Determination of the impact of creeping of furniture joints on their rigidity

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Abstract: The study presents research results on the effect of creeping on changes in the rigidity of selected joints used in constructions of upholstered furniture, expressed as the substitute modulus of elasticity \( E_z \). The modulus was calculated analytically for this purpose using the Maxwell–Mohr constitutive equation. In addition, actual runs of creeping curves were determined and a theoretical model well describing the obtained results was selected. Simultaneously, a detailed statistical analysis was carried out. It was found that creeping exerted a significant impact on the mechanical quality of the examined joints by reducing their substitute modulus of elasticity by 11%–16%. This modulus can be employed in numerical calculations using the finite elements method.

Key words: Creeping, furniture joint, rigidity, substitute modulus of elasticity

1. Introduction
The phenomenon of material creeping can be observed in all known construction materials and its intensity depends, to a considerable extent, on material structure and the value and duration of the applied loads, among other factors. The creeping process leads to the destruction of material, and its course may be divided into 3 phases. The first is characterised by decreasing velocity of deformations over time. The second phase develops at the constant velocity of deformations, whereas in the third phase, an increasing velocity of deformations leading to the destruction of material can be observed (Dietrich 1994). Safe operation limits of various equipment, objects, and constructions, including furniture, subjected to creeping are confined to the second phase of creeping. Determination of the safe range of operation at creeping in defined conditions of exploitation is one of the basic research tasks associated with creeping of construction materials.

The process of damage accumulation of construction materials under the influence of operational loads is multiphase. It begins with the initiation of defects in material structure (e.g., excessive porosity of the chipboard and the quality of strands) and is followed, during the consecutive phases, by their gradual development leading to cracks, which inevitably cause the destruction of the construction elements (joints).

Ensuring the good quality of furniture joints is a crucial aspect contributing to the safety of furniture usage. In the literature, many scientific papers concerning investigations of case furniture joints in the aspect of their strength and rigidity can be found (Zhang and Eckelman 1993; Zhang et al. 2005; Atar and Özçifçi 2008; Altinok et al. 2009; Tankut and Tankut 2009; Maleki et al. 2012). This is significant since it is commonly known that joints are the most critical points of the furniture structure. Therefore, it is important to know the parameters affecting the strength and rigidity of the joints, and thus the whole construction of furniture.

Generally speaking, all materials can be divided into the following 4 categories (Gonet 1991): ideally elastic, ideally plastic, partially elastic, and partially plastic. In the case of wood, for a low level of strain, the \( \sigma = f(\varepsilon) \) dependence is close to linear, and the material may be treated as elastic. In reality, however, wood, and in particular wood-derived materials, behave in a more complex way, especially at high levels of strain. In such conditions, wood and wood-derived materials can be treated as linearly viscoelastic bodies (Cai et al. 2002; Malesza and Miedziałowski 2003).

In the literature on the subject, it is possible to find articles associated with sustained loads of both joints and individual furniture elements. A mathematical approach to the problem of deflections of shelves subjected to sustained loads was presented by Langendorf (1970) and Kwiatkowski (1974). In their studies, the above-mentioned researchers presented a detailed mathematical description of shelf deflections, which allowed analytic calculations of...
the value of the deflection at a definite load. The problem of the creeping of shelves was also investigated by Albin (1989) and Jivkov et al. (2010). In addition, experiments were also conducted regarding the creeping of furniture joints (Güntekin 2005), in which different materials and different connectors were taken into consideration, as well as the creeping of furniture joints’ elements (Mostowski 2010, 2011). In the investigations of Güntekin (2005), the rigidity expressed by the change of the angle of rotation of the loaded joint was adopted as the criterion for the measure of creeping. Much space and time was devoted to rheological investigations of cabinet furniture elements such as shelves, sides, and rims (Laufenberg et al. 1999; Denizili-Tankut et al. 2003; Tankut et al. 2003; Tankut et al. 2007). Moreover, experiments on creeping also concerned the bearing elements of upholstered furniture (Bao and Eckelman 1995).

