Comparative Reliability Analysis of Selected Joints for Case Furniture

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Specific reliability parameters are used to determine the durability and safety of a furniture structure. An experimental study was conducted to determine the probability of failure free time and compare the reliability and hazard rates of selected joints used in case furniture. The investigations were performed on samples of joints with a connector of the screw, dowel, or eccentric type. Altogether, 600 samples were tested. The reliability tests were conducted on a specially designed laboratory stand. The reliability characteristics of the individual joints were used to designate the most reliable type of joint. The hazard rate of the dowel joint was about 8 times that of the confirmat screw joint. In the case of the eccentric joint, the hazard rate was as much as 57 times higher than it was for the screw joint. The test method presented here for determining the reliability of joints aid in the selection of a connector type during case furniture design.

Keywords: Reliability; Experimental data; Furniture joints; Connectors; Wood based material; Case furniture

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INTRODUCTION

Due to rapid advances in technology and increasing global competition, there is increasing pressure on manufacturers to produce high-quality products. The reliability of a product is a priority in manufacturing engineering and should be considered in the design stage of engineered objects. Before the product is launched on the market, it is necessary to conduct a series of strength and reliability tests to ensure the safety and quality of the product. Product reliability modeling and testing are used for quality control and to develop product reliability improvement programs.

Reliability should be considered when formulating standards in terms of operating requirements, or at the stage of planning for the wear and tear of an object. Smith and Clarkson (2007) have indicated how much conceptual decisions can improve reliability. Public demand for specific characteristics may lead to ergonomic furniture designs, requiring manufacturers to take into account the anthropometric data and to guarantee the durability of the furniture's construction (Jabłoński 2006). The issue of reliability is found in many fields of engineering and concerns various materials, including fibers and fibrous materials (Gohil and Shaikh 2013). In the relationship between human technology and environment, many factors determine the potential occurrence of undesirable events, which could considerably affect the reliability of a given object (Szopa 2016).

The issues of reliability in the wood and furniture industry have been discussed in the literature (*e.g.*, Gremyr *et al.* 2003). Reliability may be specified already at the stage of material production, *e.g.*, oriented strand board (OSB) panels, in the manufacture of various systems. In this case, important characteristics for the determination of reliability include parameters such as rigidity and tensile strength (Li and Ellingwood 2007; Kasal *et al*. 2015; Eckelman *et al.* 2017a,b). The strength of the construction of case furniture is significantly affected by the joints that are used, each of which is characterized by a different level of rigidity and strength. Depending on the type of the furniture joint used and the type of material connected, the reliability of the final product may differ considerably (Smardzewski 2008).

In the furniture industry, reliability tests have also been used, but they have not been applied on a large scale as in the field of machine design and engineering. In fact, furniture manufacturers do not determine the reliability characteristics for a given furniture construction. The problem of reliability has been investigated in the design of case furniture (Smardzewski 2005; Smardzewski and Ożarska 2005). Much attention has been placed on the analysis of construction nodes. These analyses were conducted on doweled joints and confirmat screws. Determining the reliability of these joints enabled specification of the reliability of case furniture containing these joints. The series and parallel structures of such a system were investigated. For users, the parallel structure is more advantageous, as it markedly improves the reliability of furniture and extends its lifetime.

In the furniture industry, several tests and certifications are used to evaluate the whole furniture construction, such as analysis of the strength of angle joints in case furniture using the finite element method (İmirzi and Efe 2013) and the durability of furniture subassemblies (Smardzewski and Majewski 2014; Uysal *et al.* 2015). Rigidity tests of furniture construction are also commonly conducted in terms of the applied joint, such as confirmat screws (Smardzewski and Ożarska 2005). Among the less frequently and insufficiently investigated problems are those of the durability of individual components of furniture, which are of significant importance when designing the system.

