

Dynamic Young's Modulus of Scarf- and Finger-Jointed Beams using Longitudinal Vibration Method

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The elastic properties of oak wood (solid wood, scarf-jointed beams, and finger-jointed beams) and two different, independently applied adhesives (polyvinyl acetate and isocyanate) were investigated. Using a longitudinal vibration technique and comparing the elastic modulus of the solid wood and jointed beams, it was revealed that longer fingers (10 mm) in the finger joints and larger angle joints (70° and 75°) in the scarf-jointed beams enhanced the elastic properties of the beams. Based on these findings, it was concluded that these configurations result in elastic properties that are most similar to those of solid wood. The application of polyvinyl acetate rather than isocyanate significantly ($P < 0.05$) improved the elastic properties of the joints (both scarf- and finger-jointed beams).

Keywords: Modulus of elasticity; Scarf joint; Finger joint; Longitudinal vibration; Polyvinyl acetate; Isocyanate

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INTRODUCTION

Since joint fabrication is inevitable in many wood and wood based products, both sound quality and acoustical properties of jointed woods and factors affecting the strength and durability of joints are interesting topics for both producers and consumers. Joint properties can easily be studied with non-destructive testing (NDT) methods, which are very useful methods in this regards and encompass a wide variety of analysis techniques and play an important role in quality assessment. These methods, such as the stress wave method, acoustic emission, and ultrasonic techniques, have been used frequently by the forest products industry, and their utility and accuracy have been extensively studied (Zombori 2001).

In a study by Miao *et al.* (2015), vibration-based methods were successful for examining the attenuation of energy in three different ways (logarithmic average, logarithmic regression slope, and exponential function fitting methods). The results showed that the linear correlations between the various methods were significant in terms of the entire period. The values obtained using the logarithmic average and logarithmic regression slope methods were analogous.

In evaluating the stiffness in finger-jointed timber and conducting various NDT methods, it was found that the dynamic moduli values assessed by applying numerous NDT

techniques (stress wave propagation, transverse vibration, and MSR machine) were positively correlated with three-point static bending measurements (Biechele *et al.* 2010).

Among all NDT methods, the vibration-based technique has been widely used and demonstrated as a successful and reliable method of specifying the mechanical properties of engineered wood products (Roohnia *et al.* 2010). Using a new ultrasonic technique for wood characterization, the power spectral density (PSD) and the phase velocity of the ultrasonic signal methods were shown to be successful for characterizing wood (Maia *et al.* 2014). Nondestructive methods are efficient tools in quality assessment; using vibration methods in the quality control of products, the detection of wood defects and inefficiently bonded layers in composites is possible. In one study, the dynamic Young's moduli of various joint configurations were assessed using two procedures (longitudinal and flexural vibration-based methods) (Roohnia *et al.* 2012). The results showed that vibration-based methods could be considered effective inspection tools for evaluating the mechanical properties of beams.

Finger joints have been considered prominent and valuable (Jokerst 1981); they have been used for many years in the wood industry. The increased yield of usable long parts and clear lumber from low-grade stock are products of these valuable joints. The influence of finger length on the bending strength of finger-jointed, steamed and un-steamed beech wood has been investigated. The samples with the longest fingers (9.0 mm) exhibited the highest MOR values. The steam-treated wood samples had higher MOR values than those of the reference samples (Vassiliou *et al.* 2009). In scarf joint design, cutting angles play an important role in the bending strength features of scarf-jointed European spruce wood. The strength features of small-dimension scarf joints (*Picea excelsa*) were examined. Ten cutting angles (90°, 135°, 140°, 150°, 160°, 170°, 172°, 174°, 176°, and 180°) and two adhesives (a polyvinyl acetate-based D2 type and a polyurethane D4 type) were studied. The 170° cutting angle seemed to yield the most resistant scarf joint, with PVAc glue (Karastergiou and Ntalos 2005). Using the flexural vibration technique, the modulus of elasticity of scarf-jointed wooden beam (*Quercus castaneifolia*) timbers, using two types of adhesives (polyvinyl acetate and isocyanate), was measured. The results showed that specimens joined with higher joint angles (70° and 75°) were extremely reliable in maintaining their original mechanical features (Roohnia *et al.* 2014). The elastic properties of finger-jointed beams (oak wood finger joints with polyvinyl acetate and isocyanate adhesives), including their acoustic coefficient, modulus of elasticity, and acoustic conversion efficiency, were investigated as well. Comparing the elastic properties of the solid beams with those of the finger-jointed beams, the isocyanate adhesive intensely altered the acoustic features of the jointed beams. Beams with longer finger lengths had enhanced acoustic features (Hemmasi *et al.* 2014).

