Identification of the Severity and Position of a Single Defect in a Wooden Beam

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In the present paper changes of validity in Euler-Bernoulli's elementary theory of flexural vibration for homogeneous materials were tested with respect to changing severity and position of a single defect in wood. As an orthotropic material, wood has different material properties or strengths in different orthogonal directions. A set of absolutely clear specimens of oriental beech was chosen and hand drilled in different diameters (severities) at different relative distances from an end oriented in the R direction. A clear specimen showed a steady decrease in evaluated moduli of elasticity related to increasing mode numbers. After creating the defects, this steady decrease line showed some breakages. The slope breakages of modally evaluated elastic moduli in LT and LR vibrations are suggested as potential finger-prints of single hole defects in the specimen by considering the shape and rate of breakages in the decreasing lines. The recognition scenarios of slope breakages for defect severity and position are summarized.

Keywords: Defect; Euler-Bernoulli; Nondestructive test; Young's modulus

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INTRODUCTION

The one-dimensional theories of vibration developed by Bernoulli and improved by Timoshenko are valid for homogeneous isotropic materials. This means that defects such as holes, knots, cracks, and biological deterioration may reduce the isotropic quality, affecting the validity of these theories in defect materials. As a note, the anisotropy of the wood comes from not only the defects but mainly of the inherent physiology.

A specimen of clear wood might be considered (with some connivances) to be an axial isotropic (orthotropic) material (Bodig and Jayne 1993) that can be subjected to the Euler-Bernoulli or Timoshenko's theories (Bordonné 1989). For an absolutely clear rectangular wooden beam, the Young's moduli from Euler-Bernoulli's elementary theory is decreased with an increase in resonance mode number due to the effect of shear deflection and rotary inertia mentioned by Timoshenko (Harris and Piersol 2002). Experimental values of the Young's moduli from the Euler-Bernoulli's elementary theory, however, do not always show this tendency; for example, the Young's modulus of the first resonance mode is sometimes smaller than that of the second resonance mode (Hearmon 1956). If such Young's moduli are used, the correlation coefficient of Timoshenko's improved equation would be low and the obtained results from Timoshenko's dynamic evaluations would not be reliable. Such a material is not considered a homogeneous material. In this study, it was assumed that creating an artificial defect might also affect one or more modal moduli of elasticity or the theoretical linear decreasing tendency in the modal analyses. Testing this assumption here is a continuation of a previous approach in defect detection. This experiment is aimed to obtain another new methodology for recognizing the defect region of wooden beams if the defects have an obvious effect on the described linear decreasing tendency of Euler-Bernoulli's steady modal elastic moduli.

In addition to studies done by the authors in wood defect identification (Abollahiansohi *et al.* 2011; Khademi-Eslam *et al.* 2011; Roohnia *et al.* 2010, 2011a,b), there is also a valuable directory of researchers who have published their findings on the effects of defects on the dynamic behavior of wood or other engineering materials. Just to highlight a few, Divos *et al.* (2001) estimated the defects in timbers using stress wave traveling time and amplitude. Cam *et al.* (2002) studied the vibrations due to impact shock on flexible beams. They compared the signal obtained from defective and non-defective beams in both the time and frequency domains. Using these results, the position of a defect could be determined from vibration signals. Kubojima *et al.* (2005) studied the effect of additional mass on the Young's modulus of a wooden beam. This approach was valuable for detecting the defects (*e.g.*, knots), which increase the local mass of the wood. Modal analysis technology was applied to detect the position and severity of a hole-type defect in the lumber. The peak values of their damage indicators computed from the first two mode shapes were sensitive to different damage severities and locations (Hu and Afzal 2006a). Meanwhile, their wavelet coefficients showed dominant spikes around the damage locations and were zero everywhere else except the two computing edges. The dominant spikes coincided well with the damage location (Hu and Afzal 2006b). Sobue *et al.* (2010) exploited an inverse solution procedure enabling the identification of the defect position within a beam, which was made possible by the resonance frequency of longitudinal vibrations. Song *et al.* (2011) tested larch lumber pieces using a modal analysis technique, while frequency response functions (FRF) were derived. In their approach, modal parameters, including the first four natural frequencies and the first three modal shapes, were distinguished by the single modal method. They could make qualitative and quantitative estimates to the hole-defect in the lumber by collectively considering the natural frequency and modal shape; however, they could not judge the position of the hole-defect using the change rate of frequency.

