Elastic Properties of Oak Wood Finger Joints with Polyvinyl Acetate and Isocyanate Adhesives

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In this study, the elastic properties of 23 specimens of oak timber (*Quercus castaneifolia*), including the longitudinal modulus of elasticity (MOE), acoustic coefficient (K), and acoustic converting efficiency (ACE) in free vibration using the free-free beam method with different planes of vibration, *i.e.* tangential (LT) and radial (LR), were studied. These elastic parameters were examined in both sound wood and finger jointed timbers with two different lengths of fingers (5- and 10-mm finger lengths) and individually glued with two different types of adhesives (isocyanate and polyvinyl acetate). Comparing the elastic properties of solid beams with finger jointed beams of oak wood in both (LT) and (LR) planes, 10-mm finger joints with polyvinyl acetate adhesive did not cause any serious change to the studied elastic properties of the beams, while shorter finger length (5 mm) with isocyanate adhesive severely changed the acoustic properties; therefore, beams having longer finger lengths may have enhanced acoustical properties.

Keywords: Acoustic Coefficient; Acoustical converting Efficiency; Damping, Finger joint; Modulus of Elasticity

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INTRODUCTION

Finger joints have been used in the wood industry for many years and are believed to be one of the strongest varieties of joints. Foremost, application of a finger-jointing process allows the removal of strength-reducing defects. The increase of the surface area of the glue joint has been shown to produce a product with high engineering properties (Cecilia Bustos *et al*. 2011). Finger joints with adhesives such as poly-vinyl acetate (PVA) have been studied. The behavior of adhesives depends on many factors, such as the pH, the presence of extractives, and the amount of debris (Pizzi 1983).

PVA adhesives are among the most common adhesives in production of finger joints. Promising mechanical performance of finger jointed beams glued with isocyanate adhesives have been reported in recent years (Hu and Desjardins 2010).

The purpose of this study was to determine the mechanical properties of small-dimension finger-jointed oak wood (commonly used in industry) with two different individually applied (polyvinyl acetate and isocyanate) adhesives. Application of joints in many handcrafts or engineering wooden structures is inevitable, where the most efficient joints are always preferred.

Based on the mechanical properties of beams and their elastic properties, the acoustic parameters of beams can be predicted. Non-destructive methods (vibration-based techniques) have been used as a fast and cheap way to appraise the elastic properties of materials, especially in the case of finger joints. In comparison to 10-mm finger joints, 5 mm length of finger are more expensive and time consuming due to the difficulty of fabrication; hence a good, cheap, and fast estimation of mechanical properties can be expected to be extremely useful.

To form long, continuous laminated elements and engineered wood components such as trusses and I-joists produced from individual small pieces of lumber, different types of structural end-joints have been manufactured in glued laminated timbers (glulam) (Burk and Bender 1989). In this respect, the strength of lumber has been enhanced by finger jointing (Kohler 1981). The longitudinal vibration technique may be useful as a non-destructive method for predicting the modulus of rupture in solid and finger-jointed tropical African hardwoods (Ayarkwa *et al*. 2000). The critical finger profile parameters to achieve high strength were found to be the slope and tip sharpness. The literature indicates that the tensile strength of finger-jointed lumber increases with decreasing slope and increasing tip sharpness (Mohammad 2004).

The bending strength (modulus of rupture and modulus of elasticity) properties of some finger-jointed oak woods (Turkey oak, Hungarian oak, and Holm oak) have also been examined (Vassiliou *et al*. 2005). The most effective finger-jointed connections were found for the Hungarian oak specimens. Increasing the finger length from 4 to 15 mm caused an increase in the mean modulus of rupture values. The effects of three durability classes of polyvinyl acetate bonding and of two finger lengths (4 mm and 10 mm) on the bending strength of steamed and unsteamed beech wood have been studied (Vassiliou *et al*. 2007). It was found that higher modulus of rupture values resulted from the 10-mm finger length.

