# Effect of Cyclic Loading on Modulus of Elasticity of Aspen Wood

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This article investigates the modulus of elasticity of solid and laminated aspen wood of various thicknesses after cyclic loading. A three-point static bending test was carried out to determine the modulus of elasticity. Cyclically loaded samples were compared with samples without cyclic loading. For the laminated wood, the results demonstrated a statistically significant impact of cyclic loading on the elasticity modulus. In contrast, no significant impact of cyclic loading was shown for the solid wood. The impact of the number of cycles was significant for both laminated and solid wood. When this number increased, the elasticity modulus values decreased. Generally, higher elasticity modulus values were confirmed for the laminated wood.

*Keywords: Cyclic loading; Laminated wood; Modulus of elasticity; Aspen; Number of cycles*

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## INTRODUCTION

Laminating is a process that generates a product by means of pressing small, thin layers of wood and glue together. This product can be either large-area material or lamella. Laminated veneer lumber (LVL) is used in the United States and Europe for structural and non-structural applications due to advantageous properties such as shape stability, high strength, consistency, and workability (Nelson 1997). For structural applications, LVL (Fig. 1) is used mostly in sport halls, exposition halls, storage facilities, and other large areas. The LVL can be reinforced with high-strength fibers such as carbon fibers. In the furniture industry, LVL is used for beds, sofas, chairs, and flooring (Eckelman 1993; Hayashi and Oshiumi 1993; Lam 2001).

**Fig. 1.** Use of LVL beam in a structure

Laminated veneer lumber is fabricated from veneers of various wood species in a longitudinal orientation that are glued and hot pressed (Shukla and Kamden 2008). The veneer thickness and type of glue used depend on the final application. Generally, these veneers are not thicker than 3 mm and are manufactured by peeling or cutting. Less valuable wood species are often used for LVL production. These wood species often acquire very good properties after their treatment and become as valuable as currently used wood species. For example, aspen is among the less valued and relatively cheap wood species. However, the bending properties of LVL produced from aspen veneers are comparable to those of commercially available spruce or pine LVL (Hsu 1988). A variety of thermoplastic and thermoset adhesives are used for LVL production, but polyvinyl acetate (PVAc) adhesive in the form of emulsion is the most frequently used. Its main advantage compared to formaldehyde-based adhesives is that it is non-toxic (Kim and Kim 2006). Moreover, it is soluble in water, easily applied, and is transparent after the adhesive has hardened.

Cyclic loading typically consists of repeatedly loading and unloading the product or element with an external force over a certain period of time. This loading causes material deformation or damage by a force smaller than its maximum strength. The material damage or deformation caused by cyclic loading is called material or structural fatigue. The fatigue limit is related to a certain number of cycles (fatigue life) and is expressed as a portion of the maximum strength. Typically, the fatigue limit has a value from one quarter to one third of the maximum strength, and eventually greater (Zhang *et al*. 2005). Although cyclic loading is used on structures, it is more frequent in furniture that is used for sitting or sleeping.

The aim of this work was to determine the influence of cyclic loading on the modulus of elasticity of aspen wood. This influence was monitored in solid and laminated wood with a thickness of 4, 6, 10, and 18 mm after 0, 1000, 2000, and 3000 cycles.

## EXPERIMENTAL

### Materials

European aspen trees (*Populus tremula* L.) were harvested from the Poľana region in the center of Slovakia. Sapwood, located equidistant from the pith, was chosen for the experiment. This wood was cut in 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 (Fig. 2).

The veneers for laminated wood were also chosen from the sapwood, from approximately the same distance from the center. These veneers were made by rotation peeling of steamed aspen logs. Pre-dried veneers with applied adhesive were pressed at 60 °C at a specific pressure of 1 MPa. Pressing time was set to 10 min for 4 mm thickness, and for each additional millimeter of thickness, the pressing time was extended by 2 min, *i.e*. 14, 22, and 38 min. for 6, 10, and 18 mm, respectively. The waterproof polyvinyl acetate adhesive (PVAc) Duvilax D3 Rapid (Duslo Šaľa, Slovakia) was used for the laminated wood (Table 1). Laminated wood with thicknesses of 4, 6, 10, and 18 mm (Fig. 1) was cut to the final width of 70 mm and length of 400 mm. Each thickness group of both laminated and solid wood contained 10 samples for each cycle type. The whole experiment included 320 samples (160 samples each for solid and laminated wood).