This approach was formulated to continue the investigations on the effects of defects on the dynamic responses of wooden beams. As it was introduced for a homogeneous rectangular beam, Euler-Bernoulli's Young's moduli decreases with increasing resonance mode number at a steady slope. As an objective, we wanted to test the assumption that creating an artificial defect that causes a local heterogeneous structure may also affect one or more modal elastic moduli or affect the theoretically uniform steady decrease.

EXPERIMENTAL

Materials

According to the methodology formulated in this work's main research project with the mission of defect identification in wood, a set of oriental beech (*Fagus orientalis*) specimens was collected from two commercial logs. Following ISO 3129 International Standards (1975), 100 rectangular, visually clear, and sound wooden specimens were randomly obtained from different parts of the logs. The specimens were cut to final nominal dimensions of 20 x 20 x 360 mm^3 (R x T x L) and kept in a conditioning chamber at 20 ± 1 °C and 65 ± 3% relative humidity for 2 weeks until the moisture content was stabilized (beginning from the fiber saturation point).

Experimental Protocol

The specimens were sorted based on severe and accurate clarity criteria in accordance with Timoshenko's flexural theory correlation coefficient (Brancheriau and Bailleres 2002; Roohnia *et al.* 2010) and relative differences between dynamic longitudinal modulus of elasticity obtained from radial and tangential flexural vibrations (Roohnia *et al.* 2011a). Within this community, the best 35 sorted specimens were selected and randomly divided into five groups of seven to apply step-wise drilling to tangential surface with diameters of 0, 3, 5, 8, and 10 cm oriented in the radial direction (Fig. 1) at different relative distances (RD) from the end of different samples (Table 1). The introduced RD for step-wise drillings were chosen as 0.1 L, 0.2 L, 0.3 L, 0.4 L, and 0.5L, in which "L" corresponds to the total span of the beam.

Table 1. Drilling Scenarios for 5 Groups of Specimens

Group	Number of Replications	Relative distance of drilling from an end*	Hole diameter Mm
1	7	0.1L	0 3 5 8 10
2	7	0.2L	0 3 5 8 10
3	7	0.3L	0 3 5 8 10
4	7	0.4L	0 3 5 8 10
5	7	0.5L	0 3 5 8 10

*L is the total length of the beam.

Dynamic Test

Four initial modal frequencies were obtained using a fast Fourier transform both in LR (parallel to radial surface) and LT (parallel to tangential surface) free flexural vibration in free-free beams following the methodology and devices such as the ndt-lab®

system introduced in detail in previous works (Roohnia *et al.* 2006, 2007, 2010, 2011a,b) for free flexural vibration of free-free beams. The ndt-lab® system was developed in Islamic Azad University, Karaj Branch-Iran to enable a simultaneous evaluation of dynamic modulus of elasticity, dynamic shear modulus, and damping due to internal friction. The schematic view of the setup is introduced in Fig. 1. In this work, however, Euler-Bernoulli's elementary equations rather than Timoshenko's improved equations were applied before and after drilling the holes. A brief description of the nondestructive testing system is also introduced.

To simulate the free flexural vibration, the test specimens were placed on soft thin rubber from their nodes of the first mode of vibration and excited using a steel spherical pendulum (mass 57 g, diameter 23.97 mm) from a free end, while the sound recording was done from the other free end of the beam by a unidirectional microphone (Fig. 1). The frequency of the radiated sound was plotted in the range of 40 to 12,000 Hz. The sampling frequency of the unidirectional microphone was 44,100 Hz, with a frequency resolution close to 3 Hz.

Step-wise hole widening was performed at each relative distance from an end (Table 1). The LR and LT flexural tests were studied individually, and Bernoulli's moduli of elasticity were determined based on each of the four initial modes of flexural vibration. The theoretical linear decreasing slope of the evaluated moduli of elasticity with increasing mode numbers was tested for absolute clearness of the beams.