In assessing the mechanical properties and bonding quality of finger-jointed lumber, no significant difference in the mean modulus of elasticity and ultimate tensile strength of finger-jointed lumber containing a 29-mm-long joint *versus* a 16-mm-long joint were found. Finger-jointed lumber had a lower characteristic ultimate tensile strength (UTS) and modulus of elasticity (MOE) than did un-jointed lumber (Gong *et al.* 2009).

In studying the polyvinyl acetate bonding of finger-jointed beech wood from Albania and Greece, effects of the finger length (4.5 mm, 6.5 mm, and 9.0 mm) and material origination on the bending strength of finger-jointed steamed and unsteamed beech wood were observed. The results showed that specimens with 9.0-mm finger lengths achieved higher modulus of rupture values in comparison with the specimens with 4.5-mm and 6.5-mm finger lengths (Vassilios *et al*. 2009). In assessing the stiffness of finger-jointed timber with different non-destructive testing techniques, it was found that dynamic moduli values measured using three NDT methods (stress wave propagation, transverse vibration, and MSR machine) correlated well with three-point static bending (Biechele *et al*. 2010).

In a comparison of NDT techniques for assessing the mechanical properties of un-jointed and finger-jointed lumber, lumber with finger joints had lower bending stiffness than un-jointed lumber (Biechele *et al*. 2011). Ultrasonic wave techniques, including two end-jointed methods, finger and scarf, were undertaken to quantify the effectiveness of using ultrasonic techniques to predict the static bending properties (static modulus of elasticity and modulus of rupture) (Karlinasari 2011). A poor relationship was found between the static modulus of elasticity and modulus of rupture for both finger- and scarf-jointed Meranti wood. In a nondestructive assessment of glued joints, the dynamic

Young's moduli of three different joint shapes (45° scarf joint, 30° scarf joint, and 10-mm finger joint) were evaluated using two methods (longitudinal and flexural vibration-based methods). When there were significant differences between the Young's moduli as evaluated by the two methods, the joints were determined to be weak and were required to be rejected or assigned to re-manufacturing. Additionally, the R^2 value of Timoshenko's linear model significantly decreased when there was any loss of integrity in the joints (Roohnia *et al*. 2012).

Nondestructive testing for finger joint (FJ) quality control was conducted to address the concerns of the wood industry by developing an X-ray scanning technique. It was concluded that the X-ray scanning technique has good potential for finger joint quality control and assurance. The X-ray scanning NDT technique could predict the tensile strength of joints reasonably well (Hu 2008).

METHODOLOGY

In this study, in accordance with ISO 3129, 220 clear specimens from *Quercus castaneifolia* (with nominal dimensions of 20*20*360 mm, R×T×L) were randomly collected from a region in Nowshahr, Mazandaran province, Iran. Considering the Timoshenko model that has been fitted initially to isotropic materials, higher correlation coefficients of the estimated trend lines in the Timoshenko equation denote specimens with more homogeneity (Roohnia *et al.* 2010, 2011). The selection was made based on Timoshenko trends with correlation coefficients higher than 0.99.

Sampling was selectively done, and clear samples were selected. Finger joints categorized in different controlled pathways, with two different individually applied polyvinyl acetate and isocyanate adhesives and two different lengths of joints (5 and 10 mm) (Fig. 1), were created on the tangential surface of the beams (exactly at the middle of the beams) (Figs. 2A, 2B).

