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Experimental evaluations of material damping in timber beams of structural dimensions

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Abstract Understanding the inherent damping mechanisms of floor vibrations has become a matter of increasing importance following the development of new composite floor layouts and increased span. The present study focuses on the evaluation of material damping in timber beam specimens with dimensions that are typical of common timber floor structures. Using the impact test method, 11 solid wood beams and 11 glulam beams made out of Norway Spruce (*Picea abies*) were subjected to flexural vibrations. The tests involved different spans and orientations. A total of 420 material damping evaluations were performed, and the results are presented as mean values for each configuration along with important statistical indicators to quantify their reliability. The consistency of the experimental method was validated with respect to repeatability and reproducibility. General trends found an increasing damping ratio for higher modes, shorter spans, and edgewise orientations. It is concluded from the results that material damping of timber beams of structural dimensions is governed by shear deformation, which can be expressed more conveniently with respect to the specific mode shape and its derivatives.

Introduction

Damping is of interest in many disciplines and was first investigated with regard to space structure applications (Neumark 1962). Nowadays, it is also relevant for more common structures, for example, cars or buildings, under the generic name of "comfort properties." When designing building floors, excessive vibrations are usually not a safety concern, rather a serviceability issue due to annoyance and other discomforts. When damping is close to resonance, it will have a large beneficial

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influence on the structural response since it decreases both the amplitude of steady-state oscillations as well as the duration of transient oscillations. Despite its substantial effects, damping is rarely prescribed in design codes or standards, mainly because of the lack of knowledge. For timber structures, damping evaluations are generally considered to depend too much on the engineer's judgment, because of the lack of reliability in the methods. Moreover, the poor understanding of what the damping phenomenon is exactly leads to the situation in Eurocode 5 (European Committee for Standardization 2005): Damping quantity is introduced as an arbitrary single value, nationally determined for any type of floor. A cruder criterion is commonly used that employs the natural frequency as a target value to assess the performance of the structure with respect to its comfort properties. This is despite the fact that the implementation of damping in prediction models would result in more accurate predictions and more cost-effective building solutions.

Data on the measured damping properties of wood are scarce, partly due to difficulties in retrieving reliable experimental data. In addition, damping nomenclature is often inconsistent (Lazan 1968), which increases the confusion by mixing different types and quantities of damping. Among others, the damping ratio ξ, the logarithmic decrement λ, the internal friction Q^{-1}, the loss factor η, or the loss tangent $\tan(\delta)$ were successively used in different studies. They are all related by:

$$\xi = \frac{\lambda}{2\pi} = \frac{Q^{-1}}{2} = \frac{\eta}{2} = \frac{\tan(\delta)}{2}. \tag{1}$$

From a material science point of view, material damping may be defined as internal friction by transformation of mechanical energy into heat during cyclic stress (Ouis 2002). In general, damping may be divided into three classes (Woodhouse 1998):

- internal friction throughout the material making up the structure: material damping,
- energy dissipation associated with junctions or interfaces between parts of the structure: structural damping, and
- energy dissipation associated with a fluid in contact with the structure, involving either local viscous effects or radiation into the fluid: fluid damping.

The making of musical instruments seems to have induced scientific investigations of wood properties, including damping estimations, much earlier than corresponding investigations of timber structures. In order to improve knowledge on wood for musical instruments, the frequency dependence of the logarithmic decrement was investigated (Fukada 1950), as well as the effects of moisture content and temperature (Fukada 1951). Particular attention was paid to the selection of suitable types of wood for the soundboards of musical instruments, and relationships between internal friction and dynamic Young's modulus were investigated to that end (Ono and Norimoto 1985). Investigations about the dependence of internal friction to frequency were numerous for wood specimens used in musical instruments, but were not always concordant. On the one hand, damping was found to be independent of frequency within large ranges of frequency, for example, up to about 2 kHz (Ono and Norimoto 1985) or up to 10 kHz (Nakao et al. 1985). On the other hand, damping was observed to be independent of frequency (Foster 1992), but only in the longitudinal direction, whereas it was strongly dependent on frequency in the radial direction (Foster 1992). The influence of the grain angle on the vibration properties, including damping, was also investigated more generally (Brémaud et al. 2011).

Experimental damping values have been largely available for an acoustic use of timber (Obataya et al. 2000; Ono and Norimoto 1985; Bucur 2006; Spycher et al. 2008), or else concerning the mechanical pulping use of timber (Havimo 2009). More recently, 54 tropical species were analyzed (Brancheriau et al. 2010) using free vibration and forced-released vibration tests on 350-mm-long specimens.

However, few studies in the literature report on the damping properties of timber elements for structural use. Even if, as early as 1927, Kimball and Lovell (1927) used one-meter-long specimens to measure the internal friction of 18 different solids including maple wood, and experimental damping values related to a structural use of timber were first reported by Yeh et al. (1971). They performed free flexural vibration tests on real-sized wood frames to investigate both the damping associated with the material itself and the damping associated with the joining device, such as nails or glue.

