Influence of Cyclic Stress on the Relaxation Speed of Native and Laminated Wood

Milan Gaff * and Miroslav Gašparík

This study examined the influence of cyclic stress on the relaxation speed for native beech wood and laminated wood. Various sample thicknesses were evaluated, and a testing method, which consisted of bending *via* three-point loading, was developed. The relaxation speed was measured on samples that were cyclic loaded, and the results were compared with those gathered for test samples that were not cyclically loaded. The results show that thicker materials yield a higher relaxation speed. The type of material and the number of loading cycles did not appear to have a significant effect within the measured range of values.

Keywords: Cyclic loading; Laminated wood; Beech wood; Relaxation speed; Number of cycles

Contact information: Department of Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521, Czech Republic;
** Corresponding author: gaffmilan@gmail.com*

INTRODUCTION

The relaxation speed is the speed at which a loaded component returns to its original state after being released from the stressing mechanical forces. This characteristic plays a very important role in the production of certain furniture components, as it can affect the comfort of the piece. Therefore, it is important to understand the influence of cyclical loading on the relaxation speed of both native and laminated beech wood.

In the production of laminated wood, native wood and/or laminated wood were used. Laminated veneer lumber is produced by combining multiple layers of thin wood veneers (typically 3 mm thick) that are made by slicing (Glos *et al.* 2004; Frese and Blaß 2006). The native wood pieces can vary in thickness, and the laminated wood pieces can vary in both the number of lamellas and the lamella thickness. The lifetime of the final product is influenced by the material properties of the wood used, and as a result, the lifetime of the furniture components varies considerably. The properties of the furniture components also change throughout their long-term use. Eventually, many furniture components can cease to function as intended as the piece ages.

There are many experimental methods by which the physical and mechanical properties of the materials used in furniture production can be determined. Despite the existence of these methods, there are less-known procedures for evaluating the "fatigue" of wooden furniture components. The "fatigue" of a piece represents the rate at which the parts return to their original state after the stressing forces are released. Furthermore, the material is considered "fatigued" if the measured values for the relaxation speed decrease after cyclical loading in comparison to the values before the cycles of loading. This paper introduces some suggestions as to how to measure and evaluate these utility properties.

The goals of this study were to further understand the effects of repeated stress on furniture components and to later be able to utilize this knowledge when creating furniture in order to increase its longevity and quality. The present research aimed to study the effect of cyclic loading on native beech and laminated wood in regards to their strength properties. The durability (lifetime) of these products varies considerably, which affects the properties of the material itself. Changes in the characteristics can be caused by long-term use of furniture components, which over time cease to perform the function for which they are intended (Gáborík and Dudas 2008; Gaff 2009; Maro 2012; Brutovský 2013).

EXPERIMENTAL

Materials

European beech trees (*Fagus sylvatica* L.) were harvested from the Poľana region in the center of Slovakia. Sapwood, located two-thirds of distance (always the same) away from the pith (closer to outside of the log), was chosen for the experiment. This wood was cut into boards. From the boards, samples 70 mm wide and 400 mm long were made. The individual sample thicknesses were 4, 6, 10, and 18 mm.

The veneers for laminated wood were also chosen from the sapwood, from approximately the same distance from the center. These veneers were made by rotational peeling of steamed beech trunks. Pre-dried veneers with applied adhesive were pressed for 10 min at 60 °C at a pressure of 1 MPa in pressing machine JU 60 (Paul Ott GmbH, Austria). The waterproof polyvinyl acetate adhesive (PVAc) Duvilax D3 Rapid (Duslo Šaľa, Slovakia) was used for the lamination of the wood. Laminated wood with thicknesses of 4, 6, 10, and 18 mm was cut to the final width of 70 mm and length of 400 mm. Each thickness group of both laminated and native wood contained 10 samples for each cycle type. The whole experiment included 320 samples (160 samples each for native and laminated wood).

The average density of beech wood and veneers was 746 kg/m^3. The clear laminated and native wood samples were conditioned to a moisture content of 8% in a conditioning chamber using the principle of equilibrium moisture content (EMC). The samples were conditioned for more than six weeks before testing.

Methods

Cyclic loading

The cyclic loading was carried out on a horizontal cycling machine based on uniaxial stress perpendicularly on the length of the samples. The samples underwent 1,000, 2,000, and 3,000 cycles and were compared with samples without cyclic loading (0 cycles). During preliminary bending tests, the maximum strengths and proportional limits for the given materials were measured. These values were necessary for cyclic loading to avoid the sample load exceeding 90% of the proportional limit during the loading. The cyclic loading procedure took into account previous research by Gaff and Gáborík (2014).