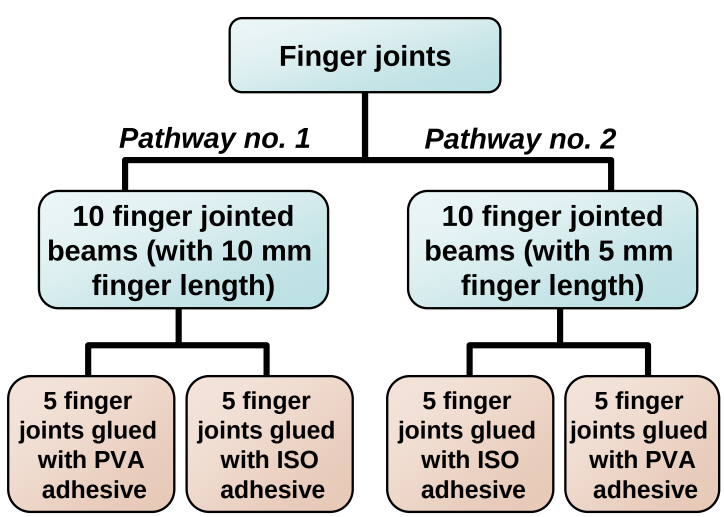

Fig. 1. Patterns and instructions used for finger jointed beams

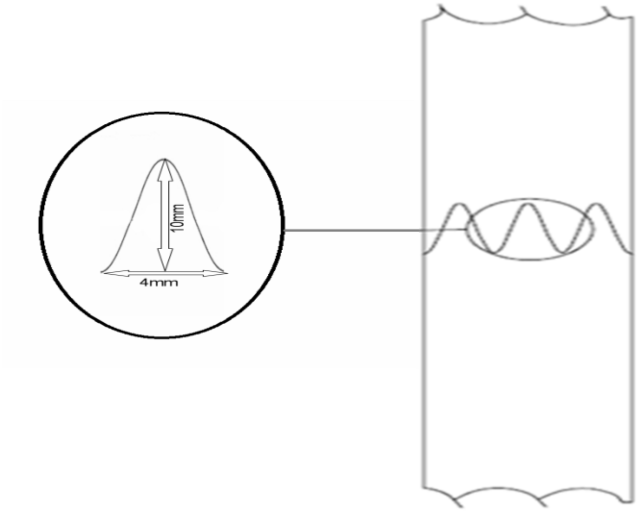

Fig. 2 A. 10-mm finger-jointed beams located precisely at the middle of the beams

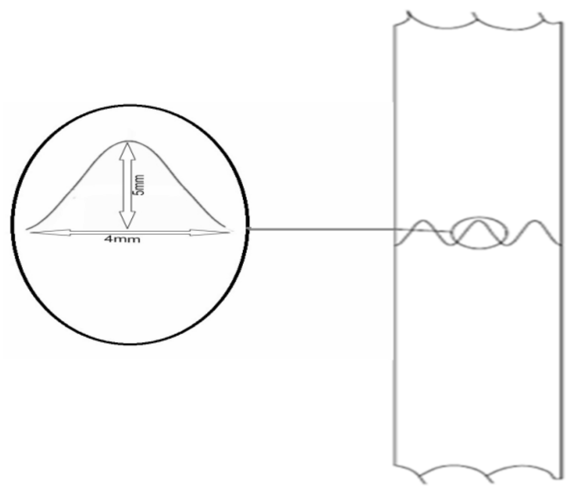

Fig. 2 B. 5-mm finger-jointed beams located precisely at the middle of the beams

The vibrational responses in the tangential and radial planes of flexurally excited samples (clear and finger-jointed) were recorded individually as audio files.

ANOVA was used for the analyses, and Duncan's test was used for grouping the analyzed parameters regarding the elastic parameters (modulus of elasticity, acoustic conversion efficiency, and acoustic coefficient) in different directions of vibration,

Regarding the longitudinal modulus obtained from the LR and LT planes of vibration for absolutely clear and sound beams, samples with $\Delta LE\%$ higher than 5 were eliminated (Roohnia *et al.* 2011). Equation (1), in which $\Delta LE\%$ is evaluated, has been illustrated here:

$$\Delta LE\% = \left| \frac{LE_{LT} - LE_{LR}}{LE_{LT}} \right| \times 100 \tag{1}$$

Here, LE_{LT} and LE_{LR} represent the longitudinal modulus of elasticity obtained in the LT and LR vibration tests, respectively.