Due to the scarce quantification of damping properties for structural use, the intention of the present study is to provide new and reliable values for material damping of timber beams that are typical for common floor structures. This work first describes an experimental method to evaluate material damping in timber beams of structural dimensions. The statistical methods used for evaluating reliability are defined in "Materials and methods." In "Result and discussion," the validity of the method is assessed with respect to repeatability and reproducibility, and the reliability of the results is demonstrated by means of statistical indicators. Governing parameters are also discussed. Some of the cited experimental damping measurements are reported in Table 1 for ease of comparison. Damping is expressed as damping ratio values ξ, as defined in Eq. (1).

Materials and methods

Experimental setup

A total of 22 beams were tested using flexural vibration estimation techniques. These were 11 solid wood beams of quality C24 (European Committee for Standardization 2009) and 11 glulam beams of quality GL32c (European Committee for Standardization 1999), all made out of Norway Spruce (*Picea abies*). The nominal dimensions and properties are summarized in Table 2, and they represent typical dimensions in common timber floor structures. All beams were measured and weighed to determine the density. Glulam beams had a mean density of 494 kg/m^3 (coefficient of variation = 2 %), while the solid wood beams had a mean density of 445 kg/m^3 (coefficient of variation = 6 %), both match the nominal properties of their respective strength class. The orientation of annual rings was not recorded.

Table 1 Experimental damping ratio presented in previous studies

Author(s)	Damping ratio ξ	Wood species	Method
Fukada (1950)	0.0027	Yezo Spruce (*Picea Jezoensis)*	Free flexural vibration
Kollmann and Krech (1960)	0.0031	Norway Spruce (*Picea abies*)	Forced flexural vibration
Matsumoto (1962)	0.0027	Japanese Cedar (*Cryptomeria japonica*)	Transverse vibration
Holtz cited in Bucur (2006)	0.0030	Spruce (*Picea abies*)	
Yeh et al. (1971)	0.0035	Hemlock (*Tsuga*)	Free flexural vibration
Wert et al. (1984)	0.0075	Sitka Spruce (*Picea sitchensis)*	Low inverted torsional pendulum
Ono and Norimoto (1985)	0.0056 (longitudinal)	Sitka spruce (*Picea sitchensis*)	Free longitudinal vibration
Nakao et al. (1985)	0.0035	Sitka spruce (*Picea sitchensis)*	Free flexural vibration
Foster (1992)	0.0030 (axially) 0.0025 (axially)	King William Pine (*Athrotaxis selaginoides*) Norway Spruce (*Picea abies*)	Uniaxial loading + phase lag measurement
Obataya et al. 2000)	0.0022–0.0037	Sitka Spruce (*Picea sitchensis*)	Free flexural vibration
Spycher et al. (2008)	0.0051 (axially) 0.0068 (axially)	Norway Spruce (*Picea abies*) Sycamore (*Acer pseudoplatanus*)	Forced flexural vibrations
Brancheriau et al. (2010)	0.0035	Tropical species (mean on 54 species)	Free vibration in bending and compression

Table 2 Nominal dimensions and nominal properties of the tested timber beams

	Strength class	Length (m)	Cross-section (m × m)	Mean density (kg/m^3)	Mean modulus of elasticity (GPa)	Mean shear modulus (GPa)
Solid wood	C24	6	0.220 × 0.070	420	11.0	0.69
Glulam	GL32c	6	0.404 × 0.088	490	13.7	0.78

Temperature and relative humidity were not controlled, but were assumed to correspond to common indoor conditions, respectively, 20 °C and 40 %. Each timber beam was simply supported with a symmetric overhang. Supports used were constructed of either rigid steel tripods or sections of thick steel cylinders. Teflon sheets were added in between the timber beam, and the steel supports in order to minimize friction and other sources of structural damping. The unique combination of span, mode, and orientation is referred to as a configuration. The configuration nomenclature is used as follows. The different test configurations are designated by: SW = Solid Wood; GL = Glulam; E = Edgewise orientation; F = Flatwise orientation; second last number = span; last number = mode number. For instance, "SW-E-3-1" corresponds to the evaluation of the damping ratio ξ for the first mode of transversal vibration for a solid wood beam lying edgewise with a span of 3 m.

Experimental evaluation of damping ratios, fundamental frequencies, and mode shapes

The modal hammer "heavy duty type 8208" from Brüel & Kjær was used to set the beam into motion. A soft tip was employed in order to excite lower frequencies. Transient vibrations due to modal hammer impact were recorded by one ceramic/quartz impedance head Kistler accelerometer type 8770A50 screwed into the beam. The load and acceleration time series were then digitalized and processed by a dynamic signal analyzer. The sampling frequency was fixed to 1,000 Hz, and 5 s data were recorded for each impact. An experimental modal analysis software was provided by National Instruments (2011) to record and process the data, using the graphical development environment LabVIEW. Experimental modal analysis (Ewins 2000) was used for determining the fundamental frequencies, the damping ratios, and the mode shapes of the timber beams, with the fundamental assumption of small damping. The frequency response function H, given with respect to the circular frequency ω, uses the fast Fourier transform (FFT) to relate the input signal spectrum $F(\omega)$ from the hammer and the output signal spectrum $X(\omega)$ from the accelerometer as:

$$H(\omega) \equiv \frac{X(\omega)}{F(\omega)} \tag{2}$$

A linear average H_{average} of the estimated frequency response function over three impacts was performed for each evaluation. Identification of transfer function models was performed by curve fitting the averaged frequency response function. The parameter identification method was based on the Frequency Domain Direct Parameter Identification fitting method, which is a frequency domain multiple degree-of-freedom modal analysis method suitable for narrow frequency band and well-separated modes. The experimental setup is displayed in Fig. 1 and is similar to the one used to predict the presence of decay in logs (Ouis 2000). The present method is considered nondestructive (Ouis 1999) since the hammer impact is soft enough not to inflict any damage to the beam or modify its properties. This also allows an unlimited number of repeated measurements to be performed on each specimen.

The driving point method (De Silva 2005) was used to evaluate the damping ratios and the fundamental frequencies. The impact and the data recording took place at the same location, 2.5 m from one end of the beams. All beams were evaluated for three different spans (3, 4, and 5 m) and on their four different faces A, B, C and D, where A and C represent the flatwise orientation, while B and D represent the edgewise orientation, as illustrated in Fig. 2.

The roving hammer method (De Silva 2005) was used for mode shape measurements, in order to extract frequency response functions at several locations along the beam. In that case, 13 impacts were performed consecutively, every 0.5 m along the timber beam. The accelerometer remained screwed 2.5 m from one end of

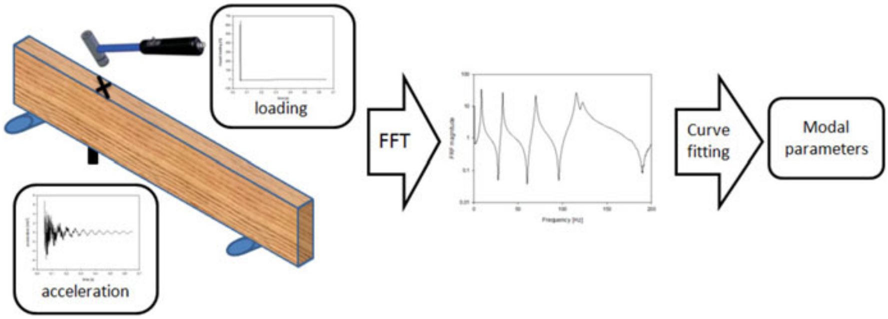

Fig. 1 Experimental setup

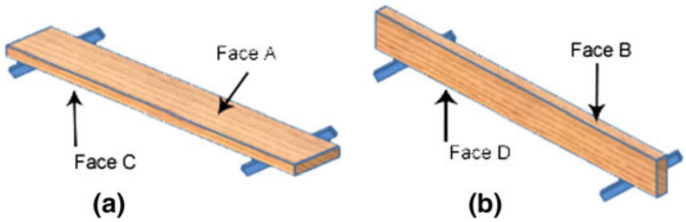

Fig. 2 Beam faces and orientations: **a** Face A and C, flatwise orientation, **b** Face B and D, edgewise orientation

the beam during all consecutive impacts. The experimental evaluation of mode shapes was performed for one solid wood beam only. Three spans: 3, 4, and 5 m were considered. The first four modes were estimated for each span of the flatwise orientation, while only the first mode was recorded for each span of the edgewise orientation.

General statistical methods

Statistical indicators

Various statistical indicators were evaluated for different sets of data X. In particular, the estimated mean value $\bar{X}$, the standard deviation S_X, the median m_X, and the coefficient of variation COV_X were evaluated. In addition, both the 95 % confidence intervals for the mean $CI_{\bar{X}}$ and for the standard deviation CI_{S_X} were evaluated. They are, respectively, defined as:

$$\begin{aligned} \mathrm{CI}_{\bar{X}} &= \left[\bar{X} - t_{0.025}\frac{S_X}{\sqrt{n}};\ \bar{X} + t_{0.025}\frac{S_X}{\sqrt{n}}\right] \\ \mathrm{CI}_{S_X} &= \left[\sqrt{\frac{(n-1)}{\chi^2_{0.025}}}S_X;\ \sqrt{\frac{(n-1)}{\chi^2_{0.975}}}S_X\right] \end{aligned} \tag{3}$$

where $t_{0.025} = t$ value with $n - 1$ degrees of freedom, leaving an area of 0.025 to the right, $n =$ number of evaluations, $\chi^2_{0.025}$ and $\chi_2{}^{0.975} =$ chi-square values with

$n - 1$ degrees of freedom, leaving areas of 0.025 and 0.975, respectively, to the right. The normalized length of the 95 % confidence interval for the mean λ_X is defined as:

$$\lambda_X = \frac{2}{\bar{X}} t_{0.025} \frac{S_X}{\sqrt{n}} \tag{4}$$

For a normal distribution, the 99th percentile is defined by:

$$\begin{gathered} P(X > X_{99}) = 1\,\% \\ \text{with } X_{99} = \bar{X} + 2.33 S_X \end{gathered} \tag{5}$$

