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Effects of fungal decay on elasticity and damping of small-diameter silver fir logs assessed by the transverse vibration resonant method

Jean Baptiste Barré[1] · Franck Bourrier[1] · Loïc Brancheriau[2] · David Bertrand[3] · Freddy Rey[1]

Abstract A number of studies have shown the ability of the vibration resonant method (VRM) to measure the modulus of elasticity (MOE) and the damping ratio (ξ) of calibrated wooden samples of various dimensions. This method based on free transverse vibrations was also studied to assess the decay extent in small stakes. Nevertheless, a need for investigations was identified in order to apply the method to decayed logs. Both decay and geometrical singularities brought heterogeneity not taken into account by the VRM. The aim of this study was to examine the effects of fungal decay on these two mechanical properties of small-diameter silver fir logs using the VRM. Fifty-five small-diameter logs were monitored over a decay process taking place in a greenhouse located near Grenoble (France). The MOE and ξ were measured in intact and decayed states. The results showed the reliability of the measurements of both properties. ξ was found to be independent of moisture content for wood above the fibre saturation point. The results validated the loss in MOE and the gain in ξ due to fungal activity. Thus, indicators based on the MOE and ξ were proposed and compared to quantify the decay extent. Indicators calculated from the first mode of vibration appeared to be relevant for that purpose. Future work is needed to validate indicators on structural size logs and to compare this quantitative assessment to those obtained by the standard EN 152 that currently serves as a benchmark.

✉ Jean Baptiste Barré
jean-baptiste.barre@irstea.fr

[1] Irstea, UR EMGR, Université Grenoble Alpes, 2 rue de la Papeterie-BP 76, 38402 St-Martin-d'Hères, France

[2] UR BioWooEB UMR AMAP, CIRAD, 34398 Montpellier Cedex 5, France

[3] INSA Lyon (National Institute of Applied Sciences of Lyon), Université de Lyon, 20, Avenue Albert Einstein, Villeurbanne Cedex, France

Introduction

Natural hazards such as erosion or small landslides may be mitigated by ecological engineering structures built from a wooden logs framework. These timber structures are mostly made of local softwoods such as, in the French Alps, larch, Douglas fir, pine or silver fir. Built in ground contact without any wood preservatives, they undergo fungal attacks since their construction starts. Fungi are well known to have dramatic effects on wood mechanical properties (Curling et al. 2002) depending on, inter alia, wood species, wood moisture content and temperature (Zabel and Morrell 1992). The two last parameters fluctuate significantly geographically and in time (Brischke and Rapp 2008). As a consequence, practitioners meet difficulties in quantifying the decay extent of logs. The standard EN 252 (CEN 2014) serves as benchmark to assess the decay extent of samples decayed in the field. It is based on qualitative method that is hardly repeatable from one experiment to another. Other standards such as EN 15083 (CEN 2006) proposed quantitative methods based on mass loss between intact and decayed states. However, the methods are applicable in controlled conditions and hardly transferable to field applications. Moreover, the mass loss due to decay is slower than the loss in mechanical properties (Curling et al. 2002). Thus, the assessment of the decay extent by means of the measurement of mechanical properties variations is more relevant in the context of ecological engineering structures, especially for the early stages of decay. For that purpose, practitioners can use non-destructive methods which have been developed to appraise structures (Cruz et al. 2015; Tannert et al. 2013; Riggio et al. 2013). However, few of them are suited to the constraints of these outdoor timber structures. The non-destructive method has to be battery powered, little influenced by moisture content (MC) of wood, especially when it is above the fibre saturation point (FSP) and, finally, applicable to little decayed logs as well as severely decayed logs including some cracks. Researches have studied methods suited to these constraints as time domain reflectometry water content measurements or methods based on species composition and population structures of basidiomycetes in wood (Previati et al. 2012; Noetzli et al. 2008). Others developed methods allowing to overcome them as methods based on near infrared spectroscopy (Barré et al. 2017; Sandak et al. 2015). However, none of them assesses impact of decay on the mechanical properties in a cost-effective way. This brings to light the vibration resonant method (VRM), another common non-destructive method.

The vibration resonant method is currently used for mechanical grading of intact (non-attacked) timber beams (Stapel and van de Kuilen 2013). The method is fast and non-destructive. It consists of recording the displacement of a freely supported beam subjected to longitudinal or transversal vibrations. From this measurement, the Euler–Bernoulli or Timoshenko beam theories allow to calculate the modulus of elasticity (MOE). The VRM has initially been elaborated to calculate the MOE for beams of regular cross section and homogeneous material. However, studies have shown its relevancy by comparison with static bending techniques for timber beam including geometric or material singularities. Wang et al. (2002) found a strong correlation ($R^2 = 0.85$ for Jack pine and 0.95 for red pine) between the MOE

obtained by transverse vibration (E_{tv}) and by static bending technique (MOE_s) for logs (3.7 m in length and MC above FSP), i.e. a piece of wood which has not been shaped by hewing or sawing. The logs diameter was between 11.9 and 27.9 cm. This result has been confirmed by Green et al. (2006) who obtained high correlation ($R^2 = 0.88$) for perfectly round large timber beams (diameter of 22.8 cm, length of 500 cm and MC of 15.5%). Finally, for wood above its fibre saturation point (FSP) and compared to other methods based on sound or ultrasound propagation, the VRM measures the MOE without being influenced by the moisture content as the MOE remains constant above the FSP (Machek et al. 2001; Barrett and Hong 2009).

