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ORIGINAL ARTICLE

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Modeling rot in wood by replacement of wood with sand: an experimental study

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Abstract Rot is known to affect the strength properties of wood. At the same time, the damping properties of the attacked material have also been shown to change. This article presents the results of an experimental study in which rot in wood was modeled by the replacement of wood with sand. The procedure entailed the drilling of holes in the body of a wooden beam, filling the holes with sand, and monitoring the changes induced by the sand-filled holes on the values of the modulus of elasticity (MOE) and of the loss factor. The MOE was calculated from the resonance frequency of the first longitudinal mode of vibration, and the loss factor was obtained indirectly from the impulse response by means of a room acoustical technique. The results show that the MOE value, and hence the strength characteristic of the wood specimen, decreases at the same time as the loss factor increases.

Key words Holes · Loss factor · Modulus of elasticity · Sand · Wood

Introduction

Wood is an important material because it is used in several applications such as building and furniture and paper manufacture, and the qualities of the finished product rely primarily on those of the raw material. However, rot often constitutes a serious problem when affecting wood, inasmuch as even when invisible to the naked eye, it may have devastating consequences on the strength properties of the material. The first direct effect of the interaction between rot fungi and wood is a substantial and fast weakening of the material followed afterward by a somehow slower process of material weakening.[1] It has also been proven that not only the modulus of elasticity (MOE) is affected, but also the loss factor, which in general terms is a measure of the ability of a material to absorb vibration energy, has been found to increase.[2,3] However, these observations cannot be considered as independent of each other for the reason that all materials would exhibit this simultaneous influence to a more or lesser degree of importance. This behavior stems primarily from the dispersion of materials, which, more specifically means that the MOE and the loss factor (η) are frequency dependent. Moreover, these frequency variations exhibit some interrelationship, the importance of which depends on the vicoelastic properties of the material. For soft materials like natural rubber or artificial polymers, the MOE–η interrelationships as functions of the frequency are quite strong, and can usually be easily demonstrated in the audio frequency range. On the other hand, for solid materials like metals, the frequency variations are much weaker and have a noticeable manifestation at rather high frequencies, often in the ultrasonic range. Wood is a material with dynamical properties that may range between these two categories of materials, and this material therefore exhibits moderate strength and damping frequency dependences.

The objective of the present study was to make a preliminary investigation toward the modeling of rot in wood. To this end a sound bar of wood was taken as a study specimen, and a progressively increasing number of holes was drilled and filled with sand. The variations in the values of the MOE and the loss factor were then recorded as a function of the number of holes. The MOE was evaluated for the longitudinal mode of vibration in the bar, and the loss factor was determined at the major resonance frequencies by means of a room acoustical technique. Both parameters were assessed from a single measurement on the test specimen, namely from its impulse response.

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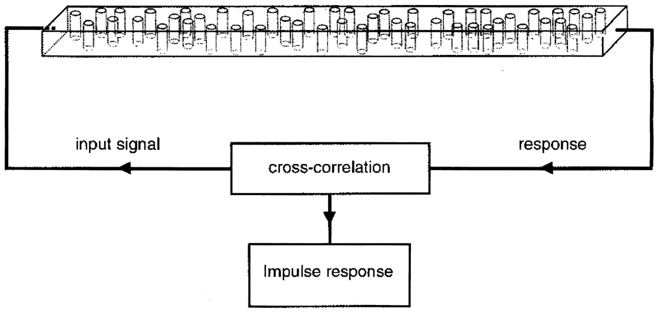

Fig. 1. Representation of the wood bar and the experimental setup for assessing its vibration impulse response under axial vibrations

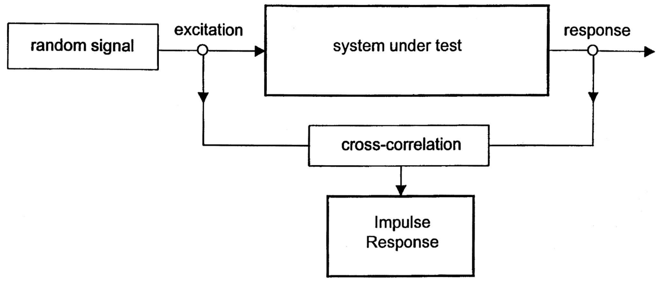

Fig. 2. Block diagram of a technique for acquiring the impulse response of a system

Materials and methods

Test specimen

The test specimen considered in this study was a beam of Norway spruce with the dimensions 70 (length) × 7.5 (width) × 5.0 (height) cm and a weight of 1.3 kg. The beam was positioned on an elastic support with one extremity connected to an electrodynamic shaker, and the other extremity had a piezoelectric accelerometer attached to it (Fig. 1).