Among the disadvantages of the approach adopted in the above-mentioned papers was the need to perform long tests in laboratory conditions, as well as a lack of possibilities to simulate such investigations using computer techniques due to the adopted comparative criteria of the assessment of the creeping process. Bearing in mind the above considerations, it was decided to conduct investigations whose aim was to ascertain the creeping of box corner joints of upholstered furniture and to determine the influence of creeping on changes in their rigidity.

2. Materials and methods

The object of the experiments comprised the angle joints of the skeletons of a corner sofa and an armchair (Figures 1–3). They constitute important construction nodes of the frames of these pieces of furniture and, in addition, were indicated by their manufacturer as those joints that undergo damage most frequently.

The joint shown in Figure 2 was made from chipboard 16 mm thick. Two dowels of ø 8 × 32 were used as connectors. The joint presented in Figure 3 was made from a chipboard 15 mm thick of density of 670 kg m⁻³ and a beech wood stile. The stile was fixed to the chipboard using PVAC glue and staples and strengthened using a block.

The elastic properties of the materials employed in the examined joints are presented in Table 1. They were...
established on the basis of the PN-EN 310 standard (Polish Committee for Standardization 1994). In the performed experiments, 5 samples from each kind of joint were applied. The moisture content of the examined samples ranged from 6.2% to 8.3%.

Prior to the determination of the course of creeping of the selected joints, it was necessary to ascertain their carrying capacity. These investigations were conducted on the Zwick 1445 testing machine and measurements of the sample dimensions were carried out with an accuracy of 0.01 mm. The applied initial loading amounted to 1 N, while loading velocity was set to 10 mm min⁻¹. The value of the force was read with 0.1 N accuracy, whereas the value of deflection was read with 0.01 mm accuracy. The frequency of measurements was set at 1 readout per second. Figures 4 and 5 show the method of support and loading of the experimental samples.

The substitute modulus of elasticity \((E_z)\) determined experimentally before and after the joint creeping process was adopted as the assessment criterion of the mechanical quality (rigidity) of the connection. Although many authors (Kratz 1969; Gressel 1972; Lyon and Barnes 1978) indicated the existence of an influence of particle board resin on the creep process, in this study, this factor is constant, and thus only the connection creep process was investigated. In experiments conducted so far, researchers employed either changes of strains or deformations in the examined materials (Czachor 2009, 2010) or changes in the voltage of the current flowing through the resistance bridge (Mitchell and Baker 1978) as the comparative criterion. In comparison with the above-mentioned methods, the method proposed here does not require special measuring equipment (e.g., a tensometric bridge) and therefore it can also be utilised in industrial conditions. In addition, the application of the substitute modulus of elasticity makes it possible to employ it directly as a substitute material constant in numerical calculations using, for example, the finite elements method.

Calculations of \(E_z\) were performed using the Maxwell–Mohr method, whose constitutive form can be described by the following equation:
where:

\[ M, M_0, N, T \] - internal forces induced by virtual load \( X = 1 \),

\[ M, M_0, N, T \] - internal forces induced by virtual load \( X_k = 1 \),

\( \kappa \) - coefficient dependent on the shape of the rod/board cross section shape,

\( A \) - cross section area,

\( G \) - board/rod modulus of shape elasticity,

\( J_0 \) - polar moment of inertia,

\( J \) - moment of cross section inertia.

Omitting the negligible impact of internal torsional, normal, and shear forces (Zielnica 1996), dependence of Eq. (1) assumed the following form:

\[ \delta_{iP} = \int_x \left( \frac{M M_k}{E J} + \frac{M_0 M^0_k}{G J_0} + \frac{N N_k}{E A} + \kappa \frac{T T_k}{G A} \right) dx, \]  

(1)

where:

\[ \delta_{iP} = \int_x \left( \frac{M M_k}{E J} \right) dx. \]  

(2)

