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Damping and layer configuration in wood veneer composites

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Abstract The aim of the present study was to find and describe the relationship between damping properties and both the number of layers and the fiber orientation in wood-veneer-composite specimens. The testing apparatus was a simple torsional pendulum in which the frequencies of the resulting free vibrations were maintained between 13 and 23 Hz. Cross-sectional (30 × 30 mm) specimens with a total length of 250 mm were used. The specimens were cut from manufactured wood-veneer-composite panels (both 0°/90° and 0°/0° oriented) with up to 13 layers. Existing problems such as nonlinearities, which are often responsible for weighting results, were taken into account by using several mathematical approaches. The results led to a consistent picture of the damping properties across the measured range. We found that the damping ratio increased for the 0°/90° orientation with increasing numbers of layers in a cross-sectional specimen of constant outer dimensions. This effect could not be reproduced for specimens oriented 0°/0°.

Key words Damping ratio · Torsional vibration · Wood · Plywood · Wood veneer composites

Introduction

Several studies have been carried out to estimate damping and energy dissipation properties of wood and wood-based materials, e.g., plywood. The viscoelastic behavior of wood and its dependence on temperature and corresponding moisture content were described by Becker and Noack.[1] However, Krüger and Rohloff[2] found no evidence for frequency-dependent damping properties in spruce, maple, pine, or beech, but showed dependencies in damping on the amplitude of the vibration. Wood is commonly accepted as being "highly damping." This conclusion often derives from practical experience, not from scientific research. Therefore, the aim of the present study was to characterize the damping capabilities of different plywoods, a frequently used type of wood material, and its original material (birch wood). Of particular interest was the relationship between damping properties and both the number of layers and the fiber orientation in wood-veneer-composite specimens (WVC), because the authors assumed that fiber direction in WVC influences vibrational properties. Exact knowledge of the damping capabilities of different plywoods allows precise improvements of construction elements in relation to damping, e.g., to reduce noise. Furthermore, the damping capabilities of plywood and conventionally used construction materials such as steel or aluminum can be compared.

Materials and methods

Specimens provided for the test series were sawn out of WVC panels manufactured from flat sawn birch wood veneer (two trees *Betula* spp. L.; global coordinates: 50°1′25.60″ N, 11°16′53.22″ E).

The WVC panels were:

- sawn parallel to the north–south direction of the trees
- dried to 8% moisture content
- bonded with phenol–resorcinol–formaldehyde resin adhesive (250 g/m^2), flashed-off for 5–8 min, and then compressed (2 kg/m^2) at 40°C (heating plates) for 12 h.

The average density of all specimen configurations was 0.67 g/cm^3. The outer dimensions were kept constant while the number of layers was increased. The minimum number of layers was 1, which was equivalent to natural wood, and the maximum number of layers was 13 for WVC-0°/0°. WVC-0°/90° was also provided for odd numbers of layers (Table 1). Each specimen was 250 mm long with a cross section of 30 × 30 mm^2. In order to accommodate the different numbers of layers, the thickness of the individual layers varied from 2.3 to 13 mm (Table 1).

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Table 1. Specimen layer configuration

		Number of layers												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Thickness of layers	WVC-0°/0°	30.0	15.0	10.0	7.5	6.0	5.0	4.3	3.8	3.3	3.0	2.7	2.5	2.3
	WVC-0°/90°	×	×	10.0	×	6.0	×	4.3	×	3.3	×	2.7	×	2.3

WVC, wood veneer composite

For each layer configuration, five specimens were provided. Each specimen was tested 10 times sequentially, therefore each layer configuration was tested 50 times. To quantify the effects of damping in wood, and especially WVC, under the aspect of lamination variations (fiber orientation, layer number, and thickness), a measurement apparatus was designed following the principle of a torsional pendulum (Fig. 1). The torsional principle was chosen because of the more advantageous stress distribution in the cross section of the specimen compared to bending loads. The simple torsional pendulum was equipped with sensors for vibration angle and torque. The free vibrations of the pendulum were recorded (Figs. 2 and 3, black line) after the deflected pendulum was released. The torque reaction measured at the lower clamping was used to fit the models (Figs. 2 and 3, gray line).

As the specimen was the only effective torsional stiffness in the system, lower and upper clamps were assumed to be infinitely stiff. Relative motion in the clamp as a reason for Coulomb's damping was assumed to be zero. The purpose was to determine the decay of the rotary vibration, and the logarithmic decrement, in particular, as a measure of damping. Preliminary tests showed that the measured damping properties were strongly influenced by the clamping parameters, namely the bolt torque of the clamps. Nevertheless, it was possible to get reproducible measurements by using a simple cordless screwdriver with electronic torque limitation to fasten the bolts. The results were retrieved by postprocessing the data via the R environment.[3] The raw data sequences of torque and angle were simultaneously recorded at a 1 kHz sample rate. Using the pretrigger values, it was possible to determine the elastic shear modulus. The coefficients of the Fourier series contained in the mechanical/mathematical models were estimated using a nonlinear least squares method.