An NDT-lab® portable system setup (Roohnia *et al.* 2006) was used to obtain the mechanical properties of *Quercus castaneifolia* using free flexural vibration on both ends of the free beam, where the modulus of elasticity (MOE), acoustic coefficient (*K*), and acoustical converting efficiency (ACE) were studied (Fig. 3).

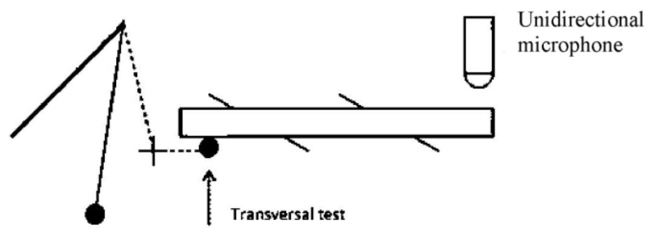

Fig. 3. Schematic views of the most common setups for free flexural vibration on a free-free beam test.

The acoustic coefficient is one the most important factors determining the acoustical properties of wood. It is influenced by the modulus of elasticity and the density (Eq. 2),

$$K = \sqrt{\frac{E}{\rho^3}} \tag{2}$$

where E is the longitudinal modulus of elasticity (Pa), ρ is the density of the air-dried wood specimens (Kg/m^3), and K is the acoustic coefficient.

The acoustic coefficient is a parameter that reflects damping due to radiation. Extending the damping is needed to consider the internal friction, where a combination would result in acoustical converting efficiency (ACE). Regarding ACE (Eq. 3), this parameter is derived from two factors: first, the acoustic coefficient of damping due to radiation (*K*), and second, the logarithmic decrease or damping due to internal friction (Tanδ) (Bodig and Jayne 1989):

$$ACE = \frac{K}{\tan\delta} \tag{3}$$

RESULTS AND DISCUSSION

As expected, results showed that finger length and joint type had effects on the modulus of elasticity (Fig 4A, B).

Impact on the tangential and radial surfaces of the beams did affect the modulus of elasticity in both directions of vibration. Moreover, the acoustic coefficient (*K*) and the acoustic converting efficiency (ACE) were substantially affected. (Fig. 5A, B) and (Fig. 6A, B)

To follow up with previous findings concerning the detection of cracked timbers (Roohnia 2010), it is confirmed again here that the specimen would be sufficiently sound and clear as long as the planes of vibration (LT or LR) do not have any significant effect on the evaluated longitudinal elastic modulus.

The following measures were used as signs of inequity in wood, indicating that both joint types resulted in lower acoustical parameters: an altered modulus of elasticity (MOE), a decrease in the acoustic coefficient (obvious for the 5-mm finger joints), and a decrease in the acoustic conversion efficiency (for both 5-mm and 10-mm finger jointed beams). Also, the magnitude of the decreasing trend was intensified with a shorter finger length (5 mm) and application of the isocyanate adhesive.

The decreased elastic parameters in 5-mm finger joints compared to 10-mm finger joints might be the result of a sharper finger tip in the 10-mm finger joints.

Looking at the results and considering the modulus of elasticity of solid beams and jointed beams of LT and LR planes when analyzing the sound of clear and jointed beams (with polyvinyl acetate adhesive), 10-mm joints did not significantly affect the dynamic Young's modulus.