It was assumed in calculations regarding the wall connection that the board from which the joint was made consisted of 2 sections of different rigidity. The rigidity of section \( l_z \) amounted to \( E_z J \), whereas the rigidity of the remaining segment \( (l_1) \) was \( E_1 J \). Following the adoption of the above assumptions, Eq. (2) was converted to produce \( E_z \).
where:
l – length of the near-node segment (for the board, it was assumed that \( l_z = 2h \)),
l_1 – length of the arm of the joint,
b – width of the board cross section,
h – thickness of the board,
\( \delta_{IP} \) – total deflection of the joint,
J – moment of inertia of the board cross section,
\[ J = \frac{bh^3}{12} \]
E – Young modulus of the chipboard of 16 mm thickness,
P – loading \((0.4P_{\text{max}} - 0.1P_{\text{max}})\).

The following equation was determined for the connection with the batten:

\[ E_z = \frac{Pl_z\left(3l_z^2 + 3l_1l_z + l_1^2\right)}{12\delta_{IP}J - \frac{Pl_z^2}{E}} \]

where:
J_1 – moment of inertia of the chipboard cross section,
\[ J_1 = \frac{b_1h_1^3}{12} \]
J_2 – moment of inertia of the wood cross section,
\[ J_2 = \frac{b_2h_2^3}{12} \]
E_1 – Young modulus of the chipboard 15 mm thick,
E_2 – Young modulus of beech wood.

When calculating the substitute modulus of elasticity \( E_z \), values determined according to the PN-EN 310 standard were taken into consideration.

The observation of the creeping process was divided into 3 stages. The first stage lasted 35 days and involved loading experimental samples with a pulling-apart force of the value of 40% \( P_{\text{max}} \). In the course of the investigations, deflection increments were measured using LIMIT digital measuring sensors with 0.01 mm accuracy. The deflection measurement system of angle joints with the assistance of a digital sensor is shown in Figure 6.

The 1st measurement was recorded 10 min after load application, the 2nd after 1 h, and the 3rd after 6 h. Consecutive measurements were taken with the frequency of 1 readout per 24 h for 72 consecutive days. In the next stage, which lasted 7 days, samples were unloaded. During the final stage, which lasted 30 days, samples were loaded again. Five samples from each type of joint were used in the investigations on creeping.

3. Results
Table 2 presents the results of the determination of immediate load-carrying capacity of joints and 10% and 40% values of the ultimate load. Data from Table 2 were used to determine the loading values of samples during creeping. Runs of the obtained curves are presented in Figures 7 and 8. It is evident from the analysis of the diagrams shown in Figures 7 and 8 that the course of creeping of the examined joints can be divided into 2 phases: initial creeping (transient) and stationary creeping. In the literature (Cai et al. 2002; Kłos 2010), a third phase of progressive creeping is distinguished, but in the presented studies, this phase was not reached due to the relatively short time of the performed experiments. The phase of initial creeping, which was characterised by relatively big deflection increments, ended after approximately 10 days and passed into stationary creeping. One-off sample unloading in the course of the performed experiments reduced deflection (relaxation), on average, by about 0.6 mm in the case of the wall joint and 0.1 mm in the connection of the side with the backrest batten. In the case of angle wall joints, maximum deflection values in the course of creeping ranged from 2 mm to 4.8 mm, while in the case of angle joints with a batten they ranged from 0.6 mm to 1.1 mm.

In order to determine the impact of creeping on the rigidity change of the examined joints, their load-carrying capacity and then \( E_z \) were both ascertained before and after creeping (Figures 9 and 10). The calculated substitute elasticity moduli for the examined joints determined before and after creeping are presented in Table 3. Based on the data from Table 3, it can be stated that the percentage difference between mean substitute modulus of elasticity \( E_z \) before and after the examination of joint creeping, in the case of the angle wall joint, amounted to 11.6%, while in the case of the joint connecting the backrest batten with the side of the frame it was 16.4%.
After the determination of the creeping curve, the next stage of investigation was to fit its course to a well-known theoretical model. In order to assess the parameters, data from the first phase of creeping, up to the moment of unloading, were taken into consideration. The Kelvin–Voigt model was adopted to carry out analyses, whose