The commonly used mechanical model – the solution of the linear homogenous equation of motion of a single degree of freedom system (SDOF) containing Fourier constants (A, B), natural angular frequency (ω_0), and the decay constant (δ) – was applied to the torque reaction [$M_t(t)$] sequence (Fig. 2, gray line). For most of the measured data, it represents the vibration decay quite well, which is also shown by the fit quality of represented by the residual square sum (RSS) values.

$$M_t(t) = [A \cdot \sin(\omega_0 \cdot t) + B \cdot \cos(\omega_0 \cdot t)] \cdot e^{-\delta \cdot t} \tag{1}$$

What we then see is that a shift in frequency (s) occurs at the end of torque decay (Fig. 2, inset). This may be an indicator of nonlinear system behavior in WVC. Therefore, a nonlinear model with time-dependent frequency was applied to the measured data (Fig. 3, gray line).

$$M_t(t) = [A \cdot \sin([\omega_0 - s \cdot t] \cdot t) + B \cdot \cos([\omega_0 - s \cdot t] \cdot t)] \cdot e^{-\delta \cdot t} \tag{2}$$

The latter model was more appropriate to analyze the measured data than the linear model was. Moreover, the quality of fit in terms of residual square sum showed a better approximation (Fig. 3, inset).

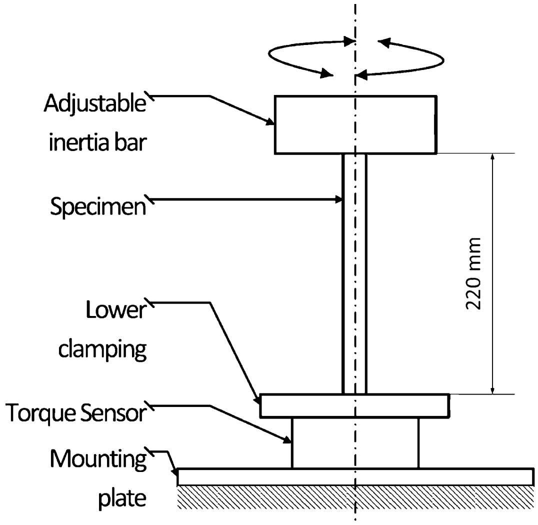

Fig. 1. Torsional pendulum setup

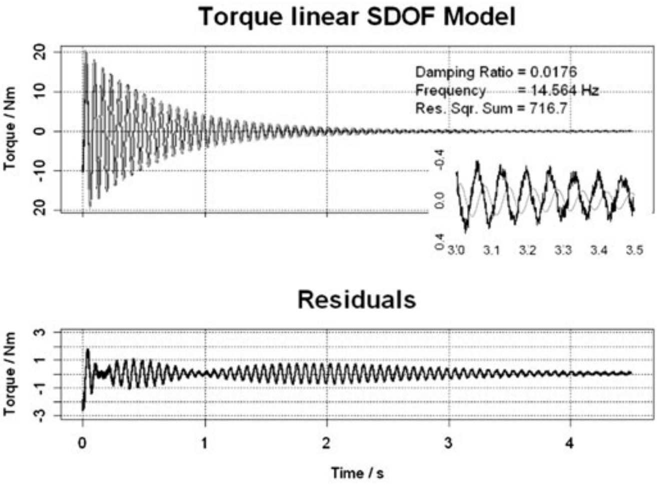

Fig. 2. Torque series and linear model. *SDOF*, single degree of freedom system. *Black line*, free vibrations; *gray line*, modeled values