The Pearson product-moment correlation coefficient estimate r (Walpole et al. 2007) was used to measure the strength of linear dependence between quantities. Similarly, the modal assurance criterion matrix (MAC) was used to measure the linear consistency (Allemang 2003) between two vectors u and e:

$$\mathrm{MAC}_{ij} = \frac{\left(\{u_i\}^T \{e_j\}\right)^2}{\left(\{u_i\}^T \{u_i\}\right)\left(\{e_j\}^T \{e_j\}\right)} \tag{6}$$

Statistical tests

Statistical tests were also performed with a p value approach, associated with a level of risk of 5 %. The Anderson–Darling test was used to test the statistical hypothesis of normality, with the following hypotheses:

$$\begin{aligned} H_0 &: \text{ the data follow a normal distribution} \\ H_1 &: \text{ the data do not follow a normal distribution} \end{aligned} \tag{7}$$

A one-way ANOVA test was performed in order to test the statistical hypothesis of equal means, which involves the following hypotheses:

$$\begin{aligned} H_0 &: \text{ the means are equal} \\ H_0 &: \text{ at least two of the means are not equal} \end{aligned} \tag{8}$$

The Leven/Brown–Forsythe test was performed in order to test the statistical hypothesis of equal standard deviations, and the following hypotheses were considered:

$$\begin{aligned} H_0 &: \text{ the standard deviations are equal} \\ H_0 &: \text{ at least two of the standard deviations are not equal} \end{aligned} \tag{9}$$

Design of experiments approach

Minitab® Statistical Software (2010) was used to capture differences between response readings (outputs) for different groups of the input changes. For each factor, a number of levels are defined to represent the range of interest. Differences are then attributed to the factors acting alone (called a single effect) or in combination with another factor (called an interaction).

Statistical treatment of damping ratio evaluations

The probability distribution for all available evaluations for each configuration was assumed to follow a normal distribution. The process of detecting and treating data to be discarded is adapted from recommended practice published by the Ministry of Environment in British Columbia (CA) (Ministry of Environment of British Columbia 2001).

Evaluations in the upper 1 % of the distribution were deemed unlikely to belong to the assumed population. The 99th percentile defined in Eq. (5) was therefore used as a lower boundary. An additional gap check was performed to investigate the inconsistency of the suspected evaluations. The associated statistical test compares the distance between the suspected evaluations and the next non-suspected data point to the predicted distance between the two largest values of the considered sample. These two largest values of the sample were reasonably assumed to correspond to the following percentiles of the assumed distribution:$100(N-1)/N$ and $100(N-2)/N$. Any evaluation showing a distance to the next data point larger than twice the predicted distance was thus discarded as inconsistent.

Repeatability and reproducibility investigations

Repeatability is defined (International Organization for Standardization 2010) as: “the precision under observation conditions where independent test/measurement results are obtained with the same method on identical test/measurement items in the same test or measuring facility by the same operator using the same equipment within short interval of time.” Reproducibility is defined (International Organization for Standardization 2010) as: “the precision under observation conditions where independent test/measurement results are obtained with the same method on identical test/measurement items in different test or measurement facilities with different operators using different equipment.”

In the present study, the repeatability and reproducibility were investigated by evaluating the damping ratio ξ for the first mode of a single solid wood beam in the configuration SW-F-5-1, through a series of 10 evaluations, with 3 averaged hits per evaluation. The test series were performed by 10 different operators, 6 males and 4 females with different weights and heights. Each operator was asked to perform 30 hits using the same equipment, same test/measurement items, and same procedure. Only one operator, operator J, had previous knowledge of the equipment and the test procedure.

Repeatability was investigated by evaluating the normality of the evaluations performed by each operator by means of the Anderson–Darling test defined in Eq. (7). Reproducibility was investigated by comparing the means and standard deviation of the series obtained for each operator, by means of a one-way ANOVA

Table 3 Selected factors and levels for the design of experiments

Factors	Levels		
Accelerometer location	X1		X2
Impact location	X1		X2
Span	3 m	4 m	5 m
Beam orientation	Edgewise		Flatwise

hypothesis test defined in Eq. (8) and the Leven/Brown–Forsythe hypothesis test defined in Eq. (9), respectively.

Parametric study

A parametric study was performed on a single solid wood beam following a full factorial design of the experiment approach. The damping ratio ξ for the first mode was evaluated for different combinations of spans, orientations, impact loading locations, and acceleration recording locations. Studied factors and their respective levels are reported in Table 3. The flatwise orientation results and the edgewise orientation results were computed as the mean values of evaluations related to faces A and C, and related to faces B and D, respectively. Locations X1 and X2 correspond to a distance of 2.5 and 3 m from one end-section of the beam, respectively.

Numerical evaluation of mode shapes

The commercial software Abaqus (Abaqus Analysis User's manual, version 6.9 2010) was used to perform the numerical analyses. Both solid wood and glulam beams were modeled using 4,536 quadratic continuum elements with reduced integration. The mesh was chosen with at least 9 elements to compose the height of the beam, and at least 8 elements along the width of the beam. Approximately, 60 elements were used along the beam in the longitudinal direction. The nominal material properties given in Table 2 were used.