### Table 2. Immediate load-carrying capacity.

<table>
<thead>
<tr>
<th>Type of joint</th>
<th>Breaking force at pulling-apart force $P_{\text{max}}$ [N]</th>
<th>10% $P_{\text{max}}$ [N]</th>
<th>40% $P_{\text{max}}$ [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall angle joint of the container for bedclothes</td>
<td>544</td>
<td>54.4</td>
<td>217</td>
</tr>
<tr>
<td>Joint of the backrest batten with the side of the frame</td>
<td>532</td>
<td>53.2</td>
<td>213</td>
</tr>
</tbody>
</table>

**Figure 7.** Creeping curve for wall angle joint.

**Figure 8.** Creeping curve for the joint connecting the backrest batten with the side of the frame.
general form is expressed by Eq. (5) (Mitchell and Baker 1978):
\[ \delta = \frac{P}{E} \left[ 1 - \exp \left( -\frac{E}{\eta} t \right) \right], \]
where:
- \( t \) – duration of the creeping test,
- \( \eta \) – viscosity coefficient,
- \( E \) – modulus of linear elasticity.

Both Czachor (2009, 2010) and Malesza and Miedziałowski (2003), as well as Mitchell and Baker (1978), accepted the Kelvin–Voigt model as the most similar to the actual course of creeping of wood and wood-derived materials. Therefore, the authors decided to verify the compatibility of the presented mechanical model with the creeping curves of joints obtained during the performed investigations.
The mechanical model for the analysed construction nodes can be assumed as a complex of materials of viscoelastic properties (Malesza and Miedziałowski 2003, 2006). On the basis of the above assumption, the authors elaborated a function of description of the creeping of the joint (6):

\[ \delta = c - at^m + bt, \]  

where:

- \( \delta \) – joint deflection,
- \( a, m, b, c \) – constants in function.

Employing STATISTICA 9.0 software, the parameters of the above model were assessed and their values are presented in Table 4. Taking into consideration data from Table 4, the Kelvin–Voigt model curve was determined. The obtained model curve with the assessed parameters and the curve of the actual course of creeping for the angle wall joint and the angle joint with the batten are presented in Figure 11. For researched joints with a batten, the values of the estimated parameters are presented in Table 5.

The verification of hypotheses regarding the significance of model parameters (by checking dependence of Eq. (7)) revealed that all model parameters were significant, both in the case of the angle wall joint and the angle joint with the batten.

\[ |t_i| > t_{\alpha} \]  

It is evident from the analysis of values from Tables 4 and 5 that the assessed parameters of both models were highly significant. Therefore, it can be assumed that the adopted exponential model constituted a correct fit to the data.

4. Discussion

As expected, the analysis of Figures 9 and 10 indicated that due to sustained loading of the examined samples, the rigidity curve after creeping in both cases is shifted downwards in the direction of the axis of ordinates. Similar results were achieved by Güntekin (2005). However, in this study, a different manner of calculating the joints rigidity, namely substitute modulus of elasticity \( E_z \), was incorporated. Comparison of those values for both joints indicates that the joint partly made of solid wood, connecting the backrest batten with the side of the frame, is about 50% more rigid than an angle wall joint, both before and after the creeping (Table 3).

Analysis of the data presented in Figure 11 allowed us to compare the experimental data curves for both examined joints with their model curves. A similar method was incorporated also by Güntekin (2005) and Mostowski (2010, 2011). Data from the creeping curve confirm that the joint with the batten is more rigid than an angle wall joint, both before and after the creeping (Table 3).

Table 3. Substitute elasticity moduli for the examined joints during the pulling-apart process determined before and after creeping.

<table>
<thead>
<tr>
<th>Type of joint</th>
<th>Mean substitute modulus of elasticity [MPa]</th>
<th>Standard deviation [MPa]</th>
<th>Variation coefficient [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall angle joint of the container for bedclothes</td>
<td>Before 259</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>After 232</td>
<td>45</td>
<td>19</td>
</tr>
<tr>
<td>Joint of the backrest batten with the side of the frame</td>
<td>Before 524</td>
<td>126</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>After 450</td>
<td>161</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 4. Determined parameters for the creeping model for the examined wall joint.