The clear laminated and solid 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.

**Table 1.** Parameters of PVAc Adhesive

| **Dry matter content** (%) | **Viscosity** (m Pa.s) | **pH** | **Working temperature** (°C) | **Working time** (minutes) | **Hardening time*** (minutes) | **Wood moisture content** (%) |
|---|---|---|---|---|---|---|
| 49 | 4000 to 8000 | 3 to 4 | 15 to 100 | 10 | 10 to 30 | 8 |

***** At 20 °C

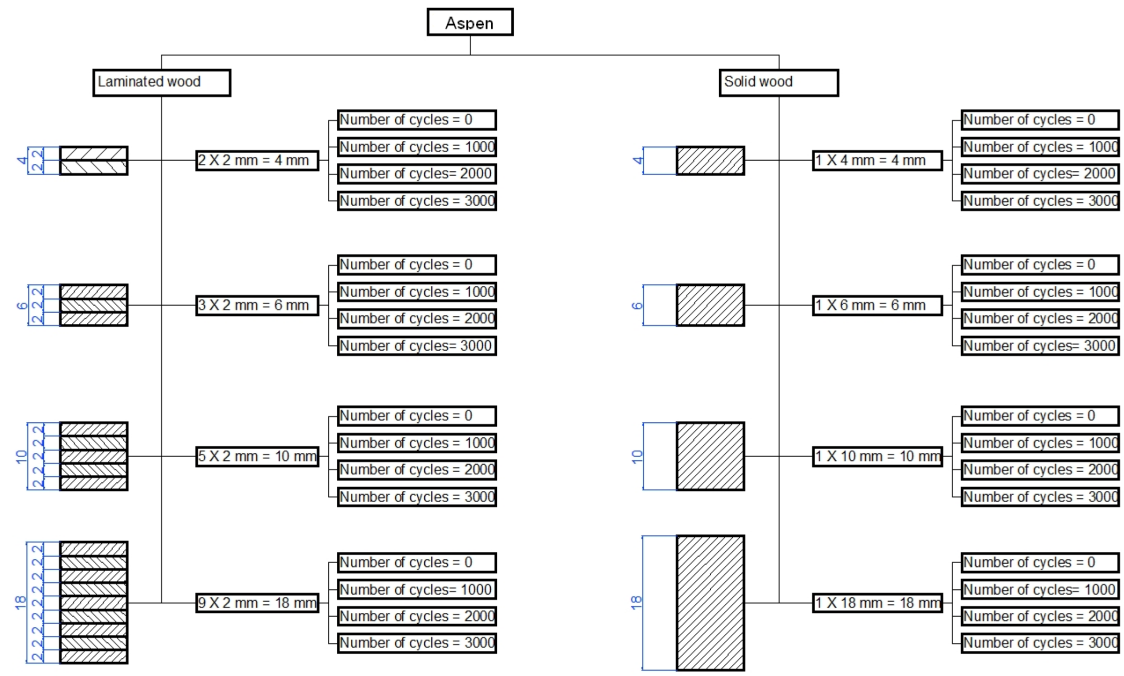


**Fig. 2.** Categorization of test pieces sets

## Methods

*Cyclic bend loading*

The cyclic loading was carried out on a horizontal cycling machine (Fig. 3) based on uniaxial stress.

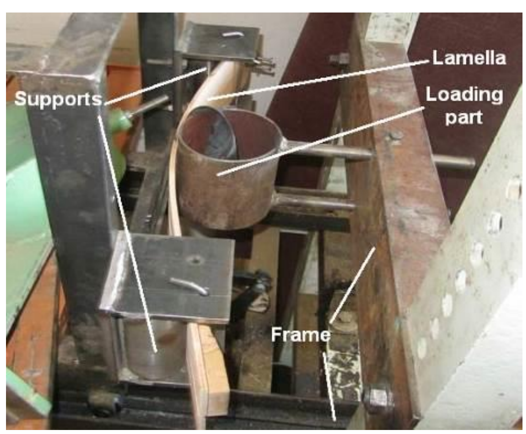


**Fig. 3.** Cycler machine

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 experiments of bending elastic modulus perpendicular to the fibers in a radial direction were carried out according to ISO 3349 (1975) and STN EN 49 0115 (1982). The samples were bent by the free-bending principle (*i.e.*, three-point bending test) according to STN EN 49 0115 (1982) and 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 at the breaking point. Test samples were placed on supporting pins (support span 20*h) so that the loading force acted in the radial direction considering the length of the sample, and a load was applied until they broke. The loading rate was set so that the breaking of the test sample occurred during 1.5 ± 0.5 min from the start of loading.