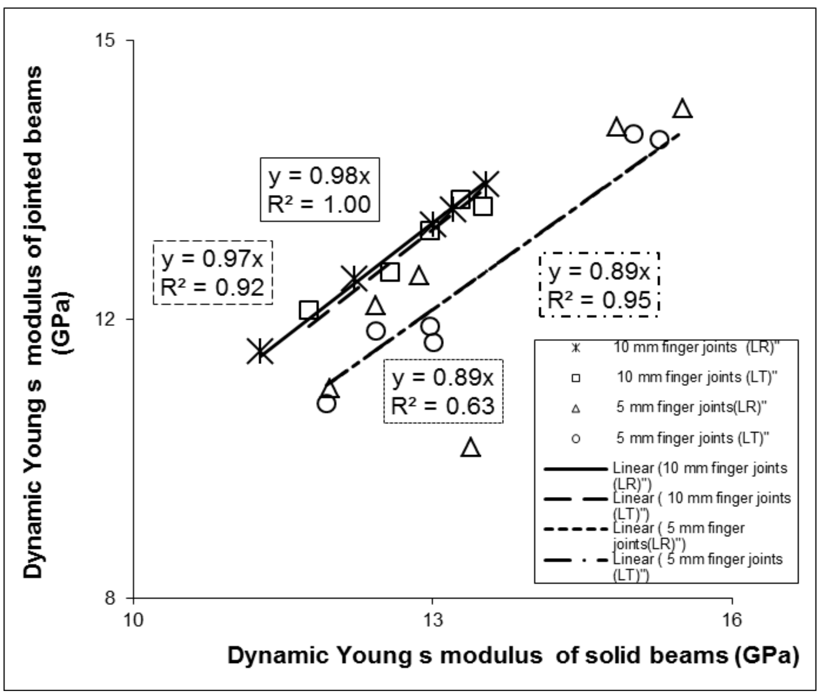

Fig. 4 A[1]. Modulus of elasticity of solid beams and jointed beams with polyvinyl acetate adhesive in the LT and LR planes

[1]As described in methodology, absolutely clear and sound beams, samples with $\Delta LE\%$ higher than 5 were eliminated so there was an overlapping with the dash-dot line in LT and LR planes of vibration of 5 mm finger jointed beams.

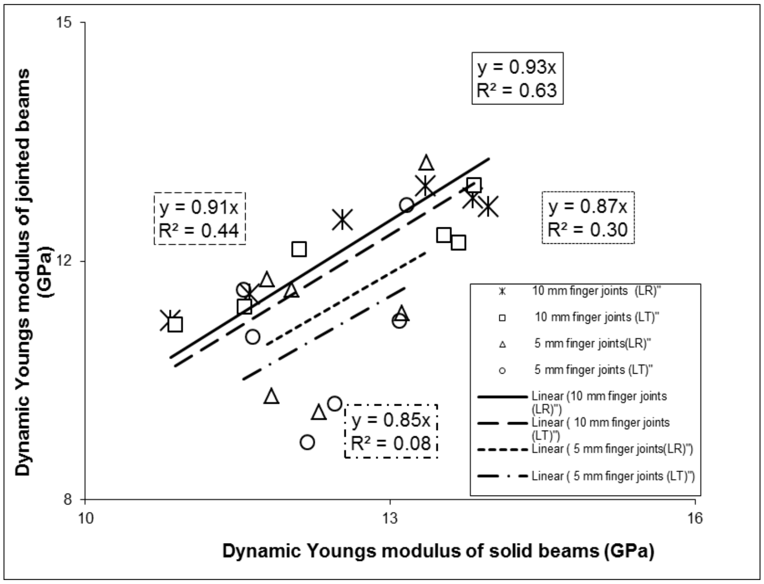

Fig. 4 B. Modulus of elasticity of solid beams and jointed beams with isocyanate adhesive in the LT and LR planes

Analyzing the sound of solid and jointed beams (with isocyanate adhesive), it is clear that the 10-mm joints significantly affected the dynamic Young's modulus, while the modulus lost its significance as the finger length was decreased.