Static bending

The determination of modulus of elasticity was carried out according to ISO 3349 (1975). The samples were bent according to the three-point bending principle as specified in ISO 3349 (1975). The bending was carried out in a ZD 10/90 tensile-pressing machine (VEB TIR Rauenstein, Germany) that contained a special jig for flexural tests and a data logger for recording the loading forces. Test samples were placed on supporting pins (support span 20×*h* according to EN 310 (1993) so that the loading force acted in the radial direction considering the length of the sample.

Measurements

The values of loading forces were directly downloaded from the data logger onto a personal computer, and the modulus of elasticity was calculated. The deflection was measured at the midpoint of the test sample. The dimensions of the samples, for calculating the moisture content and density, were measured with a digital caliper (Mitutoyo, Japan) to a precision of 0.1 mm.

Relaxation speed

Measurement of the relaxation speed was accomplished using a special apparatus designed specifically for this study. The apparatus included a high-speed camera (Fig. 1) which recorded and evaluated the behavior of the components throughout the test. The whole test was based on the bending test, except that the amount of the force was up to point that we have determined that 90% of the limit of proportionality. This point of proportionality was obtained during preliminary experimental tests.

Fig. 1. High-speed camera

The force values (corresponding with 90% of the limit of proportionality) (Table 1) were chosen to assure that the limitations of the material was never exceeded, ensuring that the test samples were stressed only in their flexible region and remained undamaged.

Table 2. Specific Parameters for Individual Thickness Group

Laminated wood				Native wood			
Thickness (mm)	Ultimate bending strength (MPa)	Limit of proportionality (MPa)	90% of limit of proportionality (MPa)	Thickness (mm)	Ultimate bending strength (MPa)	Limit of proportionality (MPa)	90% of limit of proportionality (MPa)
4	150.1	105.1	94,6	4	185.4	129.5	116.6
6	146.0	102.2	92.0	6	178.4	117.5	105.8
10	120.3	84.7	76.2	10	152.0	103.4	93.1
18	100.4	73.4	66.1	18	146.9	97.8	88.0

After reaching the 90% limits of proportionality, the loading force was released, and the sample was allowed to return to its original state. A high-speed camera recorded the return of the test sample to its original state. The trajectory and duration of the sample's return were recorded. After recording, the trajectories (a, b, b`), traveled in a given time were evaluated through a comparative equation (2).

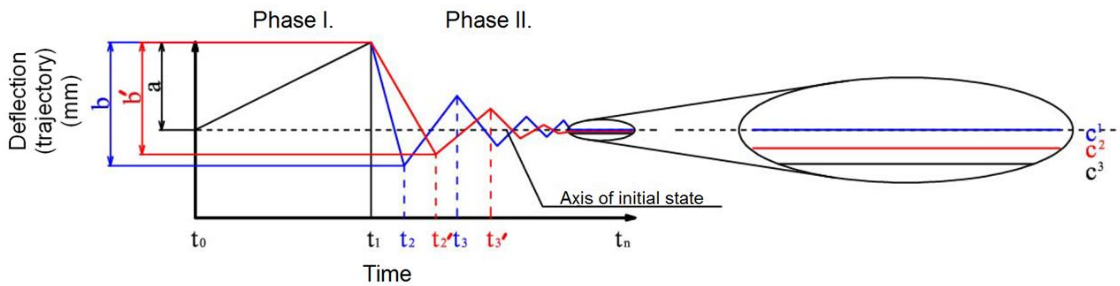

Fig. 2. Principle of shape deviation after cyclic loading
(Phase I. – loading, Phase II. – releasing, a – deflection, b, b` – trajectories, $t_0$ – initial state, $t_1$ – time of unloading, $t_2$, $t_2$`, t_3 and t_3`– times of relaxations and, c^1, c^2, and c^3 – final relaxed shapes)

A comparative equation was derived from the relation (1). A positive result corresponds to the situation in which the distance traveled was achieved in a shorter period of time. The final shape of the laminated wood may have different values (c^1, c^2, c^3). Its value after stabilization (c^1) may be the same as the original, ideal value (a), or a lower (c^2, c^3) value, respectively. The best result would be if one obtained wood whose shape stability after cyclic bending stress would take the original ideal value ($c^1 = a$).