*Measurements*

The values of maximum loading forces were directly downloaded from the data logger onto a personal computer, and the modulus of elasticity was calculated. The deflection, measured at the midpoint of the test sample (mid-span deflection), was accurate to 0.01 mm using a digital indicator gauge. The dimensions of the samples used for calculating the moisture content were measured with a digital caliper (Mitutoyo, Japan) to a precision of 0.1 mm.

*Calculations and evaluation*

The influence of cyclic loading on the modulus of elasticity was statistically evaluated using ANOVA analysis, mainly by Fisher's F-test, in STATISTICA 12 software (Statsoft, USA).

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

$$E_m = \frac{l_0^3 (F_2 - F_1)}{4bh^2 (a_2 - a_1)} \tag{1}$$

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 $F_2$ - $F_1$).

The moisture content was determined before and after conditioning. These calculations were carried out according to ISO 3130 (1975) and Eq. 2,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{2}$$

where $w$ is the moisture content of the samples (%), $m_w$ is the mass (weight) of the test sample at a certain moisture $w$ (kg), and $m_0$ is the mass (weight) of the oven-dry test sample (kg). Drying to an oven-dry state was performed according to standard ISO 3130 (1975). Samples were weighed and then dried at a temperature of 103 ± 2 °C. Samples reached constant moisture content when the weight change between two weighings at intervals of 6 h did not exceed 0.5% of the mass of the sample. After drying, the samples were cooled in a desiccator and subsequently rapidly weighed to ensure the moisture content did not increase by more than 0.1% due to humidity in the air. Weighing was carried out to an accuracy of 0.5%.

## RESULTS AND DISCUSSION

### Laminated Wood

The ANOVA results proved that both material thickness and the number of cycles are statistically significant (Table 2).

**Table 2.** Individual Factors *vs.* Modulus of Elasticity of Laminated Wood

| Monitored factor | Sum of squares | Degree of freedom | Variance | Fisher's F-test | Significance level P |
|---|---|---|---|---|---|
| Intercept | 6,703,702,163 | 1 | 6,703,702,163 | 5,679.786 | 0.00001 |
| Number of cycles | 25,155,440.6 | 3 | 8,385,146.85 | 7,104 | 0.00017 |
| Material thickness | 27,288,151.5 | 3 | 9,096,050.52 | 7,707 | 0.00008 |
| Number of cycles & material thickness | 51,885,422.8 | 9 | 5,765,046.98 | 4,884 | 0.00001 |
| Error | 169,959,421 | 144 | 1,180,273.75 | | |

Statistical significance was evaluated at a 95% confidence interval

The modulus of elasticity decreased proportionally with an increase in the number of cycles. Although the impact of the number of cycles was statistically significant, the decrease in the modulus of elasticity was not very great (Fig. 4a).