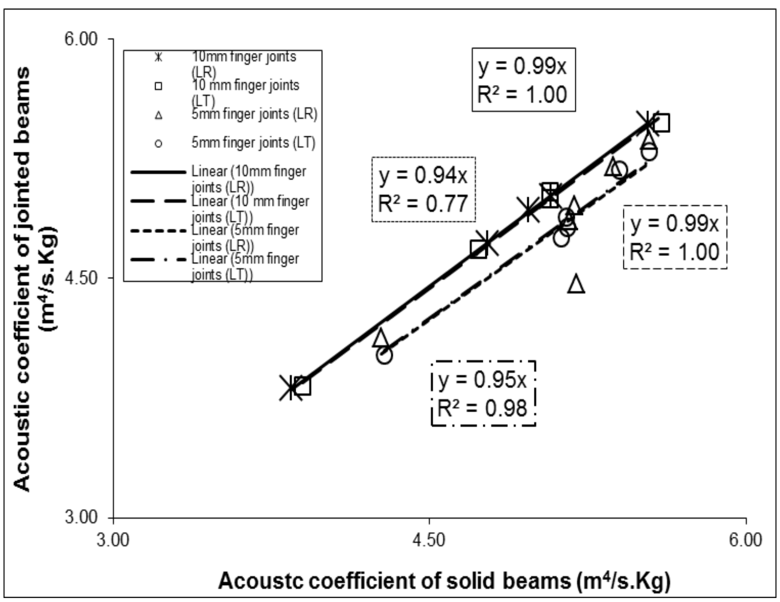

Fig. 5 A[2]. Acoustic coefficient of solid and jointed beams with applied polyvinyl acetate adhesive in the LT and LR planes

[2] As described in methodology, absolutely clear and sound beams, samples with $\Delta LE\%$ higher than 5 were eliminated so there was an overlapping with the dash-dot line in LT and LR planes of vibration (both 10 mm and 5 mm finger jointed beams).

Regarding the acoustic coefficient of solid beams and jointed beams in the LT and LR planes with individually applied polyvinyl acetate adhesive, results showed that in the LT planes of vibration, the acoustic coefficient of all jointed beams were decreased.

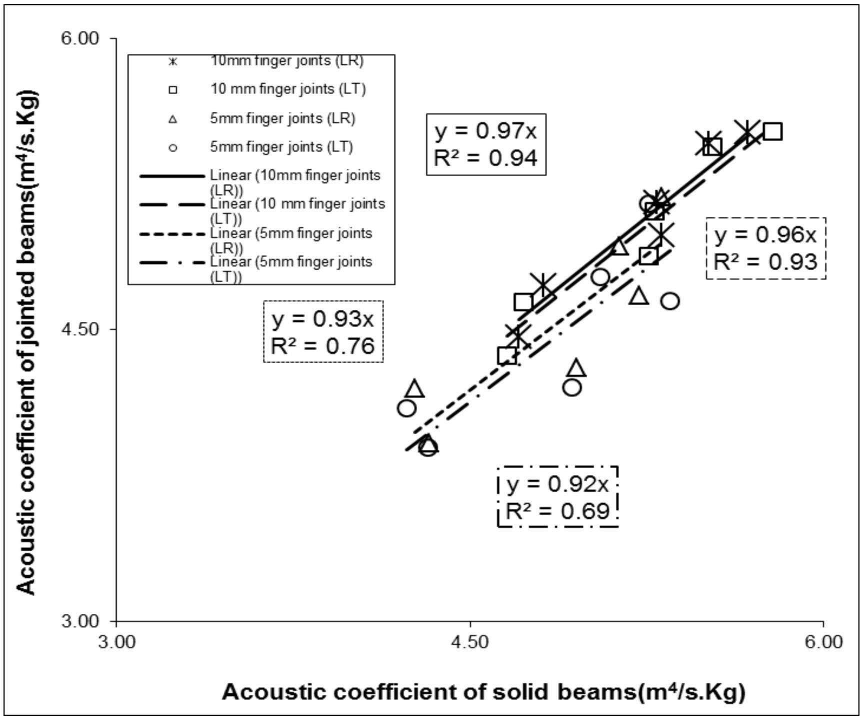

Fig. 5 B. Acoustic coefficient of solid and jointed beams with applied isocyanate adhesive in the LT and LR planes

Analyzing the sound of solid and jointed beams with isocyanate adhesive, both the 10-mm and 5-mm joints significantly affected the acoustic coefficient; moreover, the acoustic coefficient decreased with shorter finger lengths.