Figure 3 illustrates the scenarios which, depending on the properties of the laminated wood, can influence the relaxation speed. Figure 3a illustrates the three-point loading potential of a piece of laminated wood before stress is applied, while Fig. 3b illustrates the laminated wood, loaded by the maximum force (correspond with limit of the proportionality). After the external mechanical forces are released (as shown in Fig. 3c), the laminated wood returns to its original state and stabilizes, depending on its properties (Fig. 3d).

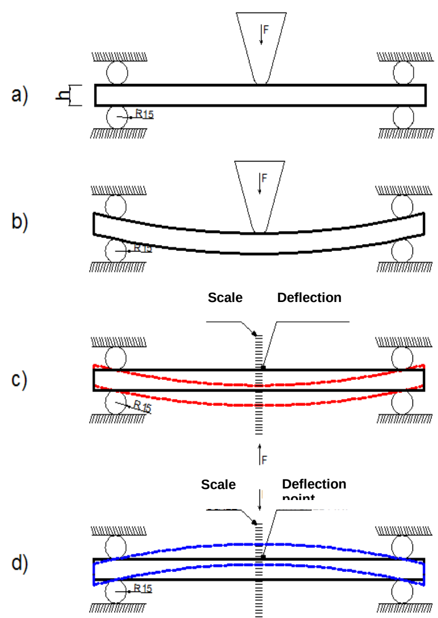

Fig. 3. Illustration of deflection for laminated wood: **(a)** before loading, **(b)** maximum load is applied, **(c)** releasing the maximum load, and **(d)** return of wood to original state

Calculations and evaluation

The results were evaluated by STATISTICA 7 software (StatSoft Inc.; USA) with ANOVA analysis using Fisher's F-test at a significance level of 95%. Based on the p-level value, it was determined whether the factor affected the values of the relaxation speed.

The relaxation speed was calculated according to Eq. 1,

$$v = \frac{s}{t} \tag{1}$$

where v is the relaxation speed (m/s), s is the trajectory or flexure (m), and t is the time/duration (s).

The modulus of elasticity (MOE) of the samples was calculated after bending. These calculations were carried out according to ISO 3349 (1975), STN EN 49 0116 (1982), and Eq. 1,

$$E_m = \frac{l_0^3 (F_2 - F_1)}{4bh^2 (a_2 - a_1)} \tag{2}$$

where E_m is the modulus of elasticity of wood (MPa), l_0 is the distance between supporting pins (mm), b is the width of the test sample (mm), h is the height (thickness) of the test sample (mm), and F_2 - F_1 is the loading increase in the loading/deflection curve linear section (N). The value of F_1 should be approximately 10% and F_2 should be approximately 40% of the breaking load. The difference a_2 - a_1 is the deflection increase in midpoint of the test sample length (corresponding to the loading increase F_2 - F_1).

To compare the relaxation speed for samples of differing dimensions, the cross-sectional area was analyzed. The instantaneous deflection was calculated, bearing attention to the cross sectional area, according to EN 310 (1993) and Eq. 3,

$$y_0 = \frac{F * l_0^3}{4 * b * h^3 * E_0} \tag{3}$$

where y_0 is the instantaneous deflection (mm), F is the loading force (N), E_0 is the modulus of elasticity (N/mm^2), l_0 is the support span when tested (l_0 = 20 × h) (mm), b is the width of test sample (mm), and h is the height of test sample (mm).

Taking the cross section into account when calculating the relaxation speed, and combining Eqs. 1 and 2, yields Eq. 4,

$$v = \frac{y_0}{t} = \frac{\dfrac{F * l_0^3}{4 * b * h^3 * E_0}}{t} \tag{4}$$

where v is the relaxation speed (m/s), y_0 is the instantaneous deflection (mm), F is the loading force (N), E_0 is the modulus of elasticity (N/mm^2), l_0 is the support span when tested (l_0 = 20 × h according to EN 310 (1993)) (mm), b is the width of test sample (mm), and h is the height of test sample (mm), and t is the time/duration (s).

Density was measured before testing and calculated according to ISO 3131 (1975) and Eq. 5,

$$\rho = \frac{m}{a*b*l} = \frac{m}{V} \tag{5}$$

where ρ is the density of the test sample (kg/m^3); m is the mass (weight) of the test sample (kg); a, b, and l are dimensions of the test sample (m); and V is the volume of the test sample (m^3).

The moisture content of the samples was measured before testing. These calculations were carried out according to ISO 3130 (1975) and Eq. 6,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{6}$$

where w is the moisture content of the samples (%), m_w is the mass (weight) of the test slice at certain moisture w (kg), and m_0 is the mass (weight) of the oven-dry test slice (kg).