Furthermore, the VRM has been studied to investigate influence of decay on bending property. Grinda and Göller (2005) and Alfredsen et al. (2006) confirmed the VRM is a relevant method to quantify decay in wood. Nevertheless, these studies consider small rectangular stakes with a maximum of 500 mm in length and 50 mm in height. The small sample size limits the number of defects, which are naturally present in wood and influence the measure of the MOE. They differ importantly from the beams used in ecological engineering timber structures (logs of diameter from 10 to 30 cm). Moreover, regarding decayed wood and the VRM, researches have been mainly focused on the effects on the MOE as it could be easily compared to static measurements. However, the VRM allows measuring the damping, another mechanical property highly involved in vibratory phenomena. Few studies have been devoted to the sensitivity of the damping of samples submitted to a fungal activity.

The damping characterizes the ability of a structure to dissipate mechanical energy when it is subjected to cyclic loading. Its origin is associated with three classes of mechanisms related to the material, the boundaries conditions and the surrounding fluid (Woodhouse 1998). In wood science, this energy dissipation is frequently quantified by the logarithmic decrement δ_{log} or the damping ratio ξ, which are both frequency dependent and related together by the following relation when $\xi \ll 1$ (Brancheriau 2002, p. 119):

$$\delta_{log} \approx 2\pi\xi \tag{1}$$

For dissipative linear structures with a single degree-of-freedom (SDOF system), which corresponds to the simplest vibrating mechanical system, the calculation of ξ has been largely studied in case of free vibration (De Silva 2005, p. 16). However, the log on its elastic supports is a multiple degree-of-freedom system (MDOF system) that possesses several vibration modes. The analysis of this system is facilitated by considering the MDOF system as a superposition of SDOF systems (Ouis 2000). The vibratory response of the log is then studied for each vibration mode separately in order to determine the damping characteristics (Brancheriau 2002, p. 122).

Labonnote et al. (2013) itemised values of ξ in the scientific literature from 1950 for several intact wood species. Species investigated in the different studies were mainly softwoods with moisture content (MC) below the FSP. The values are between 0.0022 and 0.0068. The differences are due to diversities of species, anatomical orientations and the experimental conditions. Below FSP, MC has a

significant effect on ξ (Obataya et al. 1998; Yeh et al. 1971) as it is well known for other mechanical properties. ξ increases when the MC rises. But ξ behaviour has not been studied when the MC rises above FSP. Regarding the effects of decay on damping, Ouis (1999) mentioned no significant research. Dunlop (1983) released that decay leads to an increase in the damping of longitudinal acoustic waves. Ouis (2000) confirms this fact using a room acoustical technique to detect decay in logs. Bucur (2006) introduced the damping coefficient as an indicator of microstructural modifications but without mentioning the decay.

The aim of this study was to assess the decay effect of small-diameter silver fir logs (155 cm in length, 6–10 cm in diameter), on the damping and the MOE measured by the transverse vibration resonant method. An experiment has been set up in order to decay the small-diameter logs in a wide range. Their mechanical properties have been measured by the VRM before and after the decay process. First, the validity of the MOE and ξ measurements is discussed by taking into account the geometric and material singularities of the logs. Then, the effect of decay on each of the properties is analysed. Finally, a combined analysis of the MOE and ξ is proposed to consider the effect of decay.

Materials and methods

Preparation of samples

One hundred and ten small-diameter logs of silver fir (*Abies alba*) have been taken from an alpine forest located in Lagarde-en-Oisans (Isère—France). The pruned logs were 155 cm in length and had a mean diameter of 7.4 cm (Fig. 1), in order to obtain a length-to-diameter ratio around 18 according to the standard EN 14251 requirement (CEN 2003). The bark has been preserved in the same way as for the logs of the ecological engineering structures. For each log, the diameter corresponds to the mean diameter obtained from three measurements at both ends and in the middle.

Degradation process

The degradation process has been set up in a greenhouse to accelerate the decay kinetic. From 110 logs, 55 were buried in the greenhouse under a first layer of woody debris picked up in a silver fir forest and a second one of local soil layer (Fig. 1). The logs moisture content was kept above FSP by regular watering and checked with the resistive wood moisture sensor Humitest Timb plus (Domosystem). As a consequence, the moisture content of decayed samples, i.e. samples after the degradation process, was not controlled and might vary from one sample to the other. The samples have been collected from the greenhouse in four series after 138, 347, 655 and 788 days of degradation. As the study was focused only on the decay extent, no distinction between samples according to their series was made. The kinetic of decay might actually change inside the greenhouse according to the logs position.

Fig. 1 Successive steps of sample preparation in the greenhouse: **a** The small-diameter logs laid on the ground. **b** The small-diameter logs covered by woody debris. **c** Samples covered by a local soil layer

MC and specific gravity measurement

The MC was measured on a 5 cm-transversal slice of each sample in intact and decayed states. It was calculated according to Eq. 2. The result is a mean MC of the slice and does not take into account the potential variation of the MC along the sample.

$$\mathrm{MC} = [(W_h - W_0)/W_0] \times 100 \tag{2}$$

where W_h is the wet weight and W_0 is the oven-dry weight.

The oven-dry specific gravity (SG) was measured according to Williamson and Wiemann (2010) on the same 5 cm-transversal slice used for the MC measurement. The volume measurement consists in immersing the sample in a container placed on a scale. The displayed mass thus corresponds to the volume of the sample. Before immersion and after weighing, the samples were covered by a grease layer as thin as possible to avoid rehydration. The SG was calculated with Eq. 3.

$$\mathrm{SG} = (W_0/V_0) \times 100 \tag{3}$$

where V_0 is the oven-dry volume.