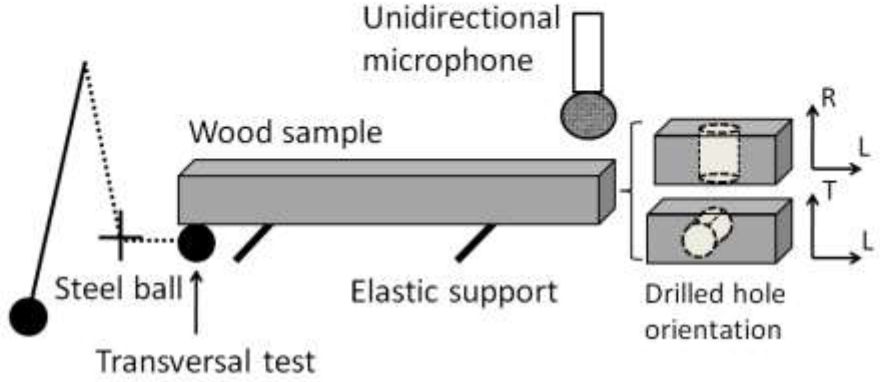


Fig. 1. A beam with a drilled hole under flexural vibration in the LR (top) and LT (bottom) directions

According to Euler-Bernoulli's theory, the Young's modulus is evaluated as:

$$E = \frac{48\pi^2 f^2 \rho L^4}{m_n^4 h^2} \tag{1}$$

where h is the height of the flexural beam and m_n is a scalar depending on the end support conditions and mode number, n. For a both ends free beam it is equal to 4.73, 7,85 for the 1st and the 2nd modes respectively. For higher modes of vibration it is a result of the following equation (Bodig and Jayne 1993):

$$m_n = \frac{2n+1}{2}\pi \tag{2}$$

As it was introduced for a homogeneous rectangular beam, the Young's moduli decreases with increasing resonance mode number at a steady slope. We wanted to test the assumption that creating an artificial defect that causes a local heterogeneous structure may also affect one or more modal elastic moduli or affect the theoretical uniform steady decrease.

RESULTS AND DISCUSSION

In each set of plots indicated in Figs. 2 through 6, the clear specimen before drillings is plotted beside the defected conditions. In Fig. 2, where the step-wise drillings were applied at 0.1 L of the clear specimens, the linear slope breakage was occasionally obvious for the larger defects, but could not be reasonably defined while changing the positions to greater distances from an end, which showed better finger-prints due to defect positions and severities. For the 0.1 L group of specimens, the plots show that step-wise hole-widening did not change the 1st mode modulus on both the LT and LR evaluations, where moving to higher modes in the wider defect led to relatively smaller values. These shifts did not affect the steady decrease.