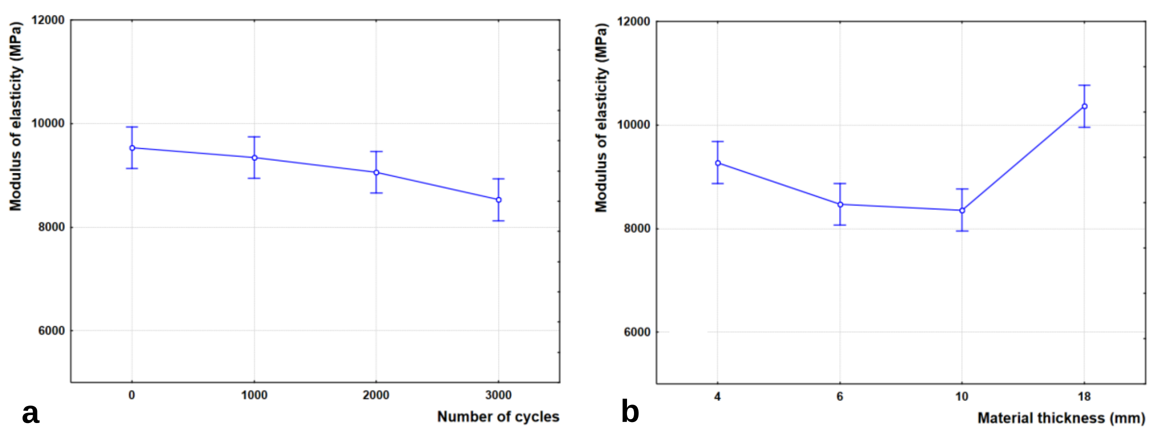


**Fig. 4.** The influence of (a) number of cycles and (b) material thickness on modulus of elasticity of laminated wood

The highest modulus of elasticity was reached for the wood without cyclic loading, thus confirming the general knowledge that cyclic loading weakens the material and reduces its strength.

The impact of the individual thicknesses was adverse (Fig. 4b). For a thickness of 4 mm, the modulus of elasticity was high. As the thickness increased, the modulus of elasticity decreased, but not beyond 10 mm. Once this thickness was exceeded, the modulus of elasticity began to increase. The 18 mm-thick wood had the highest modulus of elasticity overall.

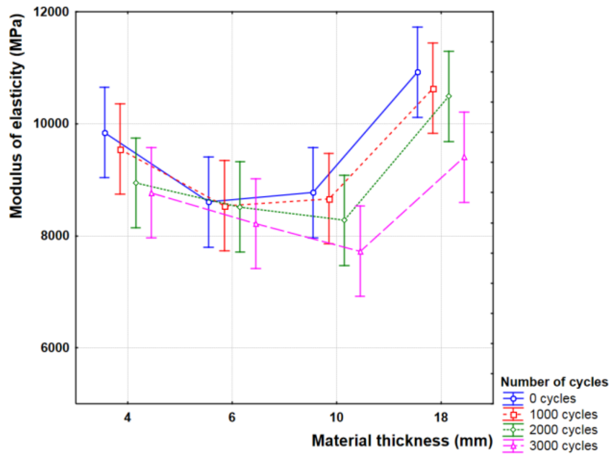


**Fig. 5.** The influence of number of cycles and material thickness on modulus of elasticity of laminated wood

Figure 5 shows the influence of the number of cycles and material thickness. Apparently, the curve shape remained the same for each cycle, *i.e.*, the highest values of modulus of elasticity were found at thicknesses of 4 and 18 mm. When comparing individual curves, the manner in which cyclic loading gradually reduced the modulus of elasticity can be seen. At a thickness of 18 mm, the modulus of elasticity decreased by 2,000 MPa after 3,000 loading cycles compared with the wood without cyclic loading.

## Solid Wood

In this case, the individual factors proved to be statistically significant. However, the interactions of material thickness and the number of cycles were not statistically significant (Table 3).

**Table 3.** Influence of Individual Factors on Modulus of Elasticity of Solid Wood

| Monitored factor | Sum of squares | Degree of freedom | Variance | Fisher's F-test | Significance level P |
|---|---|---|---|---|---|
| Intercept | 13,295,598,606 | 1 | 13,295,598,606 | 8,005.549 | 0.00001 |
| Number of cycles | 23,041,110.3 | 3 | 7,680,370.11 | 4.625 | 0.00404 |
| Material thickness | 103,067,925 | 3 | 34,355,975.1 | 20.686 | 0.00001 |
| Number of cycles & material thickness | 5,369,715.97 | 9 | 596,635.108 | 0.359 | 0.95240 |
| Error | 239,154,885 | 144 | 1,660,797.81 | | |

Statistical significance was evaluated at the 95% confidence interval

Similar to the laminated wood, the solid wood's modulus of elasticity decreased with an increasing number of cycles (Fig. 6a). However, the difference in moduli of elasticity between the non-cyclically loaded and cyclically loaded wood was greater. The differences between the individual numbers of cycles were negligible.

No proportional line was confirmed for the material thickness (Fig. 6b). The highest modulus of elasticity values were found at a thickness of 10 mm and the lowest were found at 6 mm.