When evaluating the conformity of wood-based panels with a free-vibration procedure on a free-free bar, it was demonstrated that the longitudinal excitation of the panels along their length direction could be used to evaluate the modulus of elasticity. The robust correlations gained from the plate and beam comparisons along the width of the panels were encouraging (Mirbolouk and Roohnia 2014).

In another research study, reliability analysis of adhesive bonded scarf joints based on a three dimensional (3D) finite element analysis (FEA) was conducted and frequently used failure criteria for adhesive joints was studied, according to the results scarf angle and the load were found to be of the crucial factors in evaluating failure possibility (Kimiaceifar *et al.* 2012).

Taking into account the efficiency of three acoustic emission methods to predict the strengths of finger joints, all three acoustic emission features could be applied to non-destructively predict the final tensile and bending strengths of the finger joints. The acoustic emission method seems to be a successful NDT method for predicting the tensile and bending strengths of finger joints (Ayarkwa 2010).

In a study of the rotational stiffness of timber joints by applying vibration methods, it was demonstrated that these vibrations can predict the joint stiffness of both hardwood and softwood (Crovella and Kyanka 2011).

Joints have significant influence on mechanical and acoustical performance of the beams. The present study employs vibrational analyses to evaluate the best elastic performance of the beams and strongest joints with best adhesive performance.

EXPERIMENTAL

To develop joints with accurate designs and the requisite sturdiness, 160 clear samples of *Quercus castaneifolia* (with nominal dimensions of $20 \times 20 \times 360$ mm, $R \times T \times L$) were randomly gathered from a region in Nowshahr, Mazandaran Province, Iran.

The best and finest samples lacking defects were chosen based on ISO 3129 (1975). To ensure absolute purity of the samples, numerous NDT tests were conducted, and the strictest selection technique was carried out based on Timoshenko's trends in terms of the advanced flexural theory, with Pearson correlation coefficients of over 0.99. A reduction in the correlation coefficient value predicts sample inhomogeneity because the Timoshenko model was initially fitted to isotropic materials, or the clearest samples (Bordonné 1989; Brancheriau and Bailleres 2002; Roohnia *et al.* 2011). Samples were conditioned for two weeks (20 °C and 65% relative humidity) until their moisture content was stabilized nominally at 12%.

The joint production was accomplished with a very thin layer of adhesive in the laboratory condition with constant pressure (using grip mechanism for 5 h) until the expected curing was achieved. An additional lateral grip was used to prevent the sliding of the glued surfaces.

Based on the longitudinal modulus obtained from the LR and LT planes of vibration for perfectly clear, sound beams, samples with $\Delta LE\%$ values higher than 5% were omitted (Roohnia *et al.* 2011). As shown in Eq. 1, $\Delta LE\%$ is estimated as,

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

where LE_{LT} and LE_{LR} are the longitudinal modulus of elasticity in the LT and LR flexural vibration measurements, respectively. An NDT-lab® portable system setup (Roohnia *et al.* 2006, 2007) was used to assess the mechanical parameters.

The best samples (17 clear finger joints and 37 sound scarf joints) were categorized into various control groups with two different, independently applied polyvinyl acetate and isocyanate adhesives (Table 1). So, the repeated identical samples for each following treatments were remained equal to 4 or sometimes 5.