The reliability of joints has been discussed in several other publications. Smardzewski and Ożarska (2005) focused on developing mathematical and statistical models to determine the rigidity of screw joints loaded with a bending moment. However, neither the probability of joint damage nor the failure-free operation time were determined for the entire furniture. These characteristics were defined in the case of selected fixed and unfixed joints used in cabinet furniture (Smardzewski 2009). They facilitated the determination of the probability of damage of construction during the planned service lifetime. The reliability of the constructed piece was most affected by the type and number of the joints used.

Typically, furniture manufacturers do not assume failure-free operation of the final product within the recommended service life. Thus, it is not possible to determine the reliability of final products or to predict the damage-free period of the furniture based on the stated length of service life. As stated by Migdalski (1992), the length of a warranty period should be selected so that the defects in the final product are manifested within this period with probability close to one. Intuitive determination of warranty time by designers should be replaced by determination based on statistical analysis and tests of the product.

The determination of the time and probability of damage in the construction of a piece of furniture based on subjectively adopted safety indicators should not be the basis for inferences on the durability of the furniture and its components. It is obvious that only the determination of specific reliability parameters should be the foundation for conclusions on the durability and safety of furniture usage.

This paper reports a comparative statistical analysis that determines the survival probabilities and hazard rates of selected joints applied in case furniture. Using a dedicated laboratory stand, the hazard rates of the dowel joint, confirmat screw joint, and eccentric joint were investigated. This method for determining the reliability of joints can be useful in the selection of a connector type during case furniture design.

EXPERIMENTAL

Testing Materials and Samples

The reliability tests were conducted on 600 samples of joints made from laminated three-layer particleboard of 18 mm in thickness. The shape and basic dimensions are given in Fig. 1. The elements were joined using three types of mechanical joints: confirmat screws, dowels, and eccentric joints. The connectors had the following dimensions: dowel Ø8x32 mm, screw Ø5x50 mm, eccentric of Minifix type Ø15x14,6 mm. The joint with the dowel was glued with the usage of PVAC adhesive.

To ensure that the confirmat screws and eccentric joints in all samples were screwed under application of the same moment of 2.5 Nm, a torque wrench was used. A diagram of the sample used in the test and its loading is presented in Fig. 1.

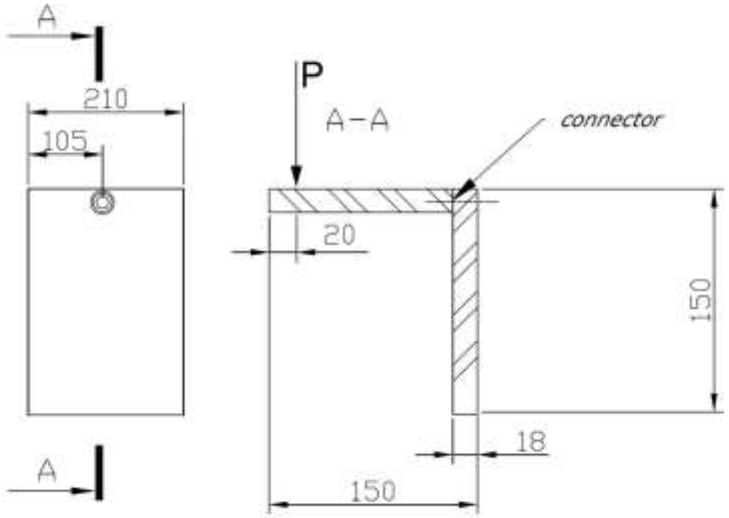

Fig. 1. A diagram of the sample used in test and its loading. The dimensions are given in mm.

Testing Station and Procedure for Analyses of Ultimate Load Carrying Capacity

The ultimate load-carrying capacity of each of the samples was determined by a static closure test. The rupture force was determined using a series of 10 pilot samples for each joint type. The arithmetic mean, standard deviation, and coefficient of variation were calculated.

Static tests to determine the rupture force for joints were conducted using a Zwick 1445 testing machine (Ulm, Germany) (Fig. 2). The first step was the determination of the temporary load carrying capacity of the selected joints. The test velocity was established at 10 mm/min, while the initial load was 1 N. The test was conducted until joint failure. As mentioned earlier, in order to determine the ultimate load carrying capacity, 10 pilot samples for each joint type, confirmat screws, dowels, and eccentric joints, were used.