RESULTS AND DISCUSSION

Native Wood

The p-values in Table 2 show the influence of factors and its interaction on relaxation speed. The number of stressing cycles had no significant effect on the relaxation speed. Furthermore, the thickness of the material did significantly affect the relaxation speed, as shown in both Table 2 and Fig. 4. However, the simultaneous influence of both factors was not statistically significant.

Figure 4 shows the effect of material thickness on the relaxation speed. As noted above, only this effect was statistically significant. With the gradual thickening of the material, there was also an increase in relaxation speed values. Although relaxation speed did not differ at thickness of 4 mm and 6 mm, a substantial change occurred above 6 mm thickness

Table 2. Influence of Factors on Relaxation Speed of Native Wood

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher T-test	Level of significance p
Free term	17.67228	1	17.67228	1166.113	0.000
Number of cycles	0.01861	3	0.00620	0.409	0.748
Thickness	8.13886	3	2.71295	179.015	0.000
Number of cycles × Thickness	0.14295	9	0.01588	1.048	0.447
Error	0.24248	16	0.01515		

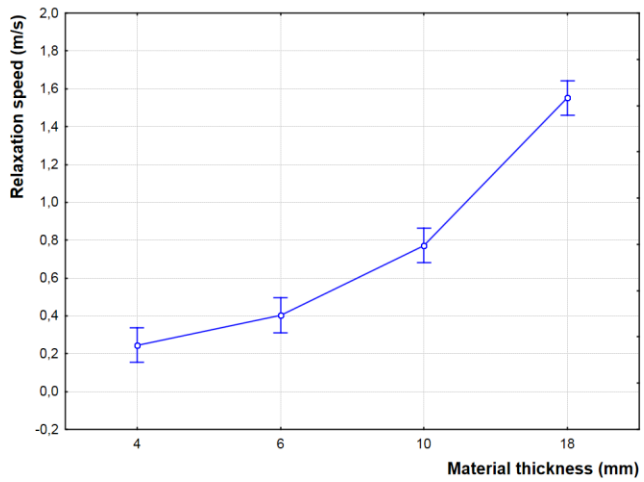

Fig. 4. Effect of material thickness on the relaxation speed for native wood. Data reported as mean ± SD

The mutual influence of material thickness and number of cycles is shown in Fig. 5. For the wood with a thickness of 4 mm, an average relaxation speed only 0.2 m/s was observed, while the wood of 18 mm thickness had an average value measured relaxation speed of 1.5 m/s. It is apparent that with the increase in thickness of the material, one can expect higher values of relaxation speed.

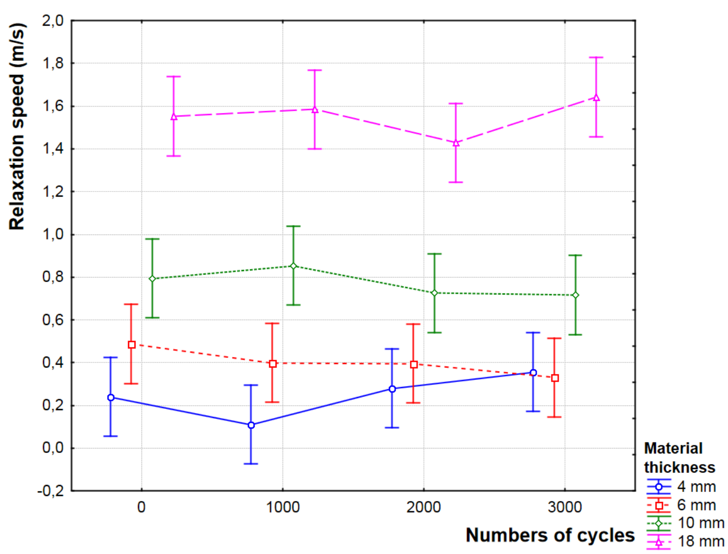

Fig. 5. Effect of numbers of cycles and thickness on the relaxation speed for native wood. Data reported as mean ± SD

Laminated Wood

Results similar to those for native wood were obtained for laminated wood (Table 3). The material thickness significantly affected the relaxation speed (Fig. 6), and as thickness increased, the relaxation speed also increased. The number of cycles, as shown in Table 3, had moderate significant effect on the relaxation speed, which is contrary to what was the case for native wood.