Two different lengths of finger joints (5 and 10 mm) joints were developed on the beams' tangential surfaces (exactly at the middle) (Fig. 1-A). Moreover, in the scarf joints,

four different cutting angles (60°, 65°, 70°, and 75°) were developed in the middle of the beams (Fig. 1-B).

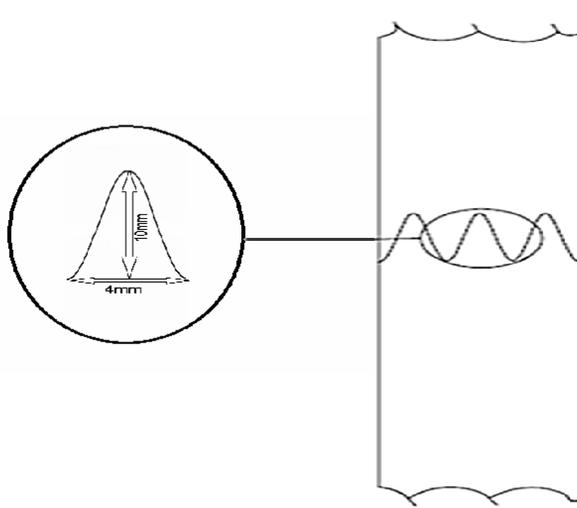


Fig. 1-A. 10-mm finger-jointed beam as an example of finger jointed beams; the joint connection is located precisely at the middle of the beam

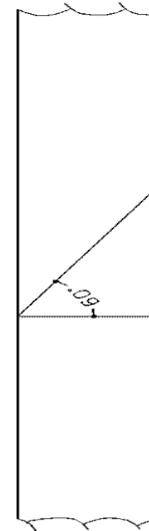


Fig. 1-B. Scarf of 60° as an example of jointed beams at different scarf degrees (scarf joint connections are located exactly in the middle of the beams on the tangential face)

SPSS V16.0 software (IBM, USA) was used. Analysis of variance was used for statistical analysis, and Duncan's test was used to determine the significance of the differences between the results. To obtain the dynamic Young's modulus of oak wood, the longitudinal free vibration with the both-ends free bar technique was conducted. LSTRESS setup (Roohnia *et al.* 2011) provided by the NDT-lab® system (Roohnia 2007) was used (Fig. 2).

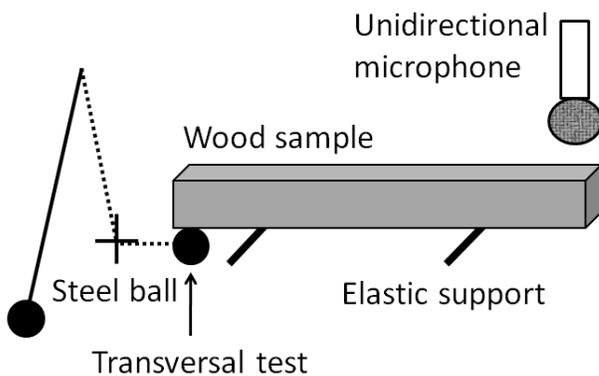


Fig. 2. View of the prismatic beam under flexural vibration

The dynamic Young's modulus was derived from the equation below, where f is the 1st mode frequency of longitudinal vibration, E is the dynamic Young's modulus, ρ is the density, and L is the total length of the bar (36 cm),

$$E = 4 f^2 l^2 \rho \quad (2)$$

where E is the dynamic modulus of elasticity in (Pa), f is frequency of the 1st mode of longitudinal vibration in (Hz), and ρ is density in (kg/m^3). In this study the density of solid oak beam was approximately 0.71 to 0.77 g/cm^3 , and as the result of gluing the density of jointed beams reached as high as 0.81 g/cm^3 . The quantity L is sound traveling distance (specimen length) in (m).