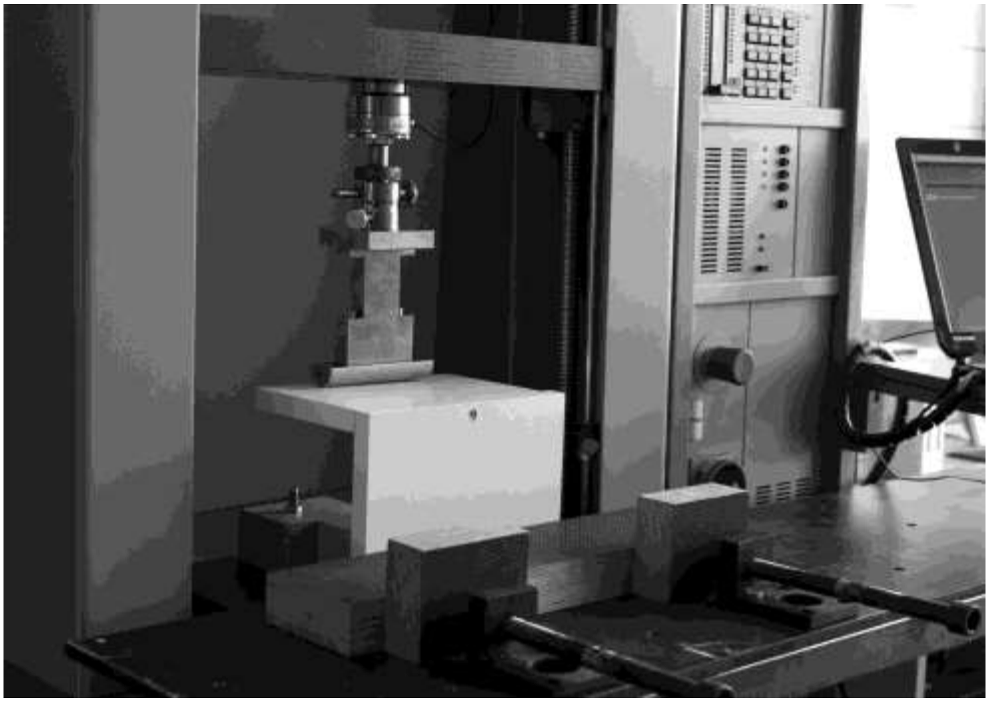

Fig. 2. A Zwick 1445 strength-testing machine with mounted tested sample

Measurements of Lifetimes for Selected Joints under Constant Load

The data recorded on the ultimate load carrying capacities were used to determine the values of the loads applied in the reliability tests. These tests consisted of the measurement of the number of working cycles of joints under the assumed load according to the diagram (Fig. 1). They supplied the input data required for the determination of reliability for selected joints applied in case furniture. The reliability tests were conducted on a specially designed laboratory stand (Fig. 3).