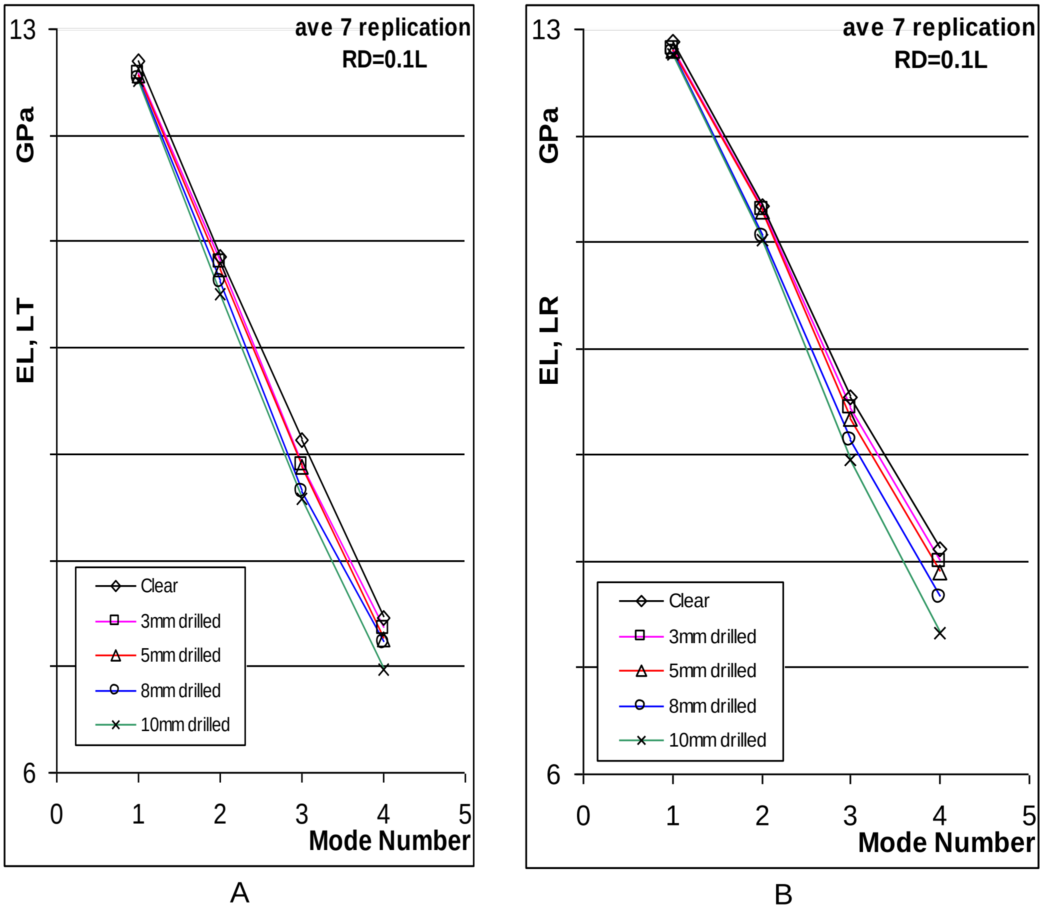
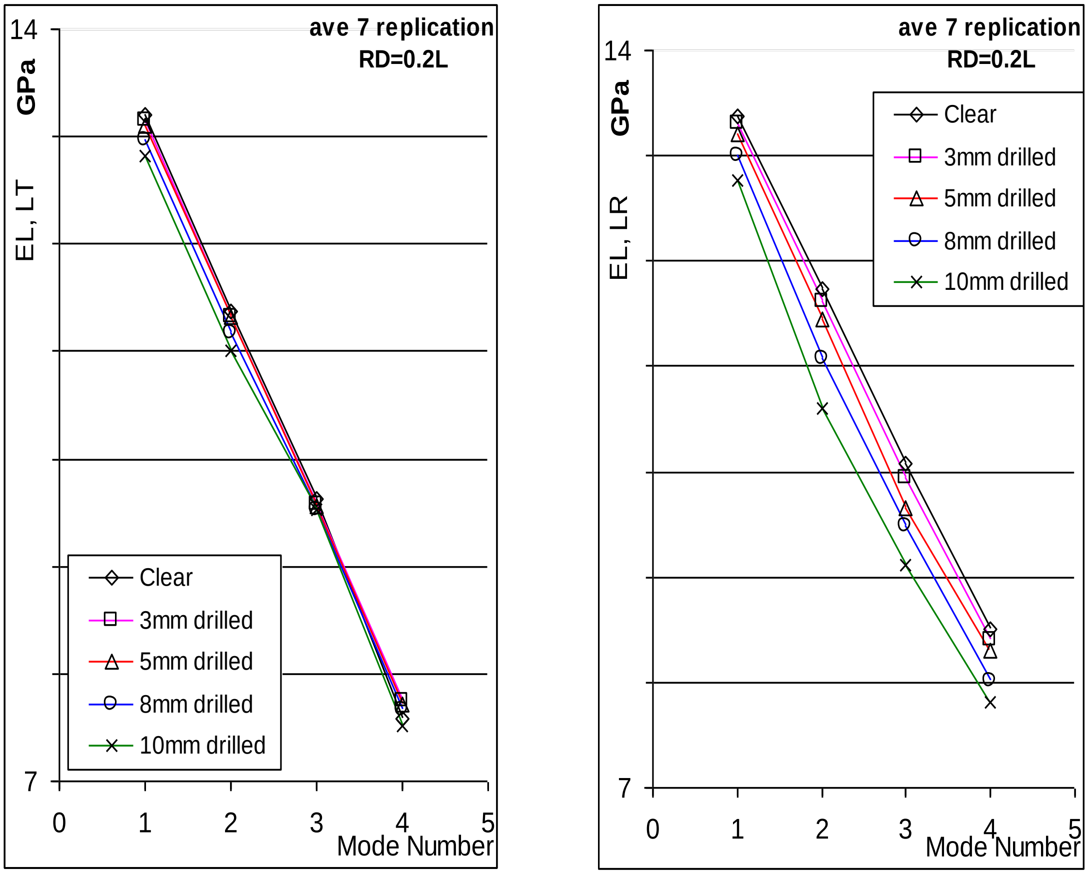