Results and discussion

Validation of the experimental protocol

Investigations on repeatability and reproducibility were performed using a panel of operators, as described in "Repeatability and reproducibility investigations," in order to evaluate the consistency and robustness of the impact testing method. Out of 100 records, one acquisition could not be processed for technical reasons. The results are reported in Fig. 3 and emphasize the presence of an outlier for operator E.

The *p* value for the Anderson–Darling test was computed as 0.310 for a level of risk of 5 %, which reveals that the normal distribution has a significant fit to the

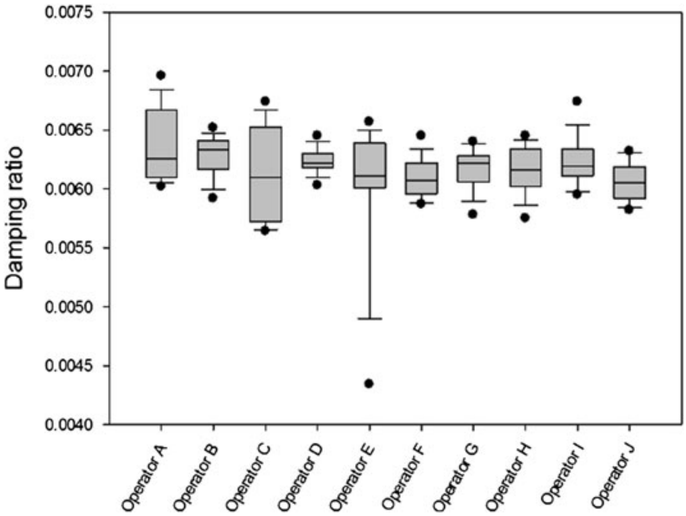

Fig. 3 *Box plot* describing all damping ratio evaluations for all operators

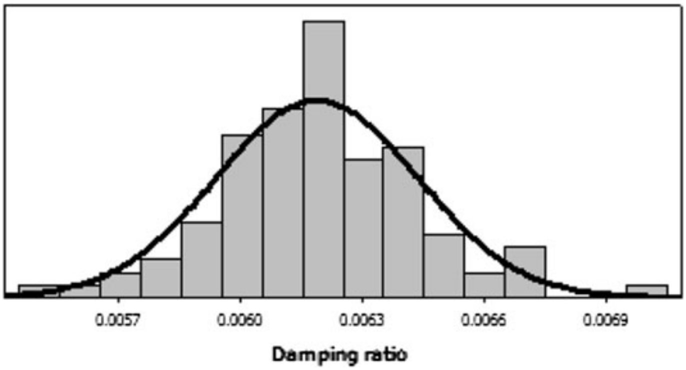

Fig. 4 Damping ratios histogram and normal distribution

data, as shown in Fig. 4. Except operator E, whose higher coefficient of variation (11 %) is due to an outlier, all operators exhibit a low coefficient of variation similar to that of operator J (3 %), which demonstrates that experience is not needed to produce good repeatability.

According to the one-way ANOVA test, the mean values show no significant differences (p value = 0.162) from one operator to another one. According to the Leven/Brown–Forsythe test, the standard deviations (p value = 0.062) have no significant difference from one operator to another. Since the experimental protocol demonstrates good reproducibility, the damping ratio evaluations are therefore independent of the strength and skills of the operator.

Excellent agreement between damped experimental fundamental frequencies and undamped numerical fundamental frequencies is observed in Fig. 5. In addition,

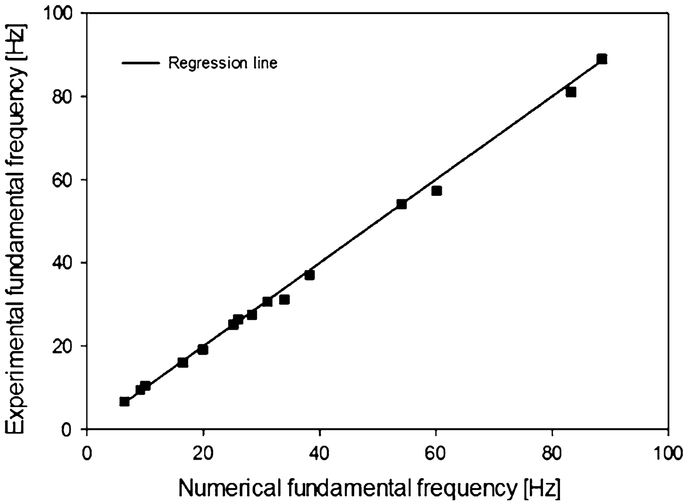

Fig. 5 Comparison of experimental and numerical natural frequencies

large diagonal values (~0.98) in the *MAC* matrix defined in Eq. (6) reveal good agreement between damped experimental mode shapes and undamped numerical mode shapes for each fundamental frequency. The assumption of small damping, which is mandatory for applying experimental modal analysis theory, is therefore valid.