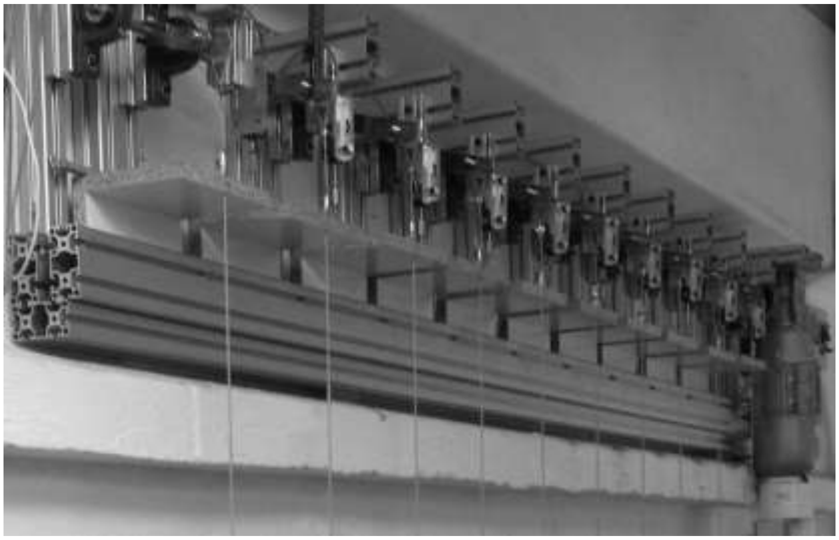

Fig. 3. The laboratory testing stands

The test was performed in 20 series, with each using 10 previously prepared uniform samples with a single mechanical joint. These samples were loaded with forces of 40% of maximum load P_{max} ($\overline{\boldsymbol{Pmax}}$) (Dzięgielewski 1978). The test was performed by applying the force acting with the frequency of 20 cycles per minute (Eckelman 1988). The stand comprised also equipment controlling the maximum deflection. This task was performed by electromechanical deflection sensors, which sent data to a comparator in real time. As soon as the assumed maximum deflection was exceeded for the first element of the joints, the comparator stopped the test. At this point, the sample was considered damaged. In the next step, used samples were dismounted and new ones were mounted (the next implication). In each series of tests, 10 samples with a single joint, *i.e.*, a confirmat screw, dowel, or eccentric joint, were mounted on a rail at equal distances. For each type of joints, 20 implications were used in the test, and thus 600 samples were used in total. The counter mounted on the stand was responsible for counting the number of working cycles of joints.

RESULTS AND DISCUSSION

From the mathematical point of view, reliability may be described using several definitions. The lifetime (*i.e.*, number of work cycles) of the joint is a non-negative random variable denoted by T. If the reliability function is absolutely continuous, it can be presented in the following form (Eq. 1) (Migdalski 1982),

$$R(t) = \int_t^\infty f(t)dt \tag{1}$$

where $f(t)$ is the probability density function of the random variable T. The reliability function, $R(t)$, describes the probability that the object can be used in a given time period. The cumulative distribution function for each specified time $t \geq 0$ assumes the value of probability of an antagonistic event (Eq. 2).

$$F(t) = 1 - R(t) = 1 - \int_t^\infty f(x)dx = \int_0^t f(x)dx \tag{2}$$

The reliability characteristics of an object may also be described using the function of intensity of damage, the so-called hazard rate or hazard function, which characterizes the acceptable level of deterioration of reliability occurring at a given moment (Eq. 3).

$$h(t) = -\frac{d}{dt}[\ln R(t)] = \frac{f(t)}{R(t)} \tag{3}$$

Another measure of reliability is provided by the accumulated intensity of damage, which specifies the depletion of the available potential for the performance of a task by the analyzed object (Eq.4).

$$\Lambda(t) = \int_0^t h(y)dy \tag{4}$$

Temporary Load Carrying Capacity of Selected Joints

In the course of the load carrying capacity test for a selected joint, a total of 10 measurements of rupture force P_{max} for selected joints commonly applied in case furniture was obtained. The results, presented in Table 1, were used to calculate their arithmetic mean, standard deviation, and the coefficient of variability.

Table 1. Rupture Force (P_{max}) During Load Carrying Capacity Tests

Rupture Force P_{max} (N)			
Number of samples	Confirmat screw	Dowel	Eccentric joint
1	117	144	55.0
2	106	139	74.2
3	116	134	60.2
4	120	133	61.4
5	116	126	53.8
6	122	132	66.6
7	125	138	56.3
8	115	139	61.4
9	103	128	49.9
10	122	122	56.3
$\overline{Pmax}$	116.2	133.5	59.51
SD	6.99	6.77	6.99
V (%)	6.01	5.07	11.7

A pilot sample of n = 10 for each type of joint was assumed. As a result of the test on the ultimate load carrying capacity, the characteristics of the course of load as a function of deflection were determined for the samples based on data obtained from the Zwick 1445 strength-testing machine. An example course for the joint with a confirmat screw is presented in Fig. 4. Within the graph, a section of linear proportionality was established at approximately 6 mm. This value was similar for all types of joints and was taken as the threshold. After exceeding this point, tests conducted on the reliability testing station were stopped, and the samples were considered damaged.