Fig. 2. Modal evaluated values for longitudinal moduli of elasticity for clear and step-wise drilled specimens at an RD of 0.1 L for a) LT flexural and b) LR flexural vibration tests. Each point corresponds to an average of seven similar specimens.

As shown in Fig. 3 for the 0.2 L specimens, the slope breakages were mostly at the 3rd mode for the LT and at the 2nd mode for the LR vibration. Greater or smaller defects in this position did not exhibit any visible differences on the 3rd modal evaluation of the elastic moduli in the LT vibrations. The observed changes in the steady decrease may be considered to be a potential finger-print, especially for wider artificial defects. To follow up the approach, this raw assumption was tested for RD = 0.3 L specimens in Fig. 4. The slope breakage was observed at the 2nd mode for LT vibration, while there were two slope breakages at the 2nd and 3rd modes in LR vibration. Greater or smaller defects in this location did not exhibit any visible differences on the 2nd modal evaluation of the elastic moduli in LT vibrations. The above-mentioned raw assumption was certified because there were different finger-prints in the RD = 0.3 L specimens.



A B

Fig. 3. Modal evaluated values for longitudinal moduli of elasticity for clear and step-wise drilled specimens at an RD of 0.2 L for a) LT flexural and b) LR flexural vibration tests. Each point corresponds to an average of seven similar specimens

Relatively different finger-prints for the RD = 0.4 L and 0.5 L specimens in Figs. 5 and 6 support the introduced finger-print hypothesis.

The slope breakage in LT vibrations were at the 3rd mode for the RD = 0.4 L specimens and at the 2nd and 3rd for the RD = 0.5 L specimens. The directions of the