Table 1. Patterns Used for Creation of Scarf and Finger Jointed Beams

Scarf and finger joints							
Isocyanate adhesive				Polyvinyl acetate adhesive			
60° (Scarf joint)	65° (Scarf joint)	70° (Scarf joint)	75° (Scarf joint)	60° (Scarf joint)	65° (Scarf joint)	70° (Scarf joint)	75° (Scarf joint)
5 mm (Finger joint)		10 mm (Finger joint)		5 mm (Finger joint)		10 mm (Finger joint)	

RESULTS AND DISCUSSION

According to previous results with respect to the effects of the joint and adhesive types on the elastic features, as examined with a flexural vibration method (Hemmasi *et al.* 2014; Roohnia *et al.* 2014), it was again demonstrated that there are strong relationships between the joint configuration and elastic modulus and the adhesive type and elastic modulus. Using two different methods, the findings were the same.

To code the numerous samples, initials were used. Table 2 contains a comprehensive description of all acronyms and abbreviations.

Table 2. Abbreviations and Acronyms

Adhesive Type	Joint type	Angle / length
I = Isocyanate	F = Finger	For fingers
P = Polyvinyl acetate	S = Scarf	1 = 10 mm
		2 = 5 mm
		For Scarfs
		1 = 60°, 2 = 65°, 3 = 70°, 4 = 75°

Considering that joint configuration has a significant effect on the mechanical properties of wood (Jokerst 1981; Mohammad 2004) here again confirming previous findings (Herak *et al.* 2009; Hemmasi *et al.* 2014; Roohnia *et al.* 2014), the same trend was observed and scarf joints with the steepest angle (75°) and finger joints with the longest length was found to be strongest joints regarding the MOE values. Thus, the importance of joint configuration was confirmed here again. Joints slope in both finger joints and scarf joints were found to have significant effects (probability values < 0.05 were considered significant) on the elastic modulus. According to these findings, the highest bonding strength was achieved at steeper joint angles, as compared to solid beams.

Equality of the elastic modulus was found at 70° and 75° cutting angles. While the connection surface area decreased, the joint strength significantly decreased and the adhesive strength decreased to a severe degree. Finally, at the 60° cutting angle, the correlation between the NTD and destructive test results lost significance completely, so proper judgment was elusive (Fig. 3).

Comparing scarf joints with finger joints, the advantages of using PVA glue over ISO glue (both in finger joints and scarf joints) were observed. Scrutiny of the figures indicated that in jointed beams (both scarf joints and finger joints), the elastic modulus decreased. The modulus of elasticity of the scarf joints glued with isocyanate adhesive was similar to those glued with polyvinyl acetate. Decreases in the elastic modulus were observed due to reduction of the connection angle in the samples. Identical findings (70° and 75° cutting angles) were obtained with isocyanate adhesive; and because of the insignificance of the correlation coefficient (smaller joint angles, 60° and 65°), a judgment of the joint strength was not possible (Fig. 4).