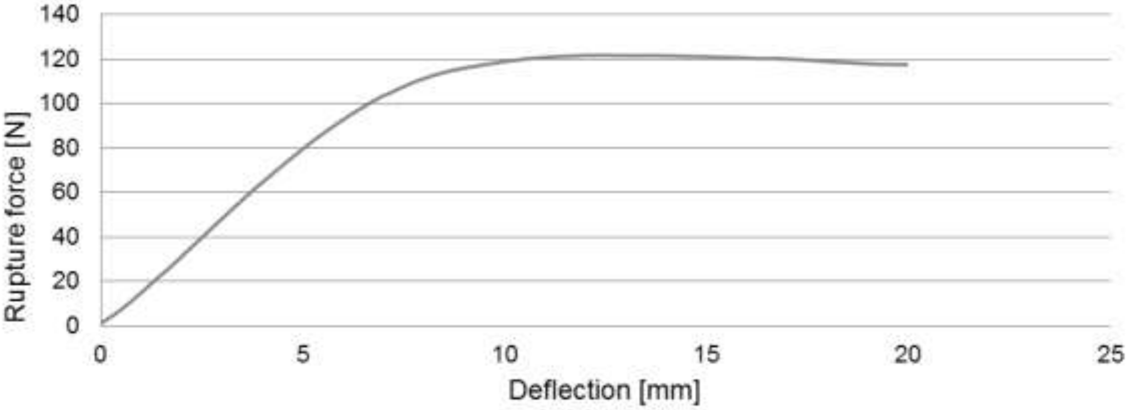

Fig. 4. The rupture force-deflection dependency

Reliability Test

In the course of conducting reliability tests on the joints, a total of 20 measurements of the number of working cycles were recorded for each tested joint at the assumed load. For each of the 20 measurements, the failure time in terms of the number of cycles of the weakest link among the 10 uniform samples with a single mechanical was recorded. Table 2 presents the experimental results in ascending order.

Table 2. Working Time Recorded in the Tests Expressed in Cycles for 10 Joints with a Single Connector

Number of Working Cycles			
No.	Confirmat screw	Dowel	Eccentric joint
1	54127	19203	5650
2	64975	20017	10658
3	65633	23344	11566
4	67706	24060	11824
5	70079	26801	12000
6	72855	28365	12442
7	72960	30968	13210
8	76251	33851	14177
9	79999	36327	14442
10	82849	37846	14882
11	86178	38257	15123
12	87609	38497	15169
13	88500	49737	16289
14	95080	51198	19165
15	107795	53748	19821
16	109961	65052	22345
17	111896	69097	22426
18	114892	72023	23178
19	128311	72900	33173
20	148450	77529	50060