MOE measurement of intact or decayed small-diameter logs

The mechanical properties of the intact and decayed samples were estimated by dynamic measurements. The boundaries conditions of the sample on the test bench

(Fig. 2a) allowed reproducing free–free transverse vibrations thanks to rubber bands supports. The supports were sufficiently elastic to neglect the effect of supports position on the MOE measurement. The small-diameter logs were positioned with an overhang of 10 cm at each extremity. A vertical impulse initiated the vibrations at 5 cm from one extremity. The vertical vibrational response was acquired at 5 cm from the other extremity with the piezoelectric accelerometer Deltraton type 4397 from Brüel and Kjær magnetised on a screw (Fig. 2b). The accelerometer was powered by Deltraton Power Supply WB 1372 and its signal converted by the analogue-to-digital converter PicoScope 4224 from Pico Technology. The digital signal was recorded with a sampling frequency of 20 kHz and an acquisition duration of 1.638 s. The frequency resolution was 0.6 Hz.

The free vibrations occur theoretically in the vertical plane passing through the longitudinal axis of the samples. The first three modes were determined from a signal processing developed with R software (R Core Team 2016) and the *signal* package (Signal Developers 2015). The fast Fourier transform (FFT) of the signal was calculated to determine the frequency of each mode. The fundamental frequency, i.e. the frequency of the first mode of vibration, corresponds to the first most energetic peak of the FFT. The frequencies of the first three vibration modes were recorded and used to calculate the MOE values.

The MOE has been calculated based on both the Euler–Bernoulli and Timoshenko models. Euler–Bernoulli theory neglects the distortion caused by shear and the effects of the elastic supports. It gives the analytical expression of the MOE for beams with a high length (l) to depth (h) ratio [$l/h > 20$ according to Brancheriau and Bailleres (2002)]:

$$E_n = 4\pi^2 \rho S L^4 \frac{f_n^2}{I X_n} \tag{4}$$

with E_n the MOE calculated for the mode n, $I = \pi \cdot d^4/64$ the moment of inertia with d the mean diameter of the sample, ρ the specific gravity at the sample MC, S area of the cross section, L the beam length, f_n the natural frequency and X_n specific coefficient: $X_1 = 500.5467, X_2 = 3803.14, X_3 = 14{,}619.72$. The modulus of elasticity E_n has been assumed consistent in the whole beam.

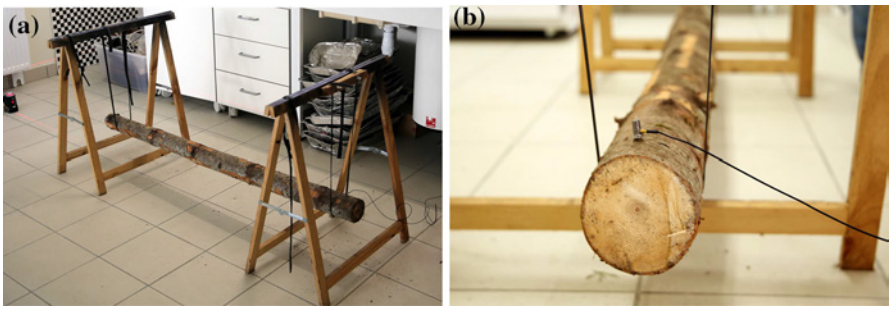

Fig. 2 **a** Small-diameter log prepared on the test bench for the dynamic test. **b** Accelerometer installed on the small-diameter log

E_n was, respectively, noted E_n^s and E_n^d for intact and decayed states. The normalized loss in E_n of a sample, $D_{w \cdot E_n}$, is defined for the mode n by:

$$D_{w \cdot E_n} = \frac{E_n^s - E_n^d}{E_n^s} \tag{5}$$

The Timoshenko theory takes into account the rotational inertia and the strain caused by shear. The effects of the elastic supports are still neglected. The modulus of elasticity is given for natural frequency n by the solution of Bordonné (Brancheriau and Bailleres 2002):

$$\frac{E_{\text{timo}}}{\rho} - \frac{E_{\text{timo}}}{KG}\left[\alpha F_2(m_n) 4\pi^2 \frac{SL^4}{I}\frac{f_n^2}{X_n}\right] = 4\pi^2 \frac{SL^4}{I}\frac{f_n^2}{X_n}\left[1 + \alpha F_1(m_n)\right] \tag{6}$$

with E_{timo} the MOE, G the shear modulus, $I = \pi \cdot d^4/64$ the moment of inertia with d the mean diameter of the sample, ρ the specific gravity, S the area of the cross section, L the beam length, f_n the natural frequency, $X_n = m_n^4$, K the shear correction factor, m_n the solution of the equation $\cos(m_n)ch(m_n) = 1$ and

$$F_1(m_n) = \theta^2(m_n) + 6\theta(m_n) \tag{7}$$

$$F_2(m_n) = \theta^2(m_n) - 2\theta(m_n) \tag{8}$$

$$\theta(m_n) = m_n \frac{\tan(m_n)\tanh(m_n)}{\tan(m_n) - \tanh(m_n)} \tag{9}$$

The modulus of elasticity E_{timo} has been assumed consistent in the whole beam. E_{timo} is, respectively, noted E_{timo}^s and E_{timo}^d for intact and decayed states. The normalized loss in E_{timo} of a sample is defined for the mode n by:

$$D_{w.E_{\text{timo}}} = \frac{E_{\text{timo}}^s - E_{\text{timo}}^d}{E_{\text{timo}}^s} \tag{10}$$

Damping ratio ξ measurement of intact or decayed small-diameter logs

It was assumed that the small-diameter log behaved like an underdamped system submitted to viscously damped free vibrations. This system with multiple degrees-of-freedom has several modes of vibration and equates to a superposition of dissipative linear structures with single degree-of-freedom (SDOF system) associated with each mode (Brancheriau 2002, p. 120). Thus, for each mode, the raw acceleration signal was filtered in spectral domain by a pass-band Tchebychev filter centred on the frequency of the considered mode. As a result, the filtered acceleration signal in temporal domain decreased exponentially over time (Thomson and Dahleh 1998) and its outer envelope $a_{\max}$ was temporally governed by Eq. 11 for the pulsation ω_n.

$$a_{\max}(t) = A\mathrm{e}^{-\xi_n \omega_n t} \tag{11}$$

where n is the number of the mode, ξ_n is the damping ratio, A is a constant and ω_n the fundamental pulsation.