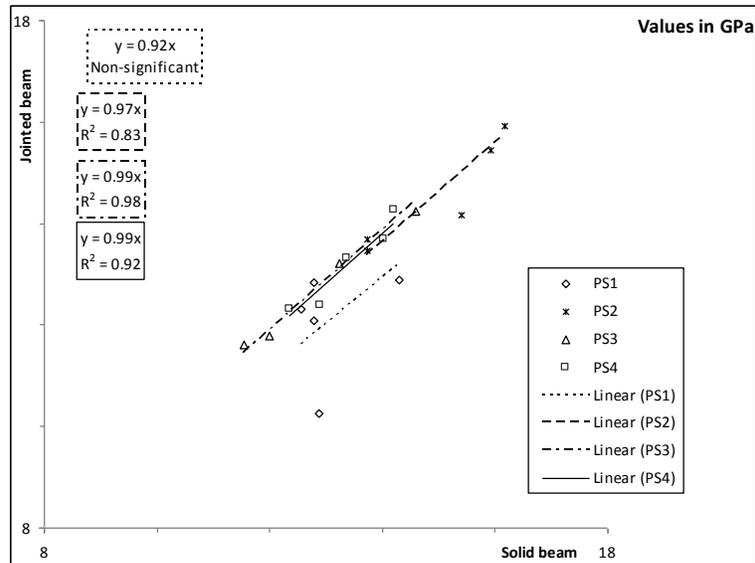


Fig. 3. Dynamic Young's modulus of solid and scarf-jointed beams with polyvinyl acetate adhesive using the longitudinal vibration method

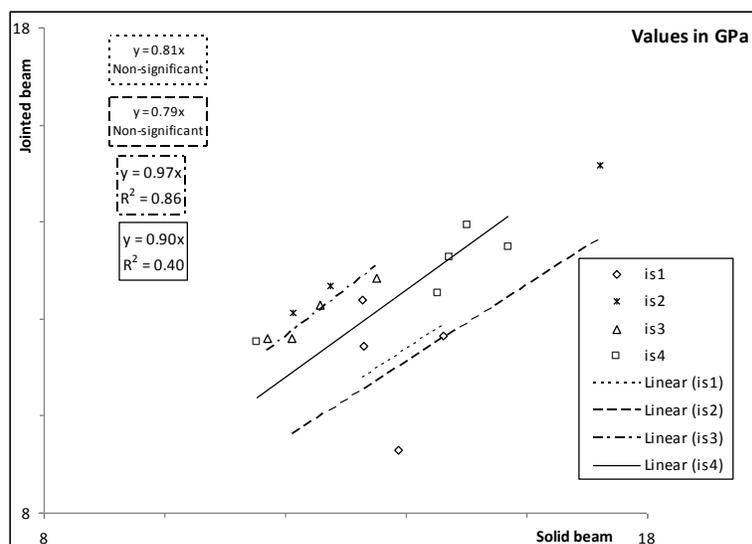


Fig. 4. Dynamic Young's modulus of solid and scarf-jointed beams with isocyanate adhesive using the longitudinal vibration method

Sufficient reasons were not apparent to justify the insignificance of the correlation coefficient, particularly when using the isocyanate adhesive. There were some presumptions that pressing features could have been responsible because the downside to using the isocyanate adhesive is that the cold press was used in this work for both adhesive types.

In addition, beyond the connection surface, which can be accounted for in the joint improvement, the cross-linking of PVA adhesive and its high degree of crystallization provide a great deal of intermolecular interaction and higher MOE than the isocyanate adhesive. This could confirm the feasibility of the high bond strength of scarf joints glued with the PVA adhesive.

Analyzing the elastic modulus of finger-jointed beams with two different finger lengths (5 and 10 mm), glued with each type of adhesive (isocyanate and polyvinyl acetate), showed that the modulus of elasticity of finger-jointed beams decreased.

The highest values for elastic modulus were observed when using longer finger lengths (10 mm) with PVA adhesives, compared to those obtained when using shorter finger joints (Fig. 5).

