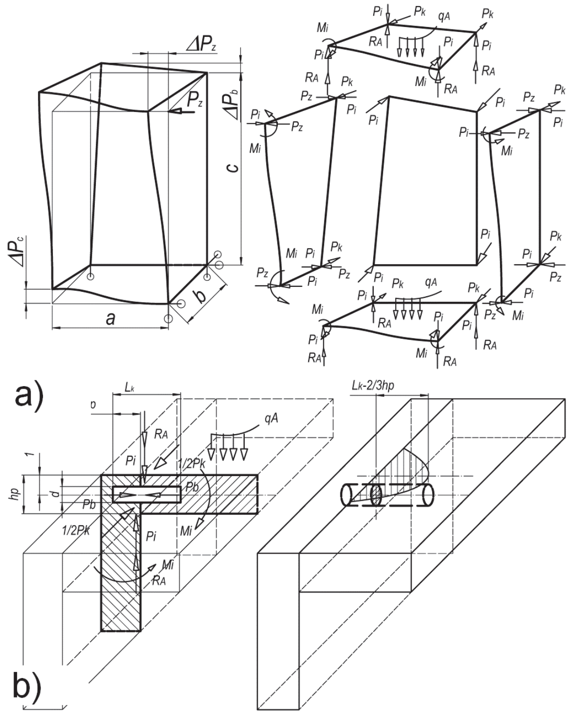

Fig. 5: Distribution of internal forces: a) in the furniture body, b) in the joint

Bearing in mind the distribution of internal forces affecting the nodes of the furniture body (Fig. 5a,b) and taking into consideration only the criterion of particle boards to interlaminar strength, stresses caused by operational loads were calculated from the dependence:

$$\sigma_R = \frac{P_i + R_A}{\left(L - 2/3h_p\right)^2} \le k_R, \tag{9}$$

where:

$$P_i = \frac{G_i h_{pi}^3}{3\left(l_1 l_2\right)_i}\zeta_i \frac{P_Z}{\sum\limits_{i=1}^{5} \frac{G_i h_{p_i}^{\ 3}}{3\left(l_1 l_2\right)_i}\zeta_i^2},$$

$$R_A = \frac{1}{4} q_{Ai}\left(l_1 l_2\right)_i,$$

$$l_1, l_2 = a, b, c,$$

$$\zeta_i = a/c; a/b.$$

It was further assumed for calculation purposes that a piece of furniture can be loaded by the user with an external force P_z of varying value (600, 490, 480, 420, 360, 300 N) and of standard deviation 105.9 N. Stresses determined for these loads are presented in Tab. 2.

Tab. 2: Stress values in the examined joints according to the particle board interlaminar strength criterion

Joint type	Symbol	Strength [MPa]	
		Mean	Std. Dev.
Dowel 6	N6	0.368	0.088
Dowel 8	N8	0.368	0.088
Confirmat	NK	0.105	0.024

RESULTS

On the basis of the calculation results from Tab. 1 and 2 of strength Z and stresses σ of selected angle joints probability characteristics were elaborated (Fig. 6) from which it is evident that the areas of inter-penetration of both distributions depend on the type of joints. A greater area of penetration indicates a greater probability of joint damage. On the other hand, absence of penetration indicates that the examined joint is failure-free in the given range of loads.

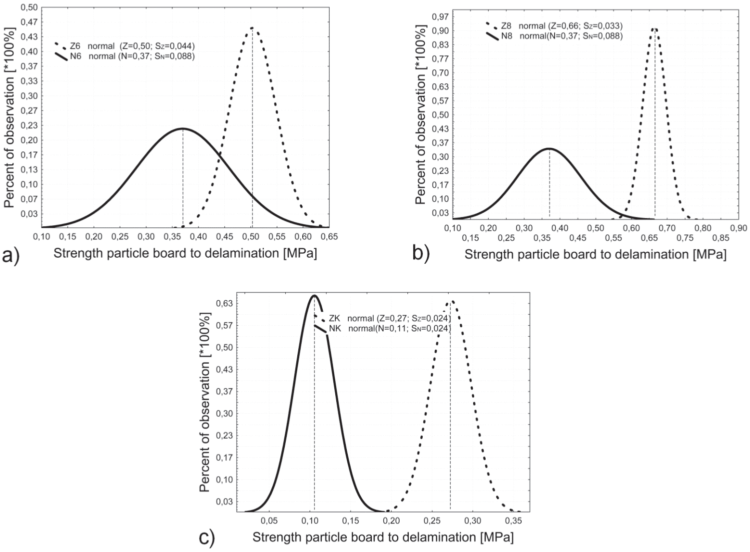

Fig. 6: Distribution of stress f(N) and strength f(Z) of a joint with: a) dowel of 6 mm diameter, b) dowel of 8 mm diameter, c) Confirmat type bolt

In order to determine numerical values of the probability of joint destruction, a new random variable was considered:

$$Y = Z - \sigma . \tag{10}$$

In this case, the safety condition for the construction was the assumption that:

$$R = F(Y > 0),$$

hence, the probability of destruction was described as:

$$F = \int_{-\infty}^{0} f_Y(Y)\,dY = \int_{-\infty}^{0}\int_{-Y}^{\infty} f_Z(Y+\sigma)\,f_\sigma(\sigma)\,d\sigma\,dY. \tag{11}$$

It was assumed, for the discussed case of joints of cabinet furniture, that both random variables Z and σ, as presented in Fig. 6, are described by the normal distribution:

$$f_\sigma(\sigma) = \frac{1}{S_N\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{\sigma-\overline{\sigma}}{S_N}\right)^2\right), \tag{12}$$

and

$$f_Z(Z) = \frac{1}{S_Z\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{Z-\overline{Z}}{S_Z}\right)^2\right),$$

where:

$\overline{\sigma} = N$ and $\overline{Z} = Z$ then the mean values of the stress and strength,
S_N and S_Z then the standard deviations of the stress and strength,
hence, the standard deviation of the new random variable Y was described by the equation:

$$S_Y = \sqrt{S_N^2 + S_Z^2}\,.$$

Therefore, the distribution of the random variable Y assumed the form (Fig. 7):

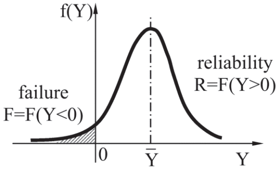

Fig.7. Characteristics of the distribution probability of the value $Y=Z-\sigma$

$$f_Y(Y) = \frac{1}{S_Y\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{Y-\overline{Y}}{S_Y}\right)^2\right). \tag{13}$$

Therefore, the probability of the failure-free operation was expressed in the form:

$$R = P(Y > 0) = \int_{0}^{\infty} f_Y(Y)\,dY = \int_{0}^{\infty}\frac{1}{S_Y\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{Y-\overline{Y}}{S_Y}\right)^2\right)dY. \tag{14}$$

Assuming the designation:

$$u = \frac{Y-\overline{Y}}{S_Y},$$

$$dY = S_Y\,du,$$

at:

$$u = \begin{cases} \dfrac{0-\overline{Y}}{S_Y} = \dfrac{\overline{Z}-\overline{\sigma}}{\sqrt{S_Z^2+S_N^2}}; & dla\ Y=0 \\ \longrightarrow \infty; & dla\ y \longrightarrow \infty \end{cases},$$

it follows that:

$$R = \frac{1}{2\pi}\int_u^{\infty} e^{-\left(\frac{u}{2}\right)^2} du = 1-\Phi(u). \tag{15}$$

The Φ(u) value corresponds to the value of the probability of the occurrence of the damage and amounts to:

$$\Phi(u) = F(u) = 0{,}5^{\left(\frac{u}{2}+1\right)^{2.46}} \quad dla \quad u \geq 0$$

On this basis, it was possible to calculate the probability of damage of individual types of joints and the results of these calculations are presented in Tab. 3. It is clear from this Table that joints which were connected using 6 mm dowels were the least reliable. In such case, the probability of failure-free operation in the set load conditions amounts to 0.927149. In the case of the ø8 mm dowel joint, this probability amounts to 0.999178, whereas for the bolt joint of the Confirmat type – to 0.999999.

Tab. 3: Values of damage probability of individual types of joints

Type of joint	Probability of damage	Probability of failure-free operation
Dowel 6	0.078251	0.927149
Dowel 8	0.000822	0.999178
Confirmat	0.000001	0.999999

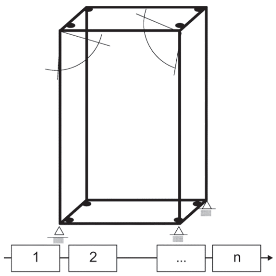

Fig. 8 A piece of cabinet furniture as a serial structure of connections

The reliability of a piece of furniture as a system consisting of many unreliable connections was calculated on the basis of component joint reliabilities. In this case, cabinet furniture was treated as a system of serially connected construction nodes (Fig. 8). The system is characterised by the fact that the destruction of one construction node leads to the destruction of the entire construction.

The probability of a failure-free operation of this construction is expressed by the quotient of probabilities of occurrences of independent components of 8 elements:

$$R(t) = \prod_j^8 R_j(t). \tag{16}$$

In the discussed case $R_1(t)=R_2(t)=...R_8(t)$, hence the probability of the failure-free operation of the furniture body connected with ø6 mm dowels amounts to:

$$R(t) = R_1^8(t) = 0.927149^8 = 0.546004\,.$$

Probabilities of a failure-free operation of the furniture body with construction employing the remaining types of joints are presented in Tab. 4.

Tab. 4: Probabilities of failure-free operation of the furniture body

Type of joint	Probability of damage	Probability of failure-free operation
Dowel 6	0.453996	0.546004
Dowel 8	0.006558	0.993442
Confirmat	0.000008	0.999992

It is evident from the calculations given in Tab. 4 that the reliability of the furniture construction declines with the number of elements connected by means of unreliable construction nodes. Therefore, systems designed using many construction elements must contain fasteners characterized by high reliability, for example, bolt joints of the Confirmat type.

Therefore, if high reliability of a system consisting of many elements is required, it is advisable to employ additional strengthening solutions which will reduce significantly the probability of damage and, at the same time, to use fasteners of lower probability of failure-free operation. In the case of cabinet furniture, especially in multiple-cell systems, two- or three-element strengthening systems are recommended.

ACKNOWLEDGMENTS

Results of the study indicate that:

1. The construction reliability of cabinet furniture is the result of the reliability of its construction nodes.
2. Bolt joints of Confirmat type are characterised by the best reliability which guarantees that the manufactured furniture will be distinguished by the highest reliability and durability in the set conditions of utilisation.
3. It is advisable to employ, in commercial conditions, construction solutions based on bolt fasteners of the Confirmat type or wood dowels of ø 8x32 mm dimensions.
4. The employment of serial solutions, in many cases, disqualifies the quality of furniture and dramatically reduces furniture durability. Only the application of high reliability joints or systems employing additional safety precautions can improve significantly the reliability of furniture and prolong the period of their utilisation.

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