ξ was estimated by a curve-fitting method: the natural logarithm of $a_{\max}(t)$ was fitted by a linear regression. ξ is defined as the ratio of the slope of the regression line and the fundamental pulsation ω_n. ξ_n^i and ξ_n^d were, respectively, the damping ratio of a sample in intact and decayed states. The normalized gain in ξ of a sample was defined by:

$$D_{w\cdot\xi_n} = \frac{\xi_n^d - \xi_n^s}{\xi_n^d} \tag{12}$$

Comparison $D_{w\cdot\xi_n}$ versus $D_{w\cdot E_n}$ and versus $D_{w\cdot E_{\mathrm{timo}}}$

$D_{w\cdot\xi_n}$, $D_{w\cdot E_n}$ and $D_{w\cdot E_{\mathrm{timo}}}$ were first graphically compared with boxplots that summarize the minimum and maximum of dataset, the quartiles, the median and, if any, the outliers. The relationships between $D_{w\cdot\xi_n}$ versus $D_{w\cdot E_n}$ and versus $D_{w\cdot E_{\mathrm{timo}}}$ were tested by a linear regression and quantified through its coefficient of determination r^2.

Results

Specific gravity measurement

On average, the SG is 463 kg m^{-3} for intact samples and 397 kg m^{-3} for decayed samples. The SD of decayed samples increases from 53 to 65 kg m^{-3} compared to SD of intact samples.

MOE measurement of intact or decayed small-diameter logs

For intact and most of decayed samples, the first three modes were always identified. The third mode was not identified for 12 decayed samples (Table 1). Furthermore, depending on the log, the identification of the natural frequency on the FFT might be disturbed by peaks very close to the main one (see peak 2 in Fig. 3). In this case, the retained value was the higher peak. The FFT of intact and decayed samples, whose MC was different, differed mainly by positive or negative frequency shifts for a considered mode. The peaks intensities were also affected. The natural frequencies of intact and decayed samples, although different for the same sample, were in the same range: the differences of their mean values were lower than 11Hz, i.e. 3% of the frequency value (Table 1). The standard deviations (SD) were significantly higher for the decayed samples (mode 1: $\mathrm{SD}_d = \mathrm{SD}_s + 10\mathrm{Hz}$, mode 2: $\mathrm{SD}_d = \mathrm{SD}_s + 21\mathrm{Hz}$, mode 3: $\mathrm{SD}_d = \mathrm{SD}_s + 22\mathrm{Hz}$).

Table 1 Physical and mechanical measurements of silver fir samples

	Intact samples					Decayed samples				
	Mean	Min.	Max.	SD	N_e	Mean	Min.	Max.	SD	N_e
MC (%)	147	43	197	30	108	37	26	67	9	55
Specific gravity (kg m^{-3})	463	354	626	53	108	397	252	554	65	55
Freq 1 (Hz)	85	48	128	16	108	84	39	154	26	55
Freq 2 (Hz)	223	128	324	40	108	226	110	392	61	54
Freq 3 (Hz)	412	236	574	69	108	401	199	587	91	43
$E1$ (MPa)	9231	5762	13,634	1568	108	4625	876	10,405	2201	55
$E2$ (MPa)	8392	5464	12,336	1353	108	4378	911	8818	1888	54
$E3$ (MPa)	7507	5158	11,235	1186	108	3784	864	7538	1507	43
Etimo (MPa)	9658	5801	14,001	1781	80	4728	898	11,213	2282	52
$\xi 1$ (–)	0.0050	0.0037	0.0076	0.0007	108	0.0086	0.0045	0.0189	0.0033	55
$\xi 2$ (–)	0.0053	0.0040	0.0078	0.0006	108	0.0096	0.0036	0.0191	0.0036	54
$\xi 3$ (–)	0.0057	0.0042	0.0080	0.0006	108	0.0110	0.0017	0.0207	0.0038	43

Range and standard deviation (SD)

Freq n the natural frequency of mode n, E_n the MOE calculated from Euler Bernoulli model for mode n, E_{timo} the MOE calculated from Timoshenko model, ξ_n the damping ratio of mode n, N_e the number of samples

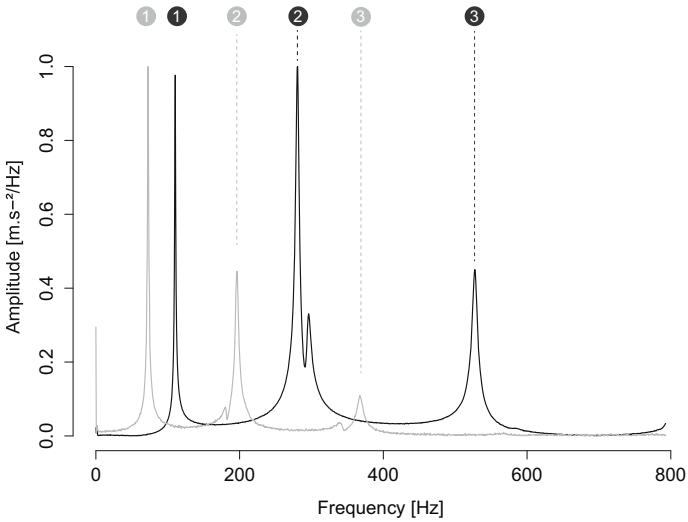

Fig. 3 FFT of the same sample in intact (black line) and decayed (grey line) states. The three first modes were identified

For the intact samples, the average of E_n decreased from 9231 (mode 1) to 8392 MPa (mode 2) and to 7508 MPa (mode 3) (Table 1). E_{timo} was of 9657 MPa on average. For the decayed samples, the modulus was significantly lower (Fig. 4). The average of E_n was of 4625, 4378 and 3784 MPa for, respectively, mode 1,