Eventually, neither impact locations (modal hammer) nor the measurement locations (accelerometer) were found to have a significant influence on the damping ratio ξ in the parametric study described in "Parametric study" section. This indicates reciprocity, which is a fundamental characteristic of experimental modal analysis methods.

Reliability of the experimental evaluations

The statistical treatment of damping ratio evaluations described in "Statistical treatment of damping ratio evaluations" section was performed twice. In total, 14 evaluations were discarded out of 420 evaluations: three evaluations for glulam beams and 11 evaluations for solid wood beams. The low percentage of discarded values: ~3 % indicates consistent results. In addition, the obtained experimental damping evaluations compare well with the results from previous studies reported in Table 1, although slightly higher. Most of the measurements reported in Table 1 were obtained from small-scale specimens with assumed low inhomogeneity, while the present study used specimens of structural dimensions, thus exhibiting larger statistical inhomogeneity. The larger statistical inhomogeneity is most probably one of the main reasons for the slight increase of damping.

The mean values of damping ratio evaluations $\bar{\xi}$ and of natural frequencies $\bar{f}$ per configuration are presented in Table 4, together with number of evaluations, number of discarded evaluations, and other statistical indicators. In general, the number of

Table 4 Evaluated damping ratios per configuration

Configuration	Number of evaluations	Number of discarded evaluations	$\bar{f}$ (Hz)	$\bar{\xi}$	$CI_{\bar{\xi}}$	S_{ξ}	$CI_{S_{\xi}}$	m_{ξ}	COV_{ξ} (%)	λ_{ξ} (%)	Anderson–Darling p value
GL-E-3-1	1		64	0.0255	–	–	–	0.0255	–	–	–
GL-E-4-1	10		46	0.0195	[0.0176; 0.0214]	0.0026	[0.0018; 0.0048]	0.0188	13.6	19	0.310
GL-E-4-2	21		146	0.0079	[0.0070; 0.0089]	0.0022	[0.0017; 0.0089]	0.0074	27.2	25	0.023
GL-E-5-1	6		32	0.0110	[0.0101; 0.0119]	0.0009	[0.0006; 0.0022]	0.0108	8.2	17	0.025
GL-E-5-2	5		154	0.0205	[0.0096; 0.0315]	0.0089	[0.0053; 0.0252]	0.0200	42.8	106	0.174
GL-F-3-1	20		14	0.0034	[0.0033; 0.0035]	0.0002	[0.0002; 0.0003]	0.0034	6.1	6	0.963
GL-F-3-2	8		20	0.0064	[0.0052; 0.0076]	0.0015	[0.0010; 0.0030]	0.0065	23.1	39	0.768
GL-F-3-3	14		40	0.0210	[0.0180; 0.0239]	0.0051	[0.0037; 0.0082]	0.0193	24.4	28	0.086
GL-F-4-1	19	2	12	0.0037	[0.0036; 0.0038]	0.0002	[0.0002; 0.0004]	0.0038	6.5	6	0.333
GL-F-4-2	18	1	35	0.0074	[0.0065; 0.0083]	0.0019	[0.0014; 0.0028]	0.0074	25.7	25	0.388
GL-F-4-3	11		45	0.0175	[0.0166; 0.0184]	0.0013	[0.0009; 0.0023]	0.0174	7.5	10	0.525
GL-F-4-4	2		62	0.0266	–	0.0039	–	–	14.2	–	–
GL-F-5-1	22		9	0.0038	[0.0037; 0.0039]	0.0003	[0.0003; 0.0005]	0.0038	8.5	8	0.336
GL-F-5-2	20		33	0.0053	[0.0048; 0.0058]	0.0011	[0.0008; 0.0016]	0.0049	20.2	79	0.015
GL-F-5-3	15		71	0.0064	[0.0057; 0.0071]	0.0013	[0.0010; 0.0021]	0.0060	20.8	23	0.558
GL-F-5-4	12		119	0.0092	[0.0073; 0.0111]	0.0030	[0.0022; 0.0052]	0.0077	33.0	42	0.014
SW-E-3-1	18	1	31	0.0089	[0.0074; 0.0103]	0.0029	[0.0022; 0.0044]	0.0076	33.0	33	0.014
SW-E-3-2	3		48	0.0163	[0.0012; 0.0208]	0.0018	[0.0009; 0.0115]	0.0172	11.2	121	0.119
SW-E-4-1	13	1	27	0.0142	[0.0117; 0.0167]	0.0041	[0.0030; 0.0068]	0.0147	29.0	32	0.507
SW-E-5-1	19	1	19	0.0095	[0.0084; 0.0106]	0.0022	[0.0017; 0.0033]	0.0084	23.4	23	0.013
SW-E-5-2	9	1	66	0.0149	[0.0140; 0.0158]	0.0012	[0.0008; 0.0023]	0.0144	8.0	12	0.110
SW-F-3-1	22		11	0.0053	[0.0049; 0.0056]	0.0008	[0.0006; 0.0011]	0.0053	14.8	13	0.939
SW-F-3-2	7		16	0.0051	[0.0031; 0.0070]	0.0021	[0.0014; 0.0047]	0.0046	41.7	77	0.163