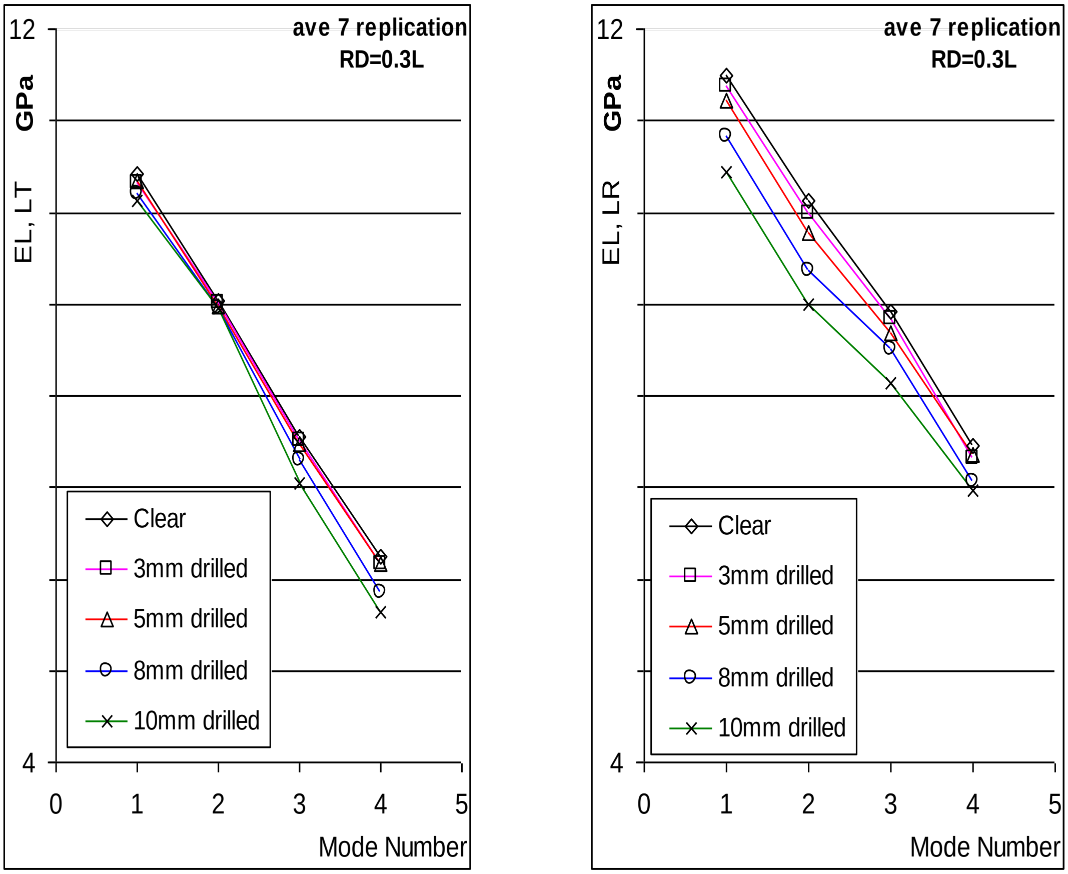


Fig. 4. Modal evaluated values for longitudinal moduli of elasticity of clear and step-wise defected specimens at an RD of 0.3L for a) LT flexural and b) LR flexural vibration tests. Each point corresponds to an average of seven similar specimens

slope breakages were different from the ones in other RDs. Neither greater nor smaller defects had any visible effect on the 4th mode in the 0.4 L specimens and on the 3rd modal evaluation of the elastic moduli in the 0.5 L specimens.

The slope breakage in LR vibrations were at the 2nd mode for both the RD = 0.4 L and 0.5 L specimens, which may have affected the assessment results on the 0.4 L and 0.5 L locations at the middle of the beam span; however, the knowledge of this finger-print hypothesis may still be considered an acceptable estimation, as the 0.4L could be considered a location in the relative middle of the span.

A hypothesis that assumes the different modal behavior changes due to hole widening at the different relative distances of defects from an end was tested. Different behaviors of LT and LR flexural vibrations due to the relative coincidence of defects with the neutral axis (Roohnia *et al.* 2011a) of bending as well as nodal points of flexural vibration were also studied.

As predicted, there were different effects of defect locations and their severity on the modal analyses.