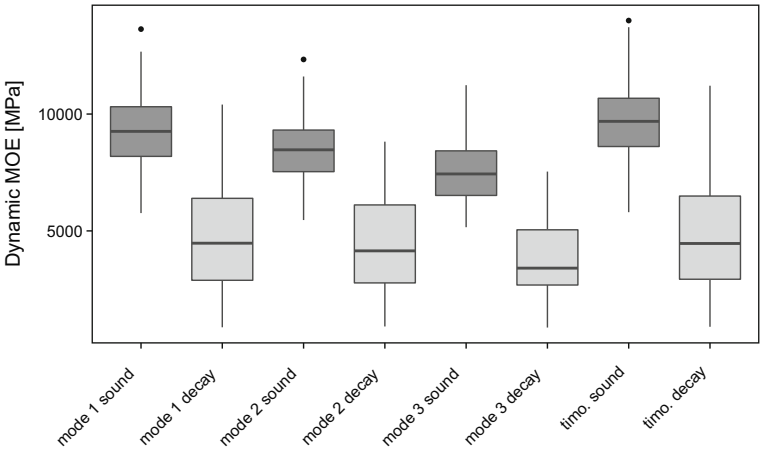

Fig. 4 Dynamic MOE of intact (black) and decayed samples (grey)

mode 2 and mode 3. The average of E_{timo} was of 4728 MPa. The Wilcoxon signed-rank test applied to intact and decayed E_n for each mode gave significantly low p value of 1.13e−10, 1.67e−10 and 2.27e−13 for modes 1, 2 and 3. For E_{timo}, the p value was of 3.61e−10.

Damping ratio ξ measurement of intact or decayed small-diameter logs

For a considered mode, the presence of multi-peaks in the FFT of the signal indicated the presence of secondary modes of lesser intensities and induced in particular by the geometrical irregularities of the samples. As a result, the signal damping presented oscillations (Fig. 5a) depending on the samples and the modes. As the damping did not follow an exponential law, the natural logarithm of $a_{\max}(t)$ was noisy (Fig. 5b). However, the coefficients of determination R^2 were high for all

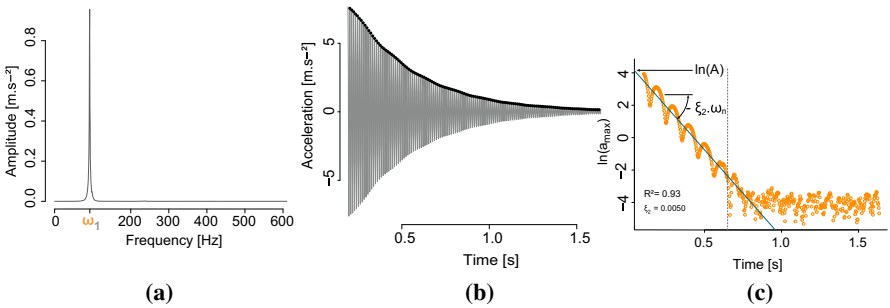

Fig. 5 Successive steps of the signal numerical treatment for ξ calculation. Example is given for mode 1. **a** FFT of the raw signal filtered by a pass-band filter centred on ω_1 (92.2 Hz). **b** First mode filtered acceleration (grey curve) and the maxima $a_{\max}(t)$ (black dots). **c** Natural logarithm of the maxima $\ln(a_{\max}(t))$ with its linear regression. The slope of this regression divided by the pulsation ω_1 allows to calculate ξ_1

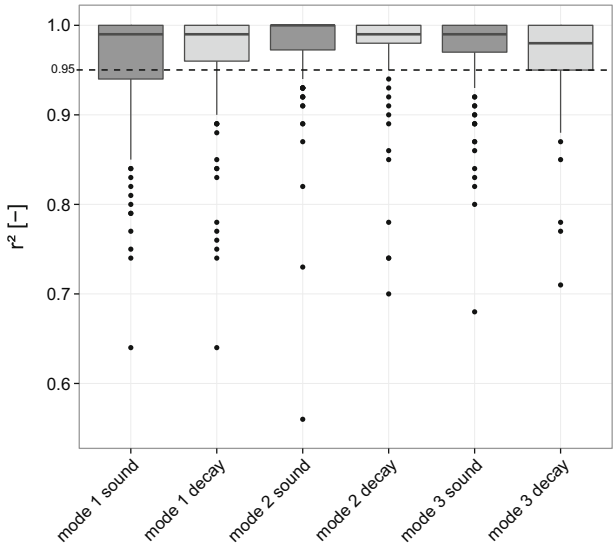

Fig. 6 Coefficient of determination R^2 of damping ratio ξ_n calculated for intact and decayed samples

modes (Fig. 6). For modes 1, 2 and 3 of intact samples, respectively, 73, 83 and 74% of R^2 were higher than 0.95. For modes 1, 2 and 3 of decayed samples, 73, 89 and 74% of R^2 were higher than 0.95. Mode 2 R^2 was the highest with an average of 0.98 compared to 0.96 for other modes. Furthermore, it was observed that the damping ratio (DR) increases with the mode order. The increase from one mode to the other was higher for decayed samples: on average, 11.5% compared to the 6.5% for intact samples. No correlation has been found between MC and ξ_n whatever mode (Fig. 7).