An increasing number of holes were then drilled in the beam, five holes at a time. The holes (10 mm in diameter) were drilled vertically in the beam and were distributed evenly over the surface of the beam. The holes were then filled with sand. Sand was chosen as the filling material for the holes primarily for its density, which approximates that of wet rot, and also for its ability to dampen vibrations. The value of the loss factor of sand lies in the range of 0.06–0.12.[4] It should be noted here that the position of the defects in the wooden bar has an influence on the modes of vibration, and that defects positioned at the antinode of stress vibration would have a stronger influence than those at the nodes. In the case of the fundamental mode of longitudinal vibration of a bar, the stress antinode is at the middle of bar, and it is expected that defects situated around this position would cause some deformation of the mode shape.

Impulse response of a bar under longitudinal vibration

In several branches of experimental physics the study of any system often necessitates the knowledge of its impulse response. This function is specific for each system and it may be used to draw much information on the system. Ideally, the impulse response is obtained through exciting the system by a so-called Dirac pulse, a very short but intense excitation signal. However, it is practically impossible to realize such a pulse for experimental purposes, and instead one relies nowadays on another method that has proved to be quite efficient in the study of vibrating and acoustical systems. The technique relies on using a random signal for exciting the system, thus making the input signal to the system, and to which a cross-correlation operation is performed with the response signal of the system. The technique is described in detail in textbooks,[5] and a summary of its block diagram is shown in Fig. 2.

Evaluation of the MOE from the modes of longitudinal vibrations

When a bar with length l is submitted to an excitation along its axis, the wave reflections at the extremities of the bar build up at specific frequencies at which the response of the bar is most pronounced. At these frequencies, the double length of the bar corresponds to an integer number n of the wavelength λ, that is $2l = n\lambda$, where $\lambda = c/f_n$, c being the speed of longitudinal wave propagation and f_n the resonance frequency of order n. Furthermore, the speed c of longitudinal wave propagation for a material with a MOE E and a material density ρ is to a first degree of approximation given by: $c = \sqrt{E/\rho}$. Hence, the expression of the resonance frequencies may be formulated according to:

$$f_n = \frac{n}{2l}\sqrt{\frac{E}{\rho}} \tag{1}$$

The expression of the speed of wave propagation is accurate for longitudinal vibrations in a bar in which the transverse dimensions are small in comparison with its length. The lowest resonance frequencies are exhibited as distinct peaks in the transfer function of the system, this latter being defined as the Fourier transform of the impulse response. At the first resonance frequency f_1, which is obtained for $n = 1$, the MOE value is expressed as:

$$E = 4\rho f_1^2 l^2 \tag{2}$$

Evaluation of the loss factor

The loss factor of a material is a measure of how efficient the material is at damping vibrations. During vibration, the dissipation of energy into heat within the material may have several causes, and independently of the mechanisms of this energy dissipation the loss factor η is defined by:

$$\eta = \frac{1}{2\pi}\frac{W_1}{W_R} \tag{3}$$

where W_l and W_R are the dissipated and the available mechanical energies, respectively, during one cycle of vibration.[4] The loss factor may alternatively be defined by means of the useful concept of complex MOE according to $E = \sigma/\varepsilon = E_d + jE_l = E_d\,(1 + j\eta)$ with E_d and E_l being the dynamic and the loss components, respectively, of the MOE, and $\eta = E_l/E_d$ is again the expression of η now in terms of the real and imaginary components of the MOE.

There are several ways that provide access to the value of the loss factor, such as the method of the half-power bandwidth at resonance, or through the logarithmic decrement of harmonic damped vibrations. In this work, η was determined indirectly from the impulse response of the test sample through a room acoustical technique. The technique and its specific applications to wood are described thoroughly elsewhere.[6] In summary, the technique involves the evaluation of the reverberation time T_{60}, which is defined as the time taken for the vibration energy level to drop by 60dB, or equivalently from the slope of the energy decay curve as a function of time. This parameter is in turn processed through an integration of the squared impulse response, and a descriptive summary of the method is presented in the block diagram of Fig. 3.

The advantage of using impulse response measurements on the test specimen is then made obvious when knowing that only one single measurement is necessary for the evaluation of several parameters, including the resonance frequencies, which are accessed through a Fourier transform operation. Calculations at different frequencies then require only frequency filtering of the impulse response prior to processing any parameter of interest. This operation is often executed by means of a convolution with the time-domain form of the filter prior to Fourier transformation. This filtering procedure is available on most measurement systems that are designed to perform impulse response measurements.