<table>
<thead>
<tr>
<th></th>
<th>c</th>
<th>a</th>
<th>m</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation</td>
<td>-0.50923</td>
<td>-0.86156</td>
<td>0.365702</td>
<td>-0.00220</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.23686</td>
<td>0.24192</td>
<td>0.077433</td>
<td>0.00087</td>
</tr>
<tr>
<td>t(27)</td>
<td>-2.14989</td>
<td>-3.56136</td>
<td>4.722846</td>
<td>-2.53091</td>
</tr>
<tr>
<td>-95% PU</td>
<td>-0.99523</td>
<td>-1.35793</td>
<td>0.206824</td>
<td>-0.00399</td>
</tr>
<tr>
<td>+95% PU</td>
<td>-0.02323</td>
<td>-0.36518</td>
<td>0.524581</td>
<td>-0.00042</td>
</tr>
<tr>
<td>P</td>
<td>0.04068</td>
<td>0.00139</td>
<td>0.000064</td>
<td>0.01751</td>
</tr>
</tbody>
</table>
of Jivkov et al. (2010). It is clearly visible that the joint with a batten has a better deflection stability compared to the angle wall joint and also shows better long-term stability. The theoretical creeping curve described by Eq. (6) for the defined parameters a, b, c, and m was suited very well to the obtained values from experimental investigations. The determination coefficient amounted to $R^2 = 0.97$ for wall joints and $R^2 = 0.98$ for joints with a batten. In joints of wooden and wood-based constructions, nonlinearity, which is caused by different factors, was noticeable from the very beginning of loading. The above-mentioned factors included (Malesza and Miedziałowski 2003):

- type of material and its basic mechanical characteristics,
- type of connector and its diameter,
- loading, its type, and its characteristics in time.

From an engineering point of view, the most important conclusion that can be drawn from this study is that after the performed creeping investigations, the value of the substitute modulus of elasticity $E_z$ (rigidity) dropped in both analysed joints. In the case of the angle wall joint, it amounted to about 11%, and in the case of the angle joint with the batten, about 16%. Moreover, on the basis of the conducted research we found that the phase of transient creeping, in the case of both of the examined joints, terminated after about 10 days. The results achieved during that experiment enabled us to determine the actual runs of creeping curves for both joints and select the theoretical model describing them. The assessed model parameters for the assumed exponential function were statistically significant. Consequently, the obtained Kelvin–Voigt model described well the creeping phase of both of the examined joints. The assumed comparative criteria of the creeping process turned out to be a good choice. Using energetic methods, especially the Maxwell–Mohr method, it is possible to determine analytically, in an easy way, the substitute rigidity of joints applied in constructions of furniture.

![Figure 11](image_url)

**Figure 11.** Diagram of creeping of the wall joint and the backrest batten joint together with the model curves.

**Table 5.** Values of the assessed parameters for the examined joints with a batten.

<table>
<thead>
<tr>
<th></th>
<th>c</th>
<th>a</th>
<th>m</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation</td>
<td>0.39475</td>
<td>0.31360</td>
<td>-0.12075</td>
<td>-0.03967</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.00721</td>
<td>0.00888</td>
<td>0.02425</td>
<td>0.00584</td>
</tr>
<tr>
<td>t(26)</td>
<td>54.74301</td>
<td>35.30309</td>
<td>-4.97999</td>
<td>-6.78674</td>
</tr>
<tr>
<td>-95% PU</td>
<td>0.37992</td>
<td>0.29534</td>
<td>-0.17059</td>
<td>-0.05168</td>
</tr>
<tr>
<td>+95% PU</td>
<td>0.40957</td>
<td>0.33186</td>
<td>-0.07091</td>
<td>-0.02765</td>
</tr>
<tr>
<td>P</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00004</td>
<td>0.00000</td>
</tr>
</tbody>
</table>
References