The average of ξ^d was significantly higher than the average of ξ^i (Fig. 8; Table 1): 0.0050 for ξ_1^i and 0.0086 for ξ_1^d, 0.0053 for ξ_2^i and 0.0096 for ξ_2^d, 0.0057 for ξ_3^i and 0.0110 for ξ_3^d. The coefficient of variation represented, respectively, 14, 11 and 11% of ξ_1^i, ξ_2^i and ξ_3^i. It was lower than SD of ξ^d, that represents 38, 38 and

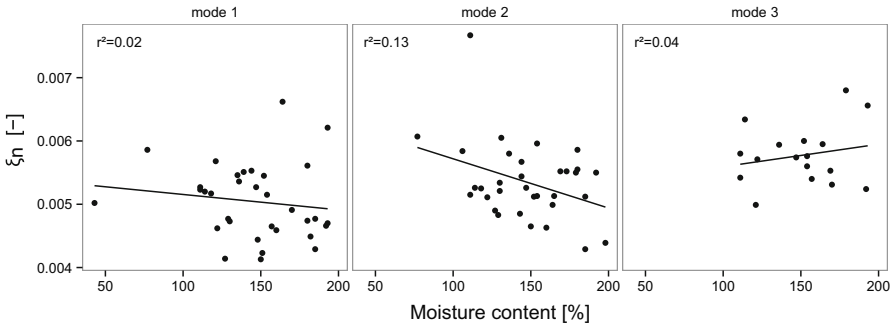

Fig. 7 Damping ratio ξ_n of the intact samples against moisture content

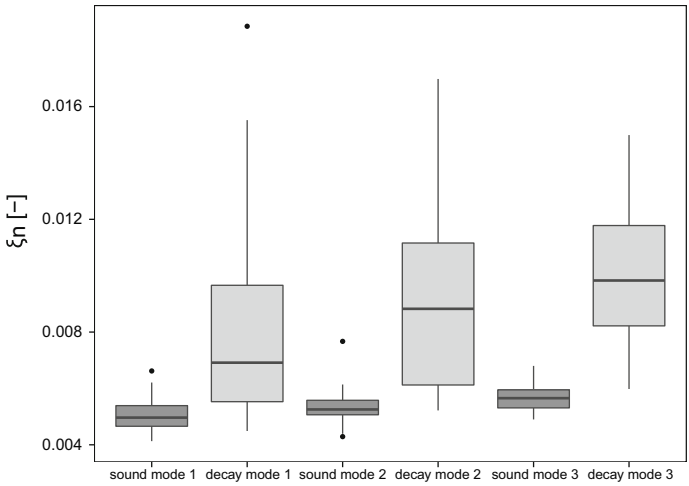

Fig. 8 Damping ratio ξ_n of intact and decayed samples calculated for the first three modes of vibration

35% of ξ_1^d, ξ_2^d and ξ_3^d. The Wilcoxon signed-rank test applied to intact and decayed ξ gave significantly low p value of $1.07 \times 10\text{e}^{-06}$, 2.9×10^{-11} and 1.7×10^{-07} for mode 1, 2 and 3.

Comparison $D_{w \cdot \xi_n}$ versus $D_{w \cdot E_n}$ and versus $D_{w \cdot E_{\text{timo}}}$

For all modes, $D_{w \cdot E_n}$ and $D_{w \cdot E_{\text{timo}}}$ were in the same range (Fig. 9). The authors noticed $D_{w \cdot \xi_1}$ has a lower mean value (0.30) than $D_{w \cdot E_1}$ (0.45) or than $D_{w \cdot E_{\text{timo}}}$ (0.50). Similar observations have been done for the two other modes. The comparison between $D_{w \cdot \xi_n}$ and $D_{w \cdot E_n}$ showed a strong relationship in mode 1 (R^2_{m1} = 0.72) and weaker for the others (R^2_{m2} = 0.55, R^2_{m3} = 0.55) (Fig. 10). In mode 1, the analytical

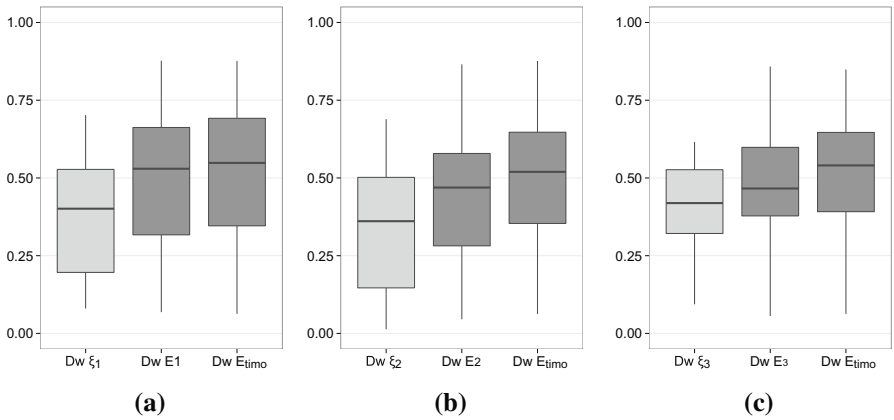

Fig. 9 Indicators D_w for mode 1 (**a**), mode 2 (**b**) and mode 3 (**c**)