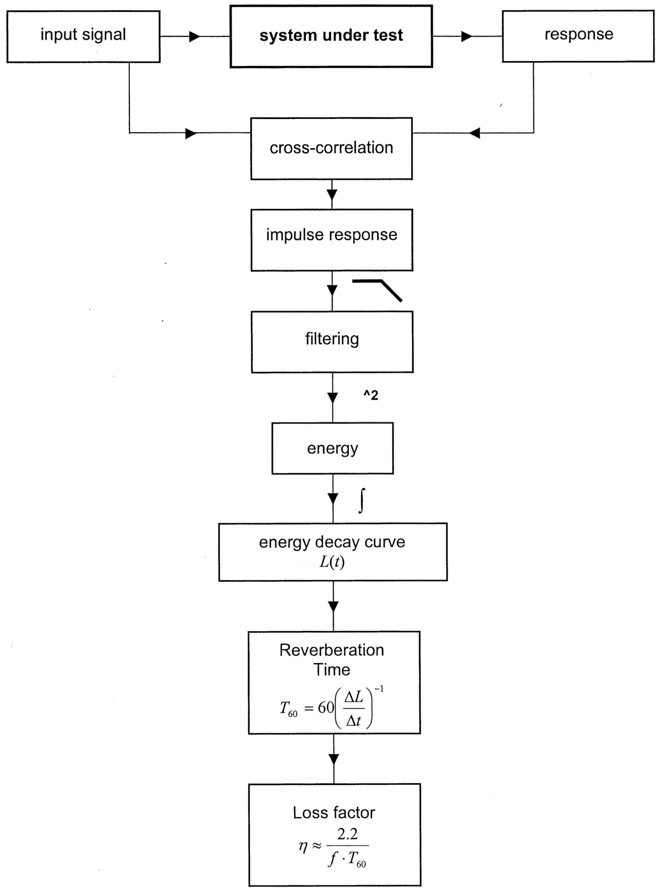

Fig. 3. Flow chart for a method for evaluating the loss factor from the impulse response

Results and discussion

The test signal used in the experiment was a broad-band random noise. A low filtering operation was executed on the signal with a choice of the highest frequency such that all the impulse response was included in a measurement time window. This allowed consideration of all of the lower and most pronounced vibration modes of interest. A typical impulse response and its counterpart in the frequency domain, the corresponding transfer function, are shown in Fig. 4.

Changes of the MOE with the number of holes in the bar

Measurements were made on the test bar with an increasing number of holes drilled in it. The value of the MOE was then evaluated for each case at the first resonance frequency by means of Eq. 2, and the curve of variation of the value of the MOE as a function of the number of holes is plotted in Fig. 5.

Along with the experimental curve, three other curves are also drawn on the plot of Fig. 5. One of these curves is hypothetical and is evaluated as if the bar were porous, that is, as if the drilled holes were unfilled. For the same volume for the bar, its mass, being initially M, decreases with increasing porosity following the introduction of holes in it. Hence taking V_h for the volume of a single hole, with n_h being the total number of holes, in the bar with the volume $V_{bar} = L \cdot B \cdot H$, the density ρ_{porous} of the porous bar when expressed in terms of the wood density ρ_{wood} and the total number of holes may be expressed as:

$$\rho_{porous} = \frac{M_{porous}}{V_{bar}} = \frac{M - n_h V_h \rho_{wood}}{V_{bar}} = \rho_{wood}\left(1 - n_h \frac{V_h}{V_{bar}}\right) \qquad (4)$$

With this correction to the expression of the material density one obtains lower values of the MOE than those obtained for a bar with unaffected material density, shown by the lowermost curve in Fig. 5.

For sand-filled holes in the wood bar other improvements to the MOE curve may be achieved through considering the mass density and MOE of sand. A first correction brought by the mass of sand is accomplished through adding the mass of sand filling the holes. If we call ρ_{sand} the density