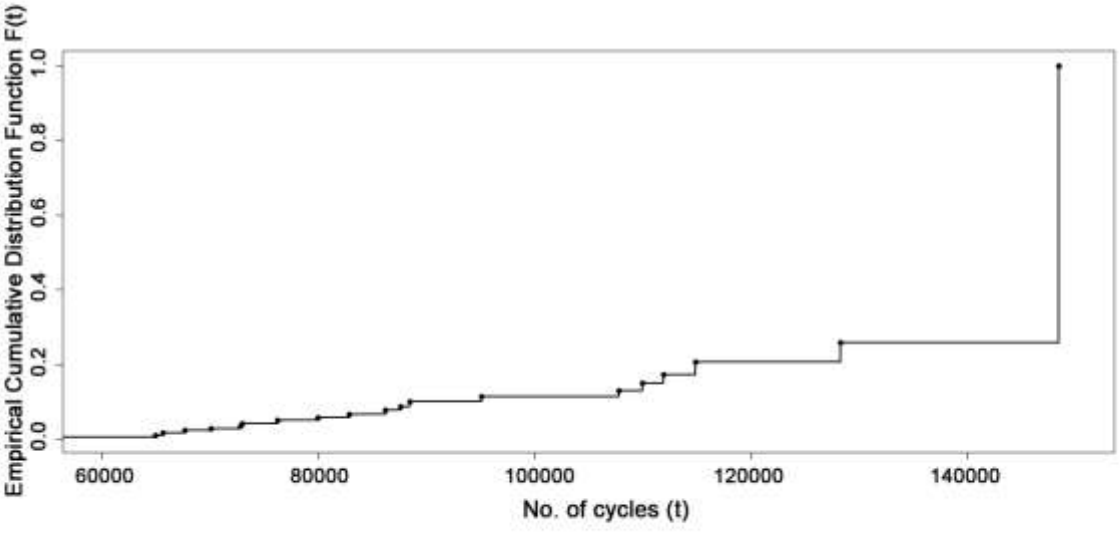

Fig. 5. An example of an empirical cumulative distribution function *F*(*t*) of confirmat screw joint

The first step in the determination of reliability characteristics was to estimate the cumulative distribution function. As was mentioned above, this facilitated determination of the cumulative distribution function *F*(*t*) in time. As may have been expected, the longer a joint was subjected to cyclic work, the greater the probability of joint damage. Let T be the lifetime of the joint and T_{min} be the lifetime of the weakest link among the 10 samples. The cumulative distribution function of the lifetime of a joint can be expressed as follows in Eq. 5,

$$F(t) = 1 - [1 - F_{min}(t)]^{1/10} \tag{5}$$

where $F_{min}(t)$ is the cumulative distribution function of T_{min}. Figure 5 shows an example of an empirical cumulative distribution function $F(t)$ for the confirmat screw joint.

Nonparametric Estimates of Reliability Characteristics

If the survival (reliability) function of T is $R(t) = \Pr(T > t)$, then the survival function of T_{min} can be expressed as follows in Eq. 6.

$$R_{\min}(t) = \Pr(T_{\min} > t) = [\Pr(T > t)]^{10} = [R(t)]^{10} \tag{6}$$

This gives $R(t) = [R_{\min}(t)]1/10$. The nonparametric estimates of the survival probabilities and the corresponding 95% confidence intervals at different numbers of cycles for the three types of joints can be computed. The results for confirmat screw, dowel, and eccentric joint are presented in Tables 3 through 5. The results are also summarized in Fig. 6. A nonparametric estimate of the survival probability was obtained from the data. For example, suppose one wants to obtain a nonparametric estimate of the survival function at 60000 cycles for a dowel (*i.e.*, the probability that the joint with an individual dowel will last more than 60000 cycles); the results from Fig. 6 and Table 4 give $\hat{R}(60000) = 0.8705506$. That is, the probability that the joint with individual dowel will last more than 60000 cycles is about 87%. The table also provides the 95% confidence interval for this estimate as [0.8069, 0.9392].

Table 3. Nonparametric Estimate of the Survival Probabilities and the Corresponding 95% Confidence Intervals for Confirmat Screw

Number of Cycles (t)	Estimate of $R(t)$	Lower Limit of 95% Confidence Interval of $R(t)$	Upper Limit of 95% Confidence Interval of $R(t)$
54127	0.9949	0.9849	1.0000
64975	0.9895	0.9752	1.0000
65633	0.9839	0.9659	1.0000
67706	0.9779	0.9567	0.9996
70079	0.9716	0.9474	0.9965
72855	0.9650	0.9377	0.9931
72960	0.9578	0.9275	0.9892
76251	0.9502	0.9168	0.9848
79999	0.9420	0.9054	0.9801
82849	0.9330	0.8930	0.9748
86178	0.9233	0.8796	0.9692
87609	0.9124	0.8648	0.9627
88500	0.9003	0.8481	0.9558
95080	0.8866	0.8292	0.9480
107795	0.8706	0.8069	0.9392
109961	0.8513	0.7799	0.9294
111896	0.8272	0.7452	0.9182
114892	0.7943	0.6966	0.9058
128311	0.7411	0.6122	0.8972
148450	0.0000	---	---

Table 4. Nonparametric Estimate of the Survival Probabilities and the Corresponding 95% Confidence Intervals for Dowel