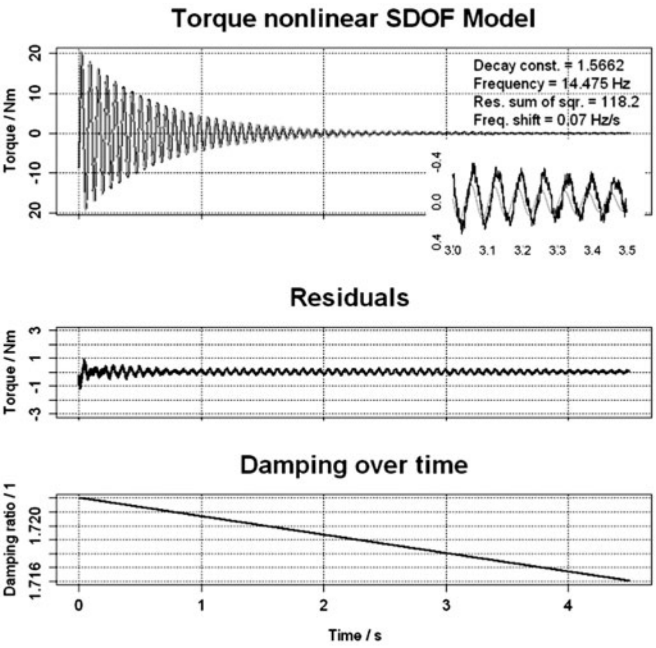

Fig. 3. Torque series and nonlinear model

A physical interpretation of such behavior leads to nonconstant stiffness, damping parameters, or both during decay (assuming the mass is constant). By ensuring that no ductile deformation takes place, stiffness is assumed to be constant. Following the latter, the damping ratio ϑ was no longer constant, but rather changed with time in terms of:

$$\vartheta = f(t) = \frac{\delta}{\omega(t)} = \frac{\delta}{\omega_0 - s \cdot t} \tag{3}$$

Assuming that the change in damping over time is related to the amplitude of the vibration, parameters δ and s were not expected to be completely independent.

Results and discussion

For WVC 0°/0°, there was no clear evidence for a change in damping ratio with increasing layer number (Fig. 4). The conspicuous variability of measured values for 5-ply WVC 0°/0° was due to observable delamination effects. Accordingly, those data were not included in the regression plots of the damping ratio. Looking at the RSS (Fig. 4), there was a tendency toward decreasing deviation between model and measured data with increasing numbers of layers. For WVC 0°/90°, we found an increase of the damping ratio (Fig. 5) with increasing numbers of layers, although the linear regression model explained only 77% of the measured data variance. The RSS shows an identical tendency to that for WVC 0°/0°. There are two possible reasons for such behavior: (1) with increasing numbers of layers, the mathematical model is more accurate, or (2) inhomogeneity is increasingly compensated by the composite structure. Equivalent results were retrieved by fitting a nonlinear model to the measured data.

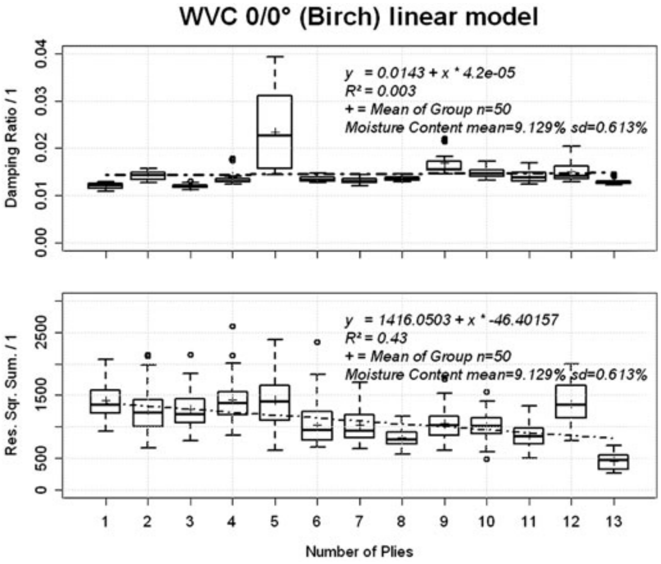

Fig. 4. Box plots of damping ratio and residual square sum (RSS) linear model for wood-veneer-composite (*WVC*) 0°/0° specimens

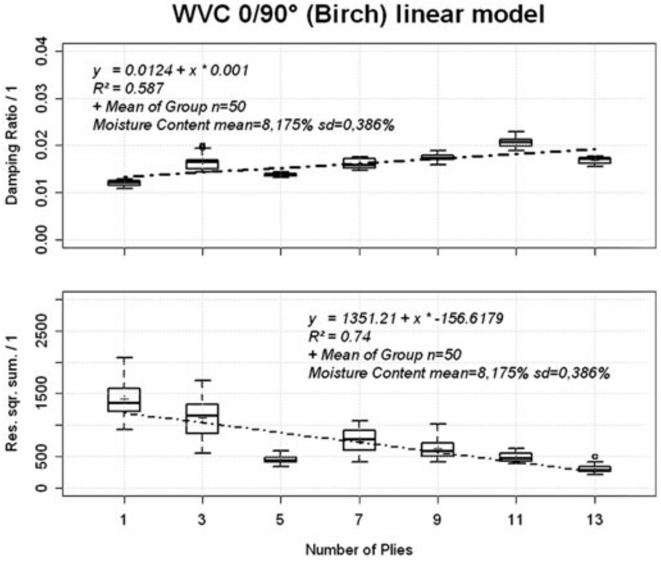

Fig. 5. Box plots of damping ratio and RSS linear model for WVC 0°/90° specimens

Considering that the damping ratio ϑ is not constant (Eq. 3), the notation is ϑ ($t = 0$). Figure 6 shows similar behavior for ϑ ($t = 0$) as that in Fig. 4. Accordingly, there is no evidence for a change in damping with increasing numbers of layers for WVC 0°/0°. In contrast WVC 0°/90° showed dependencies in damping on layer number within the nonlinear model (Fig. 7). Taking the RSS values into account, the nonlinear model fits the measured decays more exactly than the linear model does (Fig. 5).