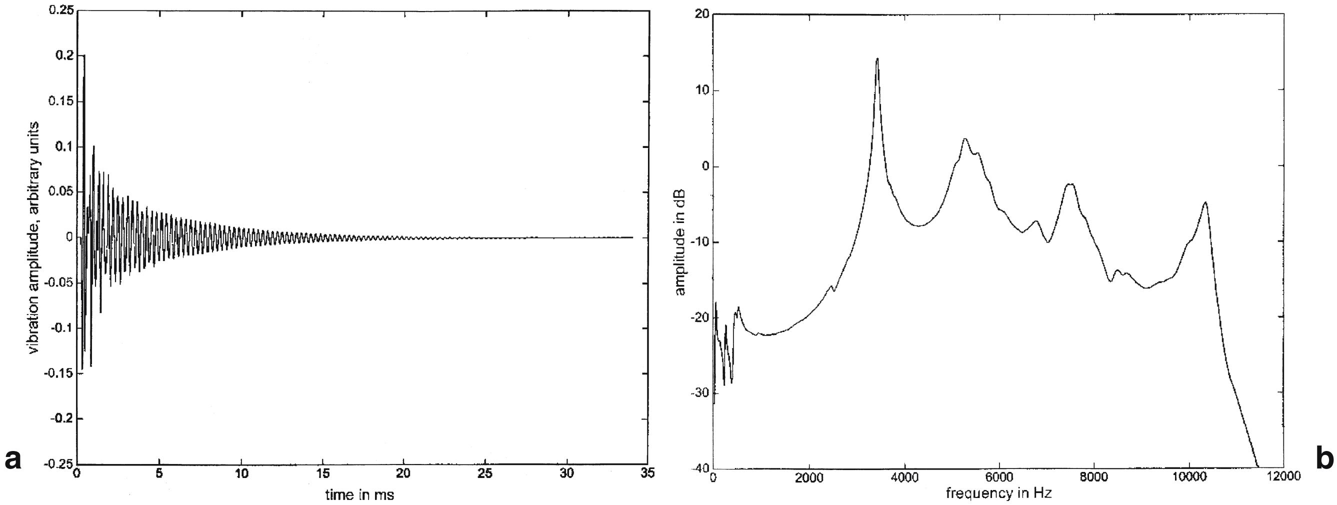

Fig. 4. **a** Impulse response for the wood bar in axial vibration. **b** The corresponding transfer function

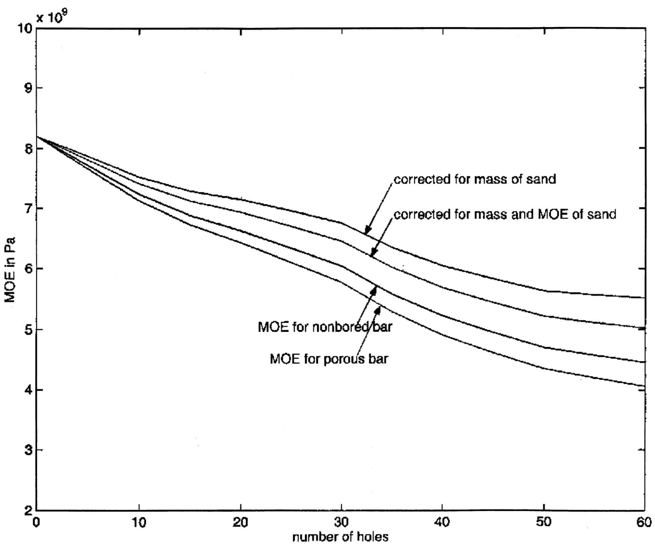

Fig. 5. Variation of the value of the modulus of elasticity (MOE) with the number of holes in the wood bar

of sand, measured in our case as $\rho_{\text{sand}} = 1.8 \times 10^3\,\text{kg/m}^3$, the new density of the bar $\rho_{\text{corr,1}}$ takes the expression:

$$\rho_{\text{corr,1}} = \frac{\rho_{\text{wood}}\left(V_{\text{bar}} - n_{\text{h}}V_{\text{h}}\right) + n_{\text{h}}\rho_{\text{sand}}V_{\text{h}}}{V_{\text{bar}}} = \rho_{\text{wood}} + n_{\text{h}}\left(\rho_{\text{sand}} - \rho_{\text{wood}}\right)\frac{V_h}{V_{\text{bar}}} \tag{5}$$

The obtained higher value of the mass density of the bar leads then to a higher value of the MOE, $E_{\text{corr,1}}$, as calculated by means of Eq. 2. In fact, this last value of the MOE is the highest of all the corrected values in this study, shown by the uppermost curve in Fig. 5. This corrected value of the MOE may be even further improved by incorporating the MOE of sand in the expression of $E_{\text{corr,1}}$. The so-obtained value, $E_{\text{corr,2}}$, is calculated by replacing in the value of $E_{\text{corr,1}}$ the value of the MOE of sand E_{sand}, with a proportion corresponding to the relative volume of the sand-filled holes in the bar:

$$E_{\text{corr,2}} = E_{\text{corr,1}}\left(1 - n_{\text{h}}\frac{V_{\text{h}}}{V_{\text{bar}}}\right) + E_{\text{sand}}n_{\text{h}}\frac{V_{\text{h}}}{V_{\text{bar}}} = E_{\text{corr,1}} - n_{\text{h}}\left(E_{\text{corr,1}} - E_{\text{sand}}\right)\frac{V_{\text{h}}}{V_{\text{bar}}} \tag{6}$$