Number of Cycles (*t*)	Estimate of *R*(*t*)	Lower Limit of 95% Confidence Interval of *R*(*t*)	Upper Limit of 95% Confidence Interval of *R*(*t*)
19203	0.9949	0.9849	1.0000
20017	0.9895	0.9752	1.0000
23344	0.9839	0.9659	1.0000
24060	0.9779	0.9567	0.9996
26801	0.9716	0.9474	0.9965
28365	0.9650	0.9377	0.9931
30968	0.9578	0.9275	0.9892
33851	0.9502	0.9168	0.9848
36327	0.9420	0.9054	0.9801
37846	0.9330	0.8930	0.9748
38257	0.9233	0.8796	0.9692
38497	0.9124	0.8648	0.9627
49737	0.9003	0.8481	0.9558
51198	0.8866	0.8292	0.9480
53748	0.8706	0.8069	0.9392
65052	0.8513	0.7799	0.9294
69097	0.8272	0.7452	0.9182
72023	0.7943	0.6966	0.9058
72900	0.7411	0.6122	0.8972
77529	0.0000	---	---

Table 5. Nonparametric Estimate of the Survival Probabilities and the Corresponding 95% Confidence Intervals for Eccentric Joint

Number of Cycles (*t*)	Estimate of *R*(*t*)	Lower Limit of 95% Confidence Interval of *R*(*t*)	Upper Limit of 95% Confidence Interval of *R*(*t*)
5650	0.9949	0.9849	1.0000
10658	0.9895	0.9752	1.0000
11566	0.9839	0.9659	1.0000
11824	0.9779	0.9567	0.9996
12000	0.9716	0.9474	0.9965
12442	0.9650	0.9377	0.9931
13210	0.9578	0.9275	0.9892
14177	0.9502	0.9168	0.9848
14442	0.9420	0.9054	0.9801
14882	0.9330	0.8930	0.9748
15123	0.9233	0.8796	0.9692
15169	0.9124	0.8648	0.9627
16289	0.9003	0.8481	0.9558
19165	0.8866	0.8292	0.9480
19821	0.8706	0.8069	0.9392
22345	0.8513	0.7799	0.9294
22426	0.8272	0.7452	0.9182
23178	0.7943	0.6966	0.9058
33173	0.7411	0.6122	0.8972
50060	0.0000	---	---

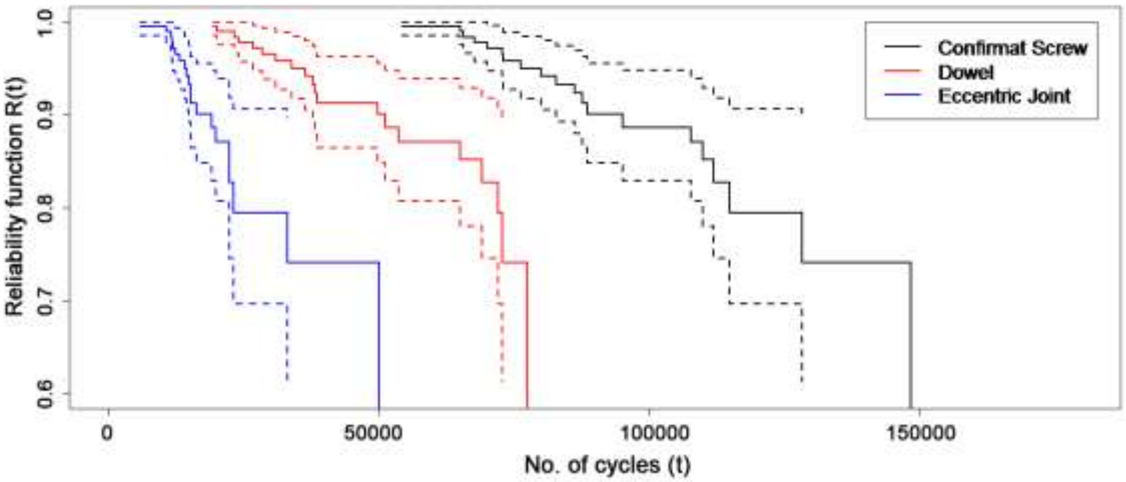

Fig. 6. Nonparametric estimates of survival curves for three different types of joints