Table 4 continued

Configuration	Number of evaluations	Number of discarded evaluations	$\bar{f}$ (Hz)	$\bar{\xi}$	$CI_{\bar{\xi}}$	S_{ξ}	$CI_{S_{\xi}}$	m_{ξ}	COV_{ξ} (%)	λ_{ξ} (%)	Anderson–Darling p value
SW-F-3-3	4		31	0.0213	[0.0077; 0.0391]	0.0085	[0.0048; 0.0319]	0.0191	40.1	148	0.391
SW-F-3-4	2		81	0.0181	–	0.0045	–	–	24.8	–	–
SW-F-4-1	20	2	10	0.0073	[0.0064; 0.0081]	0.0019	[0.0014; 0.0027]	0.0071	25.7	24	0.041
SW-F-4-2	9		26	0.0074	[0.0048; 0.0100]	0.0033	[0.0023; 0.0064]	0.0058	45.2	69	0.170
SW-F-4-3	6		37	0.0206	[0.0117; 0.0295]	0.0085	[0.0053; 0.0208]	0.0191	41.1	86	0.335
SW-F-4-4	3		57	0.0157	[−0.0001; 0.0314]	0.0063	[0.0033; 0.0398]	0.0191	40.5	201	0.071
SW-F-5-1	21	1	7	0.0072	[0.0064; 0.0081]	0.0018	[0.0014; 0.0027]	0.0064	25.6	23	0
SW-F-5-2	15	1	25	0.0072	[0.0064; 0.0081]	0.0015	[0.0011; 0.0024]	0.0070	21.4	24	0.318
SW-F-5-3	16	3	54	0.0058	[0.0055; 0.0061]	0.0005	[0.0004; 0.0009]	0.0056	9.3	10	0.218
SW-F-5-4	15		89	0.0079	[0.0067; 0.0091]	0.0022	[0.0016; 0.0034]	0.0075	27.5	31	0.490

damping evaluations decreases when the span is decreased and/or when the mode number is increased. Higher modes were difficult to obtain for shorter spans because the modal hammer supplied only a limited amount of energy to the structure. As there were few available evaluations, this led to wider 95 % confidence intervals and to a larger λ_ξ. Three configurations out of the 33 are based on three or less evaluations: GL-S-3-1, GL-W-4-4, and SW-W-3-4. In addition, four configurations exhibit a λ_ξ larger than 100 %: GL-S-5-2, SW-S-3-2, SW-W-3-3, and SW-W-4-4. Results related to these specific configurations may therefore not be reliable enough for further use.

However, results concerning long spans, low modes, or flatwise orientations revealed narrow confidence intervals and low values of S_ξ and of COV_ξ, which indicates good reliability. Similarly, the observed low values of λ_ξ indicate a limited scatter of the evaluated damping ratios, a large number of evaluations, or both. In addition, large p values for the Anderson–Darling test indicate consistent evaluations for most configurations. General good reliability of the obtained experimental damping evaluations is therefore demonstrated.

General trends

Difference glulam/solid wood

Although the total amount of damping evaluations is similar for glulam beams and solid wood beams, glulam beams show generally smaller COV_ξ and smaller λ_ξ than solid wood beams for most of the configurations. This is in accordance with the measured densities, reported in "Experimental setup" section. This confirms a generally observed lower scatter in the natural properties of glulam compared to solid wood.

Shear deformation effect

The sensitivity of damping ratio evaluations to experimental conditions was analyzed using the systematic design of experiments approach, as defined in "Design of experiments approach" section. The governing effects were found to be: (1) the beam orientation, (2) the span, and (3) the interaction between the beam orientation and the span. From the results reported in Table 4, the evaluated damping ratio appears generally larger for edgewise orientation, for higher modes, and for shorter spans. In particular, the damping ratio seems greatly dependent on the mode number, and this dependence increases as the span decreases. Glulam beams, with a cross-section that has a height-to-width ratio larger than that of solid wood beams, exhibit higher evaluated damping ratios (+20 %) than those of solid wood beams. The reported influences are captured by the influence of shear deformation, which is hence observed to significantly increase damping. Similar findings were reported concerning Timoshenko wooden beams (Nakao et al. 1985) and laminated composites (Hwang and Gibson 1991).

Experimental investigation, limitations, and uncertainties

In the present study, uncertainties are related to the measurement technique, the processing technique, the material itself, and the specimen geometry. The known limitations of the experimental setup were initially accounted for. In order to ensure that the evaluated damping was representative of only material damping, Teflon sheets were used to reduce friction and hence the structural damping contribution. Supports were resting on isolated massive concrete blocks, so that the least amount of vibration was transmitted to the supporting structure or to the surrounding fluid, in order to minimize the contribution of fluid damping.

In addition, great care was taken when sampling and windowing the signal in order to reduce signal distortion for the estimated frequency response functions. When processing the recorded data to extract modal properties, curve fitting was used for parameter identification and the residual errors were assumed to remain small.