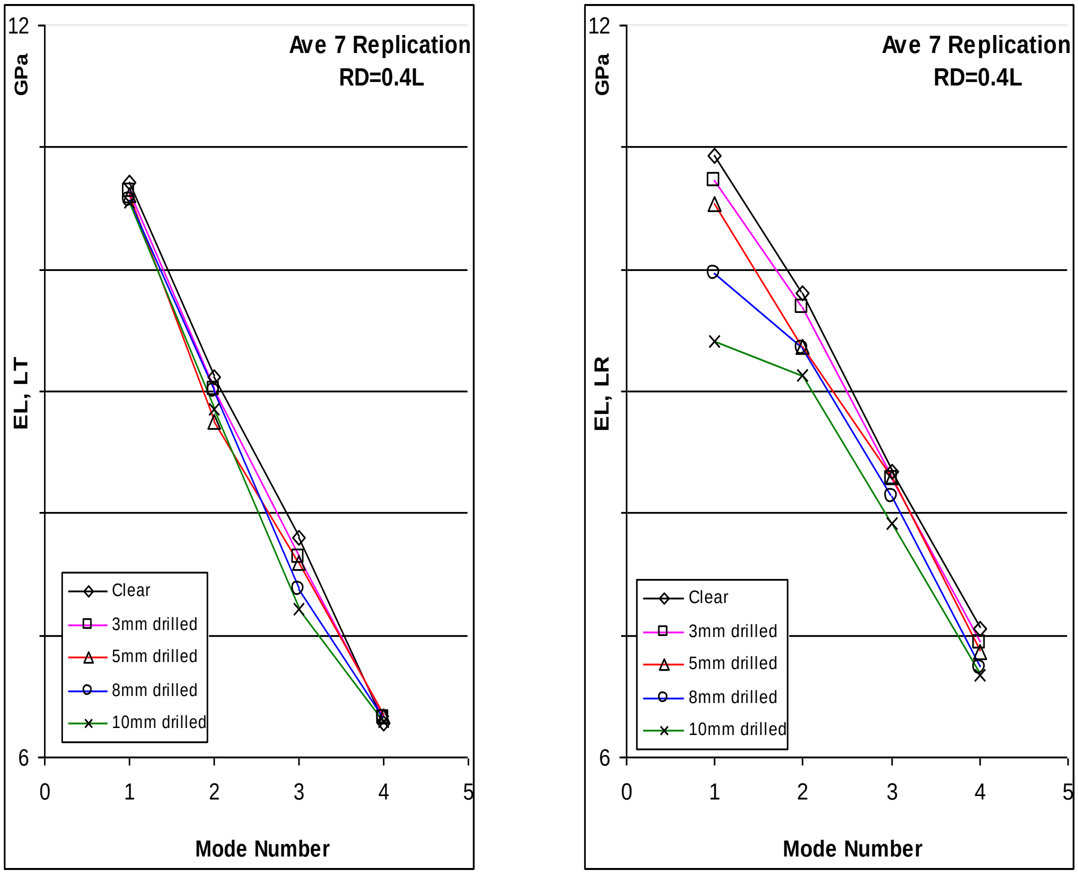


Fig. 5. Modal evaluated values for longitudinal moduli of elasticity of clear and step-wise defected specimens at an RD of 0.4 L for a) LT flexural and b) LR flexural vibration tests. Each point corresponds to an average of seven similar specimens

Following theory, the selected clear specimens also showed experimentally the steady decrease (absolutely uniform slope) of evaluated moduli of elasticity from four initial increasing mode numbers. After drilling and step-wise widening, the steady slope was broken. Concerns about the position of decreasing slope breakages in modal elastic moduli may lead to identify any probable finger-prints of defect positions and their severities. The observed plots of average values were representative enough to show the evaluated characteristics of most of the individual members in each RD group. When the data of each replication were plotted individually, all points of data coincided in a high relativity with those of data for the average values. However, the plots for the averages were obviously more regular. In order to evaluate whether the patterns depicted in the graphs were due to the hole placement or whether they simply resulted from random variation, tests were carried out to determine the scattering degree of values in each average data point after drilling and hole widening, while the changes in standard deviations were concerned. There were no increases in standard deviations of the measured elastic property after manipulating the specimens (each mode of vibration was tested separately). Even more, the standard deviations in many cases decreased after manipulations.

All of the above observations, including the different behavior of LT and LR vibrations, are expressible in terms of the coincidence value of defects with the neutral axis of bending, the nodal points of vibration, or both. When a defect coincides entirely with the neutral axis or node point, that mode and plane of vibration would not be able to detect it, so the steady slope would not show any breakage there. As the defect grows up, this coincidence value will change. These phenomena support the approach of flexural vibration to identify the severity or the position of a defect in wood.