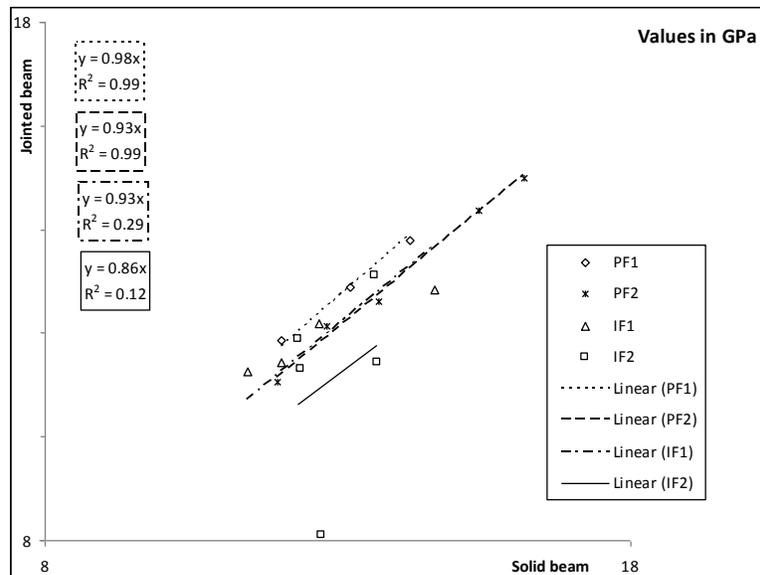


Fig. 5. Dynamic Young's modulus of solid and finger-jointed beams with isocyanate and polyvinyl acetate adhesives, using the longitudinal vibration method

Dynamic Young's modulus data, obtained in previously published flexural vibration studies (Roohnia *et al.* 2014) and data presented in Fig. 6 of this study, shows the coefficients of determination between the two different methods.

Promising R^2 values for the correlations between the results of the flexural and longitudinal vibration methods signify that both methods could be used for MOE determinations in solid or jointed beams.

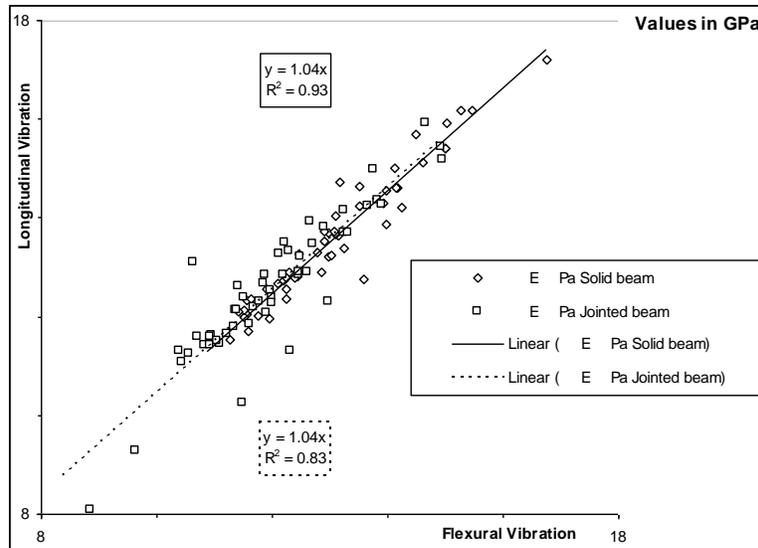


Fig. 6. Coefficients of determination of the correlations between the longitudinal and flexural vibration methods (solid and jointed beams)

CONCLUSIONS

1. Jointed beams (both scarf-jointed and finger-jointed) exhibited explicitly reduced elastic moduli as compared with those of the reference solid beams.
2. When considering the effect of the joints on the Young's modulus (obtained from longitudinal vibration method), joint design was found to be an important parameter affecting the modulus of elasticity of the beams. Longer joints (10-mm finger lengths) had better elastic features than 5-mm finger-jointed beams. In scarf joints, joints with the bonding angle of 75° had the highest Young's modulus.
3. Scarf joints have higher elastic modulus values than those of finger joints.
4. The modulus of elasticity of scarf joints and finger joints glued with isocyanate adhesive was drastically less than those of the reference samples and joints (both scarf- and finger-jointed beams) covered with polyvinyl acetate, and improved the modulus of elasticity significantly.
5. 75° scarf joints and 10-mm finger joints demonstrated the most similarity to their reference solid, clear beams and were found to be the most robust joints.
6. Applying isocyanate adhesive did not provide adequate strength especially to finger-jointed beams with shorter fingers (5 mm) and scarf-jointed beams with smaller joint angles (60 and 65°).
7. The longitudinal vibration technique results correlated very well with flexural vibration method results, proving its reliability and accuracy in evaluating the modulus of elasticity.

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