Scatter may be expected for all wood material properties because wood exhibits high variability. No quantification of variability of material damping is available in standards, but the natural variability of the longitudinal elastic modulus of GL32c (European Committee for Standardization 1999) and of C24 (European Committee for Standardization 2009) is quantified by a coefficient of variation of 12 and 20 %, respectively. Variability of the material may also induce uncertainties in the specimen geometry. Here, differences were observed for pairs of opposite faces and were probably due to initial warping. Larger differences were observed in solid wood beams, whose shapes are less stable than those of glulam beams. Foster (1992) made similar observations and concluded on the variations of the beam surface from one face to the opposite one.

Correlation investigations

The correlation between damping, natural frequency, and density was evaluated by means of the Pearson product-moment correlation coefficient, as defined in "Statistical indicators" section. In general, medium correlation ($r = 0.46$ for Solid Wood, $r = 0.15$ for Glulam) was observed between density and fundamental frequency. The longitudinal modulus of elasticity is known to be medium correlated with the density (Joint Committee on Structural Safety 2007), so it is expected that an increase of density induces an increase of stiffness and thus an increase of the natural frequency. Poor correlation ($r = -0.01$ for Solid Wood, $r = 0.11$ for Glulam) between damping ratio and density demonstrates that the evaluated damping ratio is not significantly influenced by the density. Similar findings were reported by Obataya et al. (2000), who found a high negative correlation between damping and specific modulus—that is, ratio modulus of elasticity/density. They finally assessed that both quantities depended on the microfibril angle but little on density. Poor correlation ($r = -0.04$ for Solid Wood, $r = 0.02$ for Glulam) was also observed between damping ratio and fundamental frequency. This is in accordance with previous findings (Krueger and Rohloff 1938; Ono and Norimoto 1985; Nakao et al. 1985; Foster 1992). Even if wood is considered a viscoelastic material (Ouis 2002) whose properties depend on frequency, the frequency range per configuration is very narrow (less than 5 Hz). The frequency dependence is therefore unlikely to be observed in general.

However, when computing the Pearson product-moment correlation coefficient for a *group* of configurations, rather than a single configuration, correlation can be as high as excellent between damping ratio and fundamental frequency. For instance, $r > 0.9$ for glulam beams in flatwise orientation, for any span. This indicates strong mode number dependence of the material damping for a given system, that is, when material, orientation and span are fixed. Previous studies (Lazan 1968; Kume et al. 1982) also underlined the specific influence of the mode shapes.

Influence of shear deformation and mode shape

Experimental mode shapes are observed to be similar for configurations presenting identical span and mode number but different orientations, as long as the shear deformation is not significant compared to bending deformation (i.e., for the first modes and for longer spans). As expected, similarities decrease for higher modes and shorter spans.

For slender Euler–Bernoulli beams, whose plane sections are expected to remain plane after deformation, the shear V_{EB} is related to the flexural rigidity EI. For Timoshenko beams with a smaller length-to-height ratio, the deformation due to shear is considered. Both types of shear are expressed with respect to the mode shape: $y = f(x)$:

$$\begin{aligned} V_{\mathrm{EB}} &= \mathrm{EI}\frac{\partial \kappa}{\partial x} = \mathrm{EI}y''' \\ V_{\mathrm{T}} &= -kAGy' \end{aligned} \tag{10}$$

where κ = curvature, k = shape factor, A = cross-section area and G = shear modulus.

Consequently, the shear V depends on specific characteristics of the mode shape: its third derivative y''' and/or its slope y'. Since it is difficult to quantify the shear directly from the experimental measurements, it is therefore possible and more convenient to capture the material damping variations via the influence of the mode shape and its derivatives.

Conclusion

The present study focused on examining the material damping in timber beams of structural dimensions for different experimental configurations. A total of 22 timber beams of two different types were subjected to flexural vibrations through the impact test method. Damping evaluations were performed for various configurations, which included different spans as well as orientations (edgewise and flatwise). A total of 420 evaluations were performed, out of which 14 were discarded following a rigorous statistical process. Statistical indicators to the damping evaluations were provided together with their mean values for each configuration.

The initial assumption of small damping was validated by means of mode shape analysis. The reliability of the results was assessed by carefully evaluating the consistency of the data and by concluding that no significant differences were due to the operator and/or his/her skills. In addition, the natural variability of wood and the limitations of the experimental setup were thoroughly discussed in qualitative and quantitative manner.

General trends were that the evaluated damping ratio increases with higher modes, shorter spans, and the edgewise orientation as compared to the flatwise orientation. The investigated influence of density on the evaluated damping ratio found no significant correlation. Correlation analysis between the evaluated damping ratio and the corresponding natural frequency revealed that the mode number is a significant parameter for a given system, but not for a given configuration. Instead, the shear deformation was found to be the governing factor to explain the variation of the damping ratio from one configuration to another. Shear deformation was finally conveniently evaluated by mode shape characteristics.

The comprehensive material damping database presented in this study can be used in further investigations to enhance general knowledge on damping mechanisms and improve the prediction of comfort properties for timber structures in particular.

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