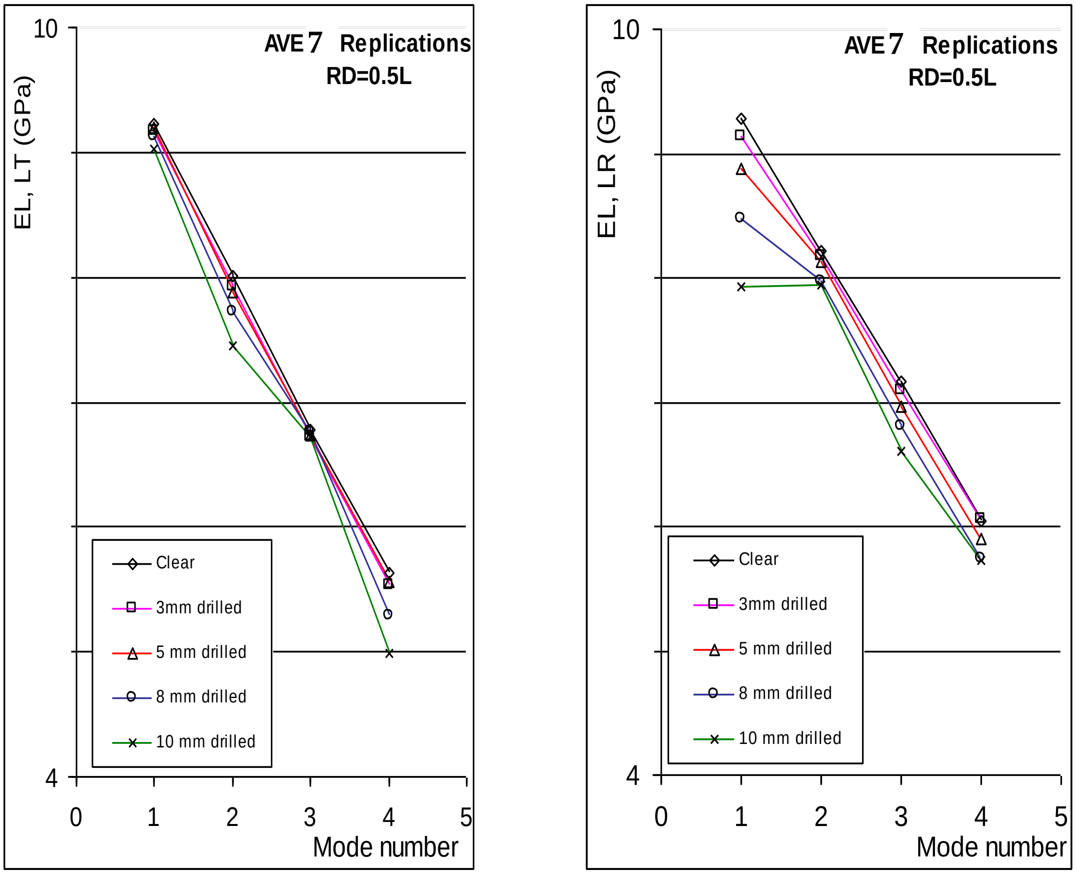


Fig. 6. Modal evaluated values for longitudinal moduli of elasticity of clear and step-wise defected specimens at an RD of 0.5 L for a) LT flexural and b) LR flexural vibration tests. Each point corresponds to an average of seven similar specimens.

Table 2. The Recognition of Slope Breakages for Defect Location

LT vibration	LR vibration	Defect
-	-	0.1 L
3rd (with higher slope)	2nd (with lower slope)	0.2 L
2nd (with higher slope)	2nd (with lower slope) & 3rd (with higher slope)	0.3 L
3rd (with lower slope)	2nd (with higher slope)	0.4 L
2nd (with lower slope) & 3rd (with higher slope)	2nd (with higher slope)	0.5 L

As mentioned earlier, this approach is continuation of the previous efforts on artificial defect localization, but it still needs to be extended using other species with reasonable intervals of specific gravities and specimen sizes.

CONCLUSIONS

1. Euler-Bernoulli's model remained valid within an acceptable interval for elasticity assessment of beams carrying imperfections if and only if the 1st mode of LT vibration is taken into account. LT vibration was less influenced, which might be due to neutral axis and defect orientation in this particular approach.
2. The slope breakage of the modal evaluated elastic moduli for LT and LR vibrations is suggested as a potential finger-print of a single hole defect in the specimen with respect to the shape and decrease in rate of modal. The recognition order of slope breakages for defect locations are summarized in Table 2.
3. In addition to the recognition orders, if the evaluated longitudinal moduli of elasticity for the 1st and 2nd modes of LR vibration are equal to one another, then it can be concluded that a large defect may be located around the middle of the beam. This finger-print is not repeated with any defect locations except the 0.4 L specimens, which are also located near the middle of the beams.

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