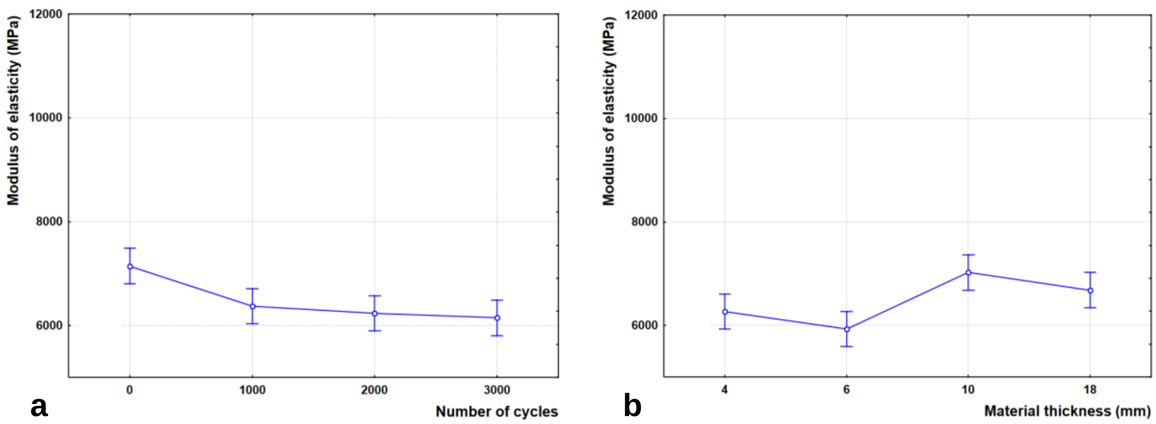


**Fig. 6.** The influence of (a) number of cycles and (b) material thickness on modulus of elasticity of solid wood

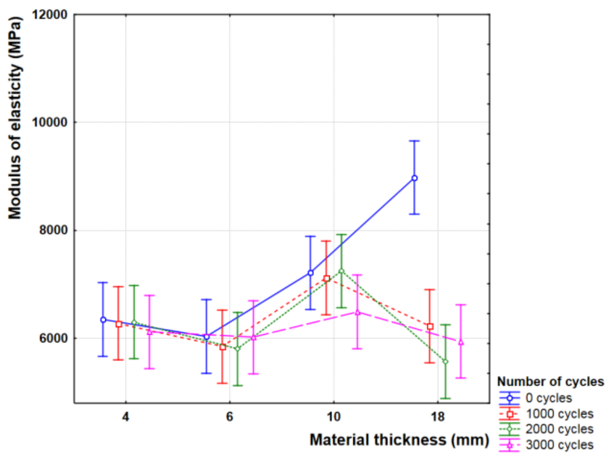


**Fig. 7.** The influence of number of cycles and material thickness on modulus of elasticity of solid wood

While evaluating the interaction of both monitored factors on the modulus of elasticity, the values for solid wood do not change significantly at a material thickness from 4 to 18 mm and with increasing number of cycles (Fig. 7). A significant increase in moduli of elasticity values can be seen only for wood without cyclic loading with a thickness of 6 mm or greater.

These moduli of elasticity values for the solid wood seemed to be relatively low. Tsoumis (1991) specified the elasticity modulus for European aspen as 10,700 MPa, while Heräjärvi (2009) found a somewhat lower value of 9,860 MPa.

When comparing the moduli of elasticity, it is evident that the laminated wood values were generally higher than those of solid wood. Bal (2014) also came to the same conclusion. In the current study, this was mainly due to the sapwood, from which the samples were made. Bao *et al*. (2001) confirmed the same finding when discovering that the sapwood contribution to the strength and elasticity is the greatest, while the impact of other factors (*e.g.*, the glue type) is secondary. Shukla and Kamden (2008) calculated that the modulus of elasticity of 3-layer aspen LVL ranges from 7,900 to 8,370 MPa.

In general, it can be stated that the present results for modulus of elasticity were affected by shear stresses. Shear stresses, during bending, depends on the thickness of the material. For material thicknesses up to 6 mm the effects of shear stresses were not clearly evident. From 6 to 10 mm, a little higher impact of shear stresses could be seen. However, in the thickness range 10 to 18 mm, the effect of shear stresses was very significant. On the other hand, the influences of shear stresses as well as the total values of the MOE were also affected by the number of glue lines, as well as the fact that the neutral axis passes through the glue line as well as through the veneer, respectively.