Table 3. Influence of Factors on Relaxation Speed of Laminated Wood

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher T-test	Level of Significance p
Free term	17.37535	1	17.37535	1236.315	0.000001
Number of cycles	0.20105	3	0.06702	4.768	0.014664
Thickness of material	3.47088	3	1.15696	82.322	0.000001
Number of Cycles × Thickness of material	1.77578	9	0.19731	14.039	0.000005
Error	0.22487	16	0.01405		

The results show that the laminated wood with a thickness of 4 mm and 6 mm may be due to cyclic stress to observe decrease in the values of relaxation speed, which is on the border of statistical significance.

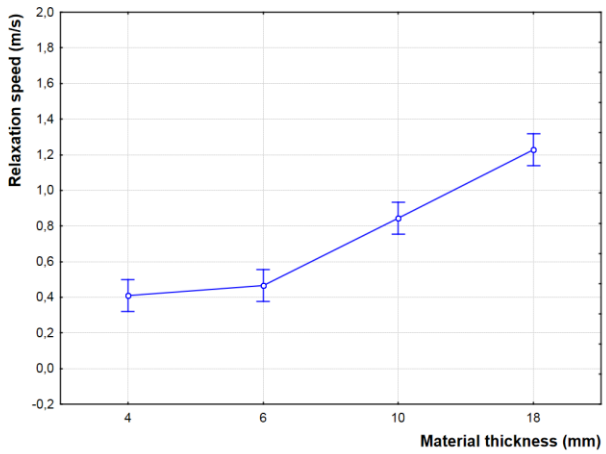

Fig. 6. Effect of material thickness on the relaxation speed for laminated wood. Data reported as mean ± SD

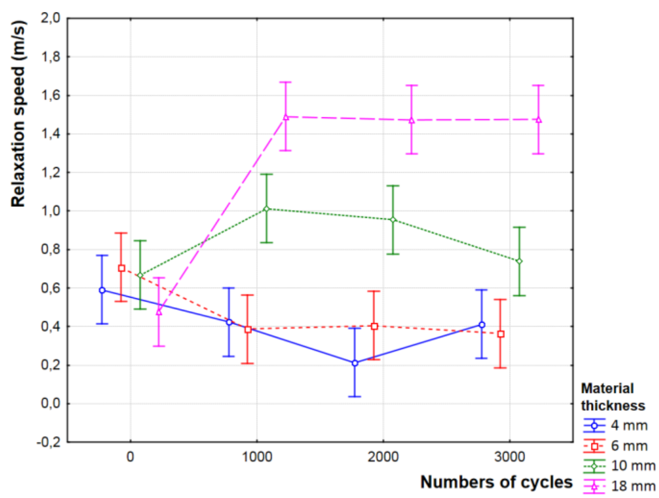

Fig. 7. Effect of numbers of cycles and material thickness on the relaxation speed for laminated wood. Data reported as mean ± SD

Conversely, laminated wood with a thickness of 10 mm achieved a significant increase in relaxation speed values caused by effect of cyclic loading with the numbers of cycles 1000 and 2000, respectively. During cyclic stress with the number of cycles of 3000, the value of relaxation speed laminated wood fell to the original level. This could be due to the thickness of the material, which is expected to marginal the thickness of the material (between 6 and 10 mm) for the effect of cyclic stress (Fig. 7). A similar limit was also observed in previous research by Gaff and Gáborík (2014), which was focused on modulus of elasticity.

When comparing the cyclically stressed and unstressed wood with a thickness of 18 mm a statistically significant increase could be observed in values of relaxation speed. This increase was caused by the cyclic loading. However, differences in values of relaxation speed between the numbers of cycles of 1000, 2000, and 3000 can be considered as not statistically significant.

CONCLUSIONS

1. Results for native wood show that the relaxation speed increases for thicker materials. Additionally, the effect of the number of cycles on the relaxation speed is statistically insignificant. Similar results were obtained for samples made of laminated wood.
2. There was no significant difference between the behaviors of native wood and laminated wood. A slightly higher value for the relaxation speed was obtained for native wood with a thickness of 18 mm.
3. If a higher relaxation speed is desired, thicker materials should be used. The type of material and number of stressing cycles were shown to have no significant effects on the relaxation speed.
4. The sets of test pieces of both native and laminated wood with thickness between 6 and 10 mm should be investigated due to finding that the marginal thickness of material may be affected by the numbers of cycles of stress during its use. Therefore, these sets of test pieces will be subjected to further research within this area.

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