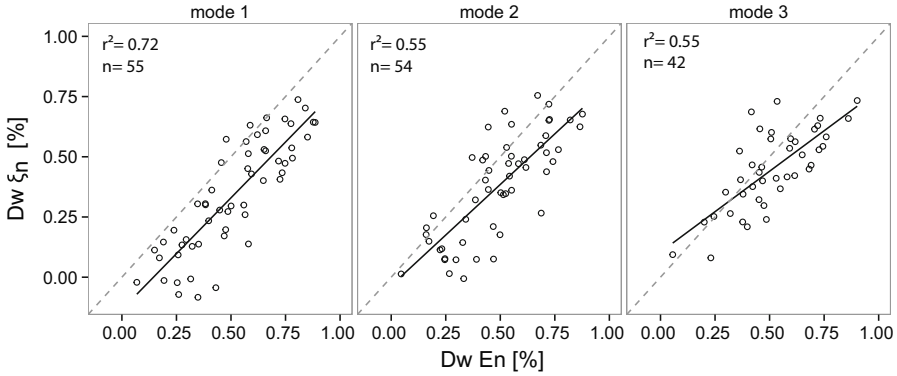

Fig. 10 Relation between $D_{w \cdot E_n}$ and $D_{w \cdot \xi_n}$

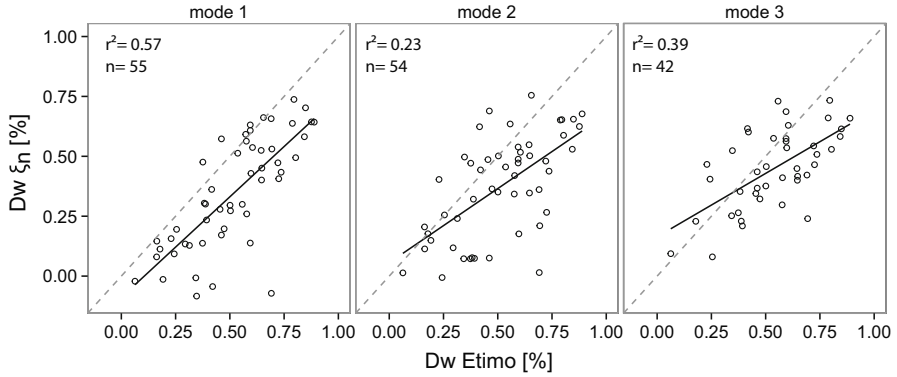

Fig. 11 Relation between $D_{w \cdot E_{\text{timo}}}$ and $D_{w \cdot \xi_n}$

expression of the regression line was $y = 0.93x - 0.13$. It was noticed the constant shift of 0.13 between $D_{w \cdot \xi_1}$ and $D_{w \cdot E_1}$. The comparison with $D_{w \cdot E_{\text{timo}}}$ did not reach the same level. The correlation coefficient was at most of 0.57 (mode 1) (Fig. 11).

Discussion

As outlined in the introduction, some studies showed that the VRM is effective to measure the MOE on intact logs. Others tested the VRM to assess the MOE of small squared small-diameter logs in wood decay testing. However, more work was needed to test the effects of decay on elastic and damping properties of small-diameter logs measured by the VRM. Significant differences were found between the MOE and ξ measured on silver fir small-diameter logs before and after the decay process. Moreover, the normalized loss of the MOE and ξ were surprisingly proportional.

Reliability of MOE and ξ measurements of intact small-diameter logs

It is necessary as a preamble to precise that the MOE calculation is based on a simplified assumption regarding the homogeneity of the wood properties. In Eqs. 4 and 6, the intrinsic variation of MOE generated by the presence of defects and differences of wood structure is not considered. Thus, E_n and E_{timo} shall be understood as estimations of the modulus of elasticity.

Effect of geometric singularities The singularities of the small-diameter logs disturbed the vibratory response to a limited extent. For a clear circular wooden beam loaded in a vertical plane, vibrations occur in this plane. Since the logs had no straight neutral fibre and the applied impulse was not strictly vertical, out-of-plane vibrations modes were activated as it can be deduced from the presence of multi-peaks in the FFT (Fig. 3 peak 2). Considering the vertical loading of the log, it was assumed that the most energetic peak belongs to the vertical vibrations. The out-of-plane vibrations modes had limited consequences on the MOE measurement. Coherent values of MOE in green state were obtained according to references yielded by the literature (Table 2). E_{timo} (9658 MPa) and E_1 (9231 MPa) were between those measured for four fresh logs by Lundström et al. (2008) (11,500 MPa on average) and those indicated by Niklas and Spatz (2010) (8100 MPa). Another comparison is also possible with values of MOE measured at 12% MC, i.e. MC prescribed by standards. MOE difference between measurements in green and 12% states is about 18% for common softwoods (Table 2). The same comparison was established taking a 12% mean MOE of 12,438 MPa, not forgetting that discrepancies established between the different values are huge and mainly due to species variability, 3000 MPa according to Tropix database Cirad (2015). Finally, MOE difference between both MC was coherent for both theories. It was 22% for E_{timo}, 26% for E_1 (see details in Table 2). Furthermore, the influence of out-of-plane

Table 2 Comparison between the MOE measured in green state (MC > 30%) and at 12% of moisture content for common softwoods

	MOE (MPa)		Variation (%)
	12%	Green	
Silver fir	14,300[2]	–	–
	12,500[3]	–	–
	10,515[4]	–	–
Mean	12,438	–	–
Silver fir	12,438	8100[5]	−34
	12,438	11,500[6]	−8
	12,438	9658[7]	−22
	12,438	9231[8]	−26
Sitka spruce	11,200[1]	9400[1]	−16
Pacific silver fir	11,300[1]	9300[1]	−17.7
Western larch	14,300[1]	11,400[1]	−20.3
Douglas fir	13,600[1]	11,100[1]	−18
Mean	–	–	−18

[1]From Kretschmann (2010), [2]from Cirad (2015), [3]from Haines et al. (1996), [4]from Verkasalo and Leban (2002), [5]from Niklas and Spatz (2010), [6]from Lundström et al. (2008), [7]cf E_{timo} Table 1, [8]cf E_1 Table 1

modes on ξ_n measurements remained limited. The damping was affected in varying proportions by out-of-plane modes depending on the intensities of the secondary peaks. The acceleration damping deviated from an exponential decrease when the secondary peaks are of high intensity (Fig. 5a). However, the quality of ξ_n measurement was high according to the determination coefficients values, especially for the second mode (Fig. 6).

Effect of moisture content For wood above FSP, ξ_n was found to be independent of MC. No correlation has been found between MC and ξ (Fig. 7). As a consequence, the difference of MC of a log between measurements taken before and after the decay process did not prevent the comparison between ξ_n^i and ξ_n^d.