As shown in Eq. 2, increasing the elastic modulus and decreasing the density intensified the acoustic coefficient.

In this study, the acoustic coefficient was greatly affected by the finger joints, which may be a result of increasing density. The density of a solid oak beam is approximately 0.75 g/cm^3, while the density in jointed beams can reach 0.81 g/cm^3 (PVA and isocyanate adhesives are much denser than solid oak wood) (Tables 1 through 3).

Table 1. Density Comparison of Jointed and Solid Beams

Material	Solid oak beams	Polyvinyl acetate (adhesive)	Isocyanate (adhesive)	Jointed beams
Density (g/cm^3)	0/75	1/19	1/10	0/81

Table 2. Physical And Chemical Properties of Isocyanate adhesive

Ingredients (w/w)	CAS No.	EINE CS No.	Conc. (%)	Classification
Methylene diphenyl diisocyanate isomers homologues	101-68-8	202-966-0	2.5-4.5%	Xn; R 40-42/43
Benzoyl Chloride	98-88-48	202-710-	2.5-10%	Xi; R 36/38
Form and Colour	Density (water=1)			Solubility
Liquid ,Light brown	1.10 g/mL (10,43 – 10,85 lb/gal)			Not miscible with water

Table 3. Technological Properties of PVA Adhesive

Trade name	Viscosity (M.Pa.s)	pH	Ash ratio (%)
Express 45n	22000	6	48.30%

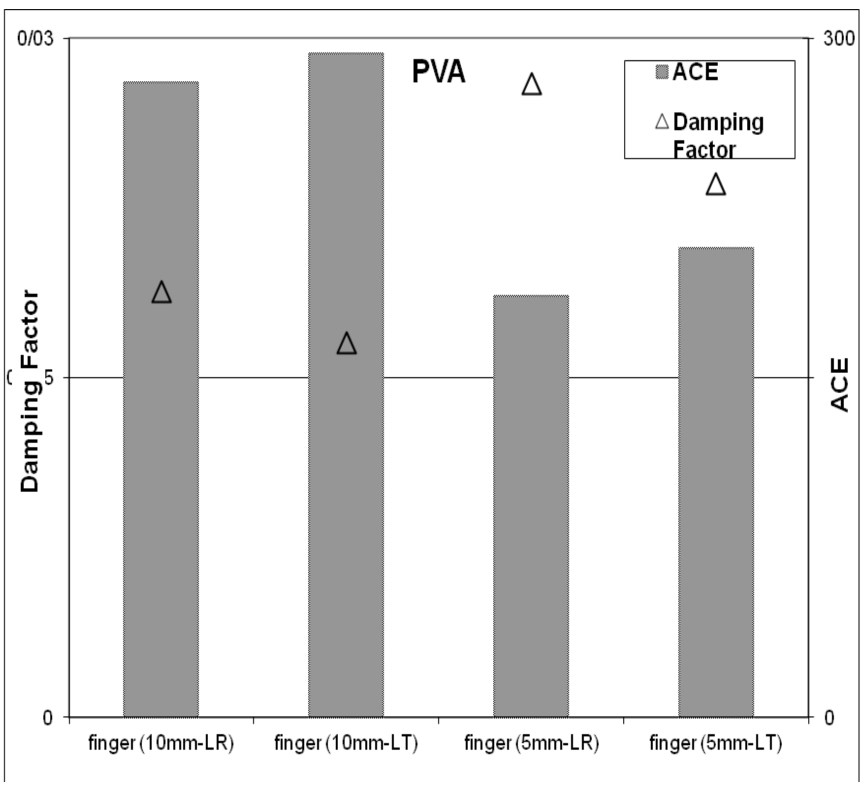

Fig. 6A. Acoustic converting efficiency of solid and jointed beams with polyvinyl acetate adhesive in the LT and LR planes