Conclusions

Even with a simple torsional pendulum, it was possible to assess damping in terms of a highly variable material-

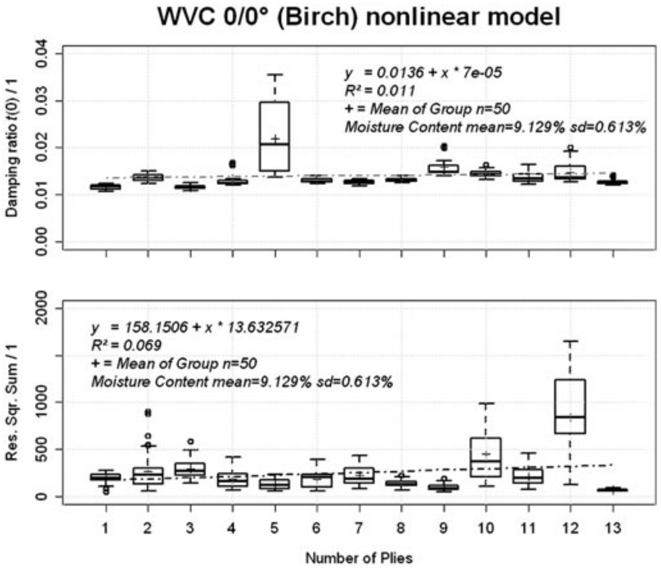

Fig. 6. Box plots of damping ratio and RSS nonlinear model for WVC 0°/0° specimens

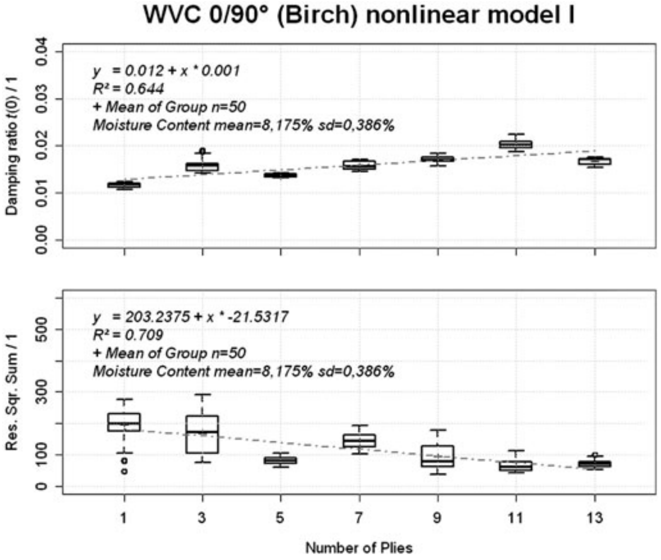

Fig. 7. Box plots of damping ratio and RSS nonlinear model for WVC 0°/90° specimens

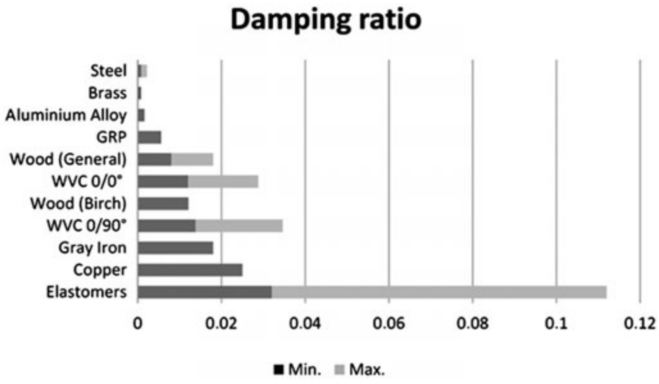

Fig. 8. Damping classification. *GRP*, glass-reinforced plastics; *Min.*, minimal values found in literature; *Max.*, maximal values found in literature

and structure-dependent property. Besides the identified relationship between layer number and damping ratio, it is important to consider the mentioned amplitude dependency. In fact, plywood (so-called WVC) showed intermediate damping ratios between metallic materials at the lower range and long chain polymers at the higher range (Fig. 8).

However, even if damping values derived from different measurement designs are not always directly comparable, some classification in relation to other materials can be made. Except for WVC 0°/0°, WVC 0°/90°, and wood (birch), the damping values in Fig. 8 were taken from VDI[4] and Petersen.[5] Neither publication specified the underlying types of wood for the term “Wood (General).”

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