Effects of decay on MOE and ξ measurements of small-diameter logs

The variation of MOE generated by the random development of fungi is not considered in Eqs. 4 and 6. As a consequence, E_n and E_{timo} shall be understood as equivalent moduli of elasticity.

For a given mode, a shift distinguishes natural frequencies of intact and decayed states (Fig. 3). According to Eq. 4, two factors explain this shift: the loss in MOE induced by decay and the variations in logs mass as the MC was not controlled in the greenhouse. Thus, the natural frequencies do not give directly relevant information on decay. The calculation of E_{timo} and E_n allows to overcome the mass variations.

Regardless of the mode, a significant effect of decay on E_n or E_{timo} has been noted (Fig. 4). The VRM has measured the decrease in MOE due to decay even for small-diameter logs decayed by a microbial community. On that basis, it is proposed to define $D_{w \cdot E_n}$ and $D_{w \cdot E_{\text{timo}}}$ as references to quantify the effect of decay on the small-diameter logs. Thus, defined as normalized differences, these two indicators limit the consequences of simplifying assumptions related to the small-diameter logs characteristics such as consideration of a mean diameter.

These results confirm that the damping ratio increases when wood is submitted to fungal activity. ξ_n^i and ξ_n^d remained actually comparable as the frequency dependence of ξ_n is limited for frequencies below 1000 Hz (Gibson 1989; Holz 1996). The sensitivity of damping to decay has been quantified by the indicator $D_{w \cdot \xi_n}$ (Fig. 9).

Comparison $D_{w \cdot \xi_n}$ versus $D_{w \cdot E_n}$ and versus $D_{w \cdot E_{\text{timo}}}$

As shown above, the effect of decay on ξ_n^i, E_n and E_{timo} was measurable by the VRM. The ξ_n^i and MOE values gave inherently information about the decay extent thanks to significant properties variations between intact and decayed states. But the variability of these properties is so high for silver fir [SD of MOE at 12%: 3000 MPa—(Cirad 2015)] that this observation should be limited to this study. Furthermore, the decay increases the heterogeneity of the properties that reduces the accuracy of measurement. As a consequence, to avoid the adverse effects of the variability, the assessment of decay extent by means of indicators $D_{w \cdot \xi_n}$ and $D_{w \cdot E_n}$ is

more relevant. Moreover, these indicators varied proportionally. This relationship was especially strong in mode 1 between $D_{w \cdot E_1}$ and $D_{w \cdot \xi_1}$ ($R^2 = 0.72$) (Fig. 10). Even if the second mode of vibrations was better for ξ calculation, the first mode was more relevant to assess decay in small-diameter logs. Concretely, $D_{w \cdot \xi_1}$ underestimated the decay by 0.13% against $D_{w \cdot E_1}$. Thus, $D_{w \cdot \xi_1}$ could be an alternative to quantify decay instead of $D_{w \cdot E_1}$ when neither the mass nor the geometrical characteristics of samples are known. This result raises, however, the question of the frequency influence on the relationship as the best results have been obtained with quite low frequencies (48Hz < Freq 1 < 128Hz). Further investigations must be conducted to assess whether the results are still significant for small-diameter logs vibrating at different ranges of frequency.

Potential of the VRM

From these results, the VRM can meet the expectations of practitioners who seek to assess the decay extent by a quantitative and repeatable measurement. Actually, the method proposed by the standard EN 252 (CEN 2014), to assess the extent of decay of samples decayed in the field, is based on a qualitative approach. The assessment combines a visual inspection with a superficial assessment of the hardness and requires the debarking of samples. It is true that EN 252 refers to the possibility of assessing decay by the loss of MOE, but it highlights the difficulty of measuring the ratio normatively due to the geometrical changes of the sample and its variation in moisture content. This study shows the VRM is a promising solution for assessing degradation of field degraded samples in quantitative terms. As EN 252 serves actually as a benchmark to assess the decay extent of samples decayed in the field, it would be necessary to perform a comparison of both methods. Furthermore, the VRM imposes measurements under particular support conditions allowing the free vibrations of the sample. For compatibility with the evaluation of the degradation of structural elements of a structure, it can be considered making measurements on removable test specimens placed at different points of the structure during its construction. The monitoring of these test samples from the intact state would make it possible to inform the practitioner about the structural conditions of the logs.

Conclusion

This study aims to investigate the potential of a non-destructive method to assess the decay extent in wooden small-diameter logs. The effect of fungal activity on the module of elasticity (MOE) and the damping ratio ξ of silver fir small-diameter logs was investigated using the vibration resonant method (VRM). Experiments confirm that the VRM measures coherent MOE values with both Euler–Bernoulli and Timoshenko theories despite geometric and material singularities. The study also points out that the moisture content (MC) has no influence on ξ for wood MC above the fibre saturation point.

In addition, the study shows the significant effect of the fungal activity on MOE and ξ assessed by the VRM. MOE decreases and ξ increases when wood is subjected to decay. Besides, the study highlights that their normalized variations $D_{w\cdot\xi_n}$, $D_{w\cdot E_n}$ and $D_{w\cdot E_{\text{timo}}}$ change proportionally, especially for $D_{w\cdot\xi_1}$, $D_{w\cdot E_1}$ (first mode of vibrations: $R^2 = 0.72$). This initial work confirmed the VRM as an effective method to quantify the decay extent in logs. Furthermore, $D_{w\cdot\xi_n}$ is promising for logs whose mass nor geometric characteristics are known. Researches dedicated to the influence of the first-mode frequency value and the logs size are of interest to confirm the potential of the method. Finally, the assessment by the VRM may be considered for other applications provided that comparative tests between assessments with the VRM and the standard EN 252 are made.

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