Proportional Hazards Model

This subsection considers a proportional hazards model for the lifetime data for the joints with a single connector presented in Table 2. The binary variables were defined as follows: $x_1 = 1$ for "dowel" and $x_1 = 0$ otherwise, $x_2 = 1$ for "eccentric" and $x_2 = 0$ otherwise, and $x_3 = 1$ for "screw" and $x_3 = 0$ otherwise. In the proportional hazards model proposed by Cox (1972), it is assumed that the hazard rates of the three types of joints are proportional to each other, *i.e.*, $h(t; x_1, x_2, \alpha_1, \alpha_2) = h(t; 0, 0)\, g(x_1, x_2, \alpha_1, \alpha_2)$, where $h(t; 0, 0)$ is the (baseline) hazard at time *t* for "screw", and $g(x_1, x_2, \alpha_1, \alpha_2) = \exp(\alpha_1 x_1 + \alpha_2 x_2)$.

The estimates of α_1 and α_2 and the corresponding standard errors and 95% confidence intervals are presented in Table 6. The Cox proportional model was chosen because of the fact that it was not necessary to make the assumption that the lifetimes of the joints were following a particular statistical distribution.

Table 6. Parameter Estimates and the Corresponding Standard Errors and 95% Confidence Intervals

Parameter	Estimate	Standard Error	95% Confidence Interval
α_1 (dowel)	0.05124	0.21249	(-0.3697, 0.4701)
α_2 (eccentric)	2.00107	0.27844	(1.4650, 2.5634)

Table 7. Parameter Estimates with the Corresponding Standard Errors and 95% Confidence Intervals

	Risk Ratio	95% Confidence Interval
Eccentric/Dowel	7.0275	(3.3013, 15.4222)
Screw/Dowel	0.1220	(0.04820, 0.2825)
Screw/Eccentric	0.0174	(0.00567, 0.0484)
Dowel/Eccentric	0.1423	(0.06484, 0.3029)
Dowel/Screw	8.1952	(3.5401, 20.7484)
Eccentric/Screw	57.5916	(20.6554, 176.3446)

The risk ratios between the two types of joints and the corresponding 95% confidence intervals are presented in Table 7. The *p*-values from the likelihood-ratio chi-square test that the risk ratio is different than 1 were all < 0.0001, which indicated that there were significant differences between the hazards of the three types of joints.

Based on the risk ratios calculations presented in Table 5, the hazard function for the "eccentric" joint was 7.02 times that of the hazard function for "dowel" joint, that the hazard function for the "dowel" joint was 8.19 times that of the hazard function for "screw" joint, and the hazard function for "eccentric" joint was 57.59 times that of the hazard function for "screw" joint. In conclusion, the confirmat screw was the most reliable joint among the three types of joints considered here.

Further studies, taking into account the different variables (*i.e.*, type of material and thickness), should be performed towards the goal of creating a library of reliability characteristics for various furniture joints for use in the design departments of furniture factories.

CONCLUSIONS

1. The presented method of determining the reliability of joints may be helpful in the process of case furniture design in selecting the type of connector to be used.
2. Experimental investigations allowed determination of the likelihood of damage for the joints under cyclic loading, and thus allowed assessment of the probability of failure free time for different connectors used in the joints. The probability that the joint would last, *i.e.*, withstand more than 50000 cycles, was about 99% in case of the joint with confirmat screw, 89% for the joint with dowel connector, and 0% for the joint with eccentric connector.
3. Of the three tested types of joints, with dowel, screw and eccentric connectors, the highest reliability expressed in the hazard function was calculated for the joint with the confirmat screw. The hazard rate of the dowel joint was about 8 times greater than that of the confirmat screw joint. In the case of the eccentric joint, the hazard rate was as much as 57 times higher than for the screw joint.

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