In future research it will be important to determine the impact of glue lines as well as their number on values of MOE and other properties.

## CONCLUSIONS

1. This work suggests that laminated wood can be considered significantly more elastic than solid wood, due to the fact that modulus of elasticity values were, on average, lower by 2,000 MPa for solid wood.
2. The effect of the number of cycles on the modulus of elasticity of both solid and laminated wood was the same, *i.e.*, the modulus of elasticity decreased with an increasing number of cycles. However, this decrease was more pronounced for solid wood.
3. The impact of material thickness was different for laminated wood and solid wood. The greatest modulus of elasticity was achieved at the thickness of 18 mm for non-loaded and for cyclic loaded wood while the values at thicknesses of 6 and 10 mm were identically lower. No significant differences in moduli of elasticity were found, even between loaded and non-loaded solid wood.

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## REFERENCES CITED

Bal, B. C. (2014). “Flexural properties, bonding performance and splitting strength of LVL reinforced with woven glass fiber,” *Construction and Building Materials* 51(1), 9-14. DOI: 10.1016/j.conbuildmat.2013.10.041

Bao, F., Fu, F., Choong, E. T., and Hse, C. (2001). “Contribution factor of wood

properties of three poplar clones to strength of laminated veneer lumber," *Wood and Fiber Science* 33(3), 345-352.
Eckelman, C. A. (1993). "Potential uses of laminated veneer lumber in furniture," *Forest Products Journal* 43(4), 19-24.
Gaff, M., and Gáborík, J. (2014). "Effect of cyclic loading on the elasticity of beech solid and laminated wood," *BioResources* 9(3), 4288-4296. DOI: 10.15376/biores.9.3.4288-4296
Hayashi, T., and Oshiumi, S. (1993). "Bending strength distribution of laminated veneer lumber for structural use," *Mokuzai Gakkaishi* 39(9), 985-992.
Heräjärvi, H. (2009). "Effect of drying technology on aspen wood properties," *Silva Fennica* 43(3), 433-445. DOI: 10.14214/sf.198
Hsu, W. E. (1988). "Laminated veneer lumber from aspen," *Proceedings of the 22nd International Particleboard/Composite Material Symposium*, March 22-24, Pullman, WA, pp. 257-269.
ISO 3130. (1975). "Wood-Determination of moisture content for physical and mechanical tests," *International Organization for Standardization*, Geneva, Switzerland.
ISO 3349. (1975). "Wood-Determination of modulus of elasticity in static bending," *International Organization for Standardization*, Geneva, Switzerland.
Kim, S., and Kim, H.-J. (2006). "Study of miscibility of melamine-formaldehyde resin and poly (vinyl acetate) blends for use as adhesives in engineered flooring," *Journal of Adhesion Science and Technology* 20(2-3), 209-219. DOI: 10.1163/156856106775897739
Lam, F. (2001). "Modern structural wood products," *Progress in Structural Engineering and Materials* 3(3), 238-245. DOI: 10.1002/pse.79
Nelson, S. (1997). "Structural composite lumber," in: *Engineered Wood Products: A Guide for Specifiers, Designers, and Users*, S. Smulski (ed.), PFS Research Foundation, Madison, WI, pp. 147-172.
STN EN 49 0116. (1982). "Wood-Determination of modulus of elasticity in static bending," *Slovak Office of Standards, Metrology and Testing*, Bratislava, Slovakia.
Shukla, S. R., and Kamdem, D. P. (2008). "Properties of laminated veneer lumber (LVL) made with low density hardwood species: Effect of the pressure duration," *Holz als Roh- und Werkstoff* 66(2), 119-127. DOI: 10.1007/s00107-007-0209-1
Tsoumis, G. T. (1991). "*Science of Technology of Wood: Structure, Properties, Utilization*," Van Nostrand Reinhold, New York, pg. 494.
Zhang, J., Baozhen, C., and Daniewicz, S. R. (2005). "Fatigue performance of wood-based composites as upholstered furniture frame stock," *Forest Products Journal* 55(6), 985-992.

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