With a value for $E_{\text{sand}} = 3.0 \times 10^7\,\text{Pa}$, a common value for sand,[4] the new obtained value of $E_{\text{corr,2}}$ is slightly lower than that of $E_{\text{corr,1}}$. Comparing the values of the MOE value as determined using Eq. 2 without considering the change of mass in the bar and the value given by Eq. 6, one finds that the relative error committed increases with increasing porosity in the bar.

The maximum error committed in this study amounts to around 30% (which depends on the density and MOE of sand), and is about three times the maximum relative error in the mass density of the bar when making calculations with an intact bar instead of a porous one. Thus, the relative value of the MOE value decreases almost linearly for an increasing porosity of the bar, although at a slower rate, and this variation shows a slowing variation trend toward higher porosity of the bar.

Changes of the loss factor with the number of holes in the bar

The curve of variation of the loss factor as a function of number of holes is plotted in Fig. 6. The loss factor was determined at the first resonance frequency, and at which the bar length corresponds to half a wavelength.

Considering the loss factor, its overall increase is clearly seen as a function of the number of holes in the wood bar. The damping of vibrations in this case can be attributed not only to the material damping brought about by the introduc-

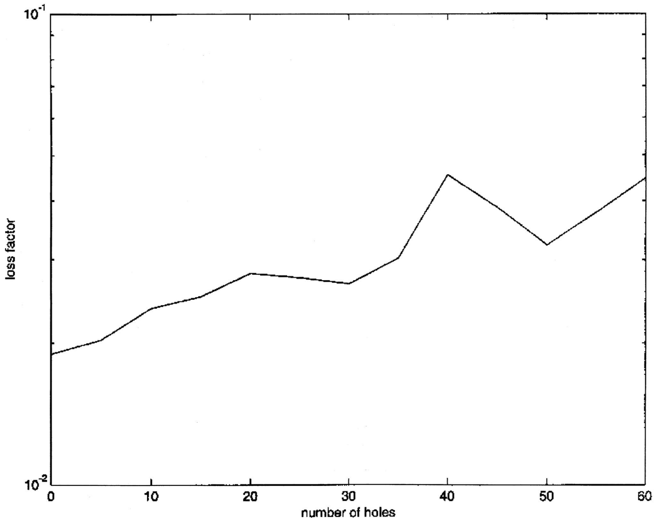

Fig. 6. Variation of the value of the loss factor with the number of holes in the wood bar

tion of sand, but also to the loss of vibratory energy every time the elastic wave within the material bounces at the boundaries of a hole. In any case, the present experimental results herewith support earlier qualitative findings that rot increases the damping properties of wood and lowers its strength.[2,3] It may be pointed out that the reverberation time from which the loss factor has been determined in this study was not T_{60} corresponding to the 60-dB decay in signal level as described earlier. Instead, another variant, the early decay time, EDT, was used for the calculations of η for the reason that in the case of weak excitation signals or when dealing with highly damped systems, it may happen that the dynamics of the decay curve does not have the required 60dB to evaluate the original T_{60}.

Conclusions

This article presents the results of an experimental study on the effects of structural defects on the MOE and loss factor of a solid material. The example of a wooden beam has been taken for experimental practicality. The defects consisted of holes drilled in the beam, which was set into longitudinal vibration through excitation along the grain. The longitudinal excitation was considered instead of, for instance, the bending mode of vibration for the reason that the experimental results may be affected by some coupling between the different modes of vibration due to the high anisotropy of wood.

The MOE and loss factor were evaluated at the fundamental resonance frequency, i.e., the frequency at which the length of the bar corresponds to half a wavelength. The loss factor was evaluated by means of an acoustical technique conceived originally for making measurements of sound absorption for room acoustical applications. The technique used in this study, which consists of measuring the impulse response of the test specimen, is attractive in that the measurements are perfectly repeatable and that there are available affordable measurement packages for conducting measurements in the audio frequency range. This, however, does not prevent the technique being applied in the ultrasonic frequency range. The results from the present study reveal and confirm other earlier studies conducted on wood affected by rot that the MOE decreases steadily with an increasing number of defects in the wood element and that at the same time the loss factor increases, although at a somehow slower rate.

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