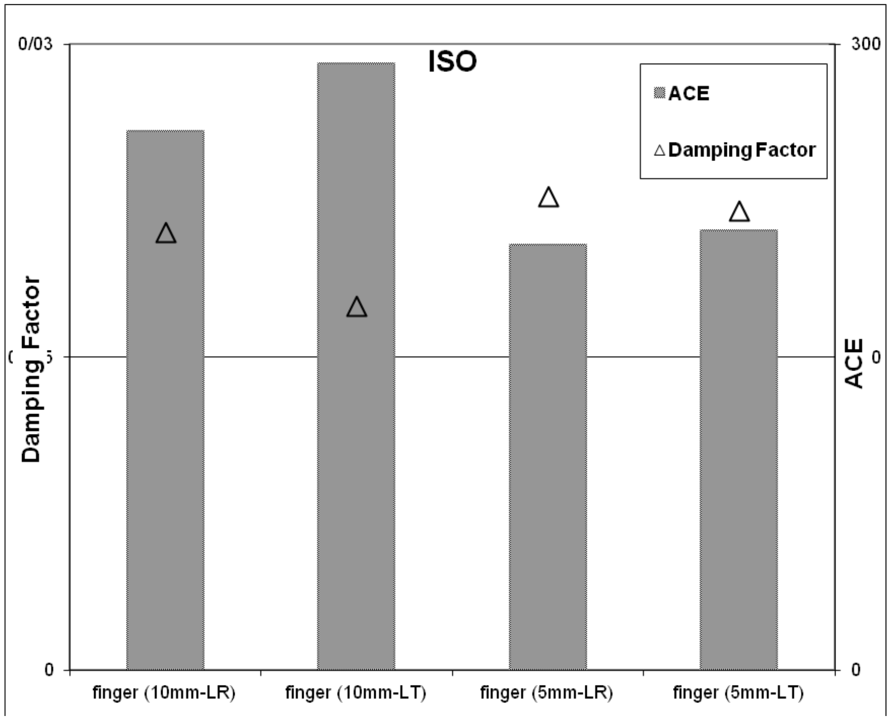

Fig. 6B. Acoustic converting efficiency of solid and jointed beams with isocyanate adhesive in the LT and LR planes

With respect to the acoustic converting efficiency of solid beams and jointed beams in the LT and LR planes, analyzing the sample responses showed that the acoustic converting efficiency of 10-mm finger-jointed beams in the LR plane of vibration decreased; moreover, the acoustic converting efficiency of other finger-jointed beams, including 10-mm (in the LT plane) and 5-mm (in both the LT and LR planes) decreased considerably. As indicated in Figs. 6A and 6B, ACE increased as damping decreased, regardless of adhesive type (ISO or PVA adhesives). In 10-mm finger joints, this amount (ACE) would reach its highest value, which is influenced by acoustic coefficient (*K*) and can be attributed to the tip sharpness in 10-mm finger joints (visible in Fig. 2A and 2B).

CONCLUSIONS

1. Joints with 10-mm finger lengths were found to have better elastic properties than 5-mm finger-jointed beams.
2. Compared with isocyanate adhesive, finger joints with polyvinyl acetate adhesive were found to have better elastic properties.
3. The planes of vibration (LT and LR) did not have a significant effect on the elastic properties of finger-jointed beams; conversely, inefficiency of joints was observed in samples with unequal elastic parameters (as the planes of vibration changed).
4. The elastic properties of finger-jointed beams (with both polyvinyl acetate and isocyanate adhesives) notably decreased compared with those of solid beams.

5. In addition, regardless of the type of adhesive (polyvinyl acetate or isocyanate), based on analysis of the dynamic Young's modulus and the acoustic coefficient efficiency, using 10-mm finger joints in wood and wood resonators can be recommended.

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