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ORIGINAL ARTICLE

Modulus of elasticity in scarf-jointed wooden beams: a case study with polyvinyl acetate and isocyanate adhesives

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Abstract In the present study, elastic properties of scarf-jointed oak *(Quercus castaneifolia)* timbers with the application of two different types of adhesives (polyvinyl acetate and isocyanate) were evaluated using free flexural vibration of free–free beam method in different flexural directions of vibration, i.e., tangential and redial directions. Samples were taken from trees of Hyrcanian forests in Iran with nominal dimensions of 20 × 20 × 360 mm^3. Comparing the results of elastic properties of clear oak wood beams with scarf-jointed samples wood showed that scarf joints with the bonding angles of 70° and 75°, covered by polyvinyl acetate adhesive, did not demonstrate any significant effect on modules of elasticity. Scarf-jointed beams with smaller joint angles (60° and 65°) were considerably weaker or totally unreliable in their moduli of elasticity. It is also shown that the magnitude of effect gets worst by using isocyanate rather than polyvinyl acetate adhesive.

Keywords Isocyanate · Modulus of elasticity · Oak · Polyvinyl acetate · Scarf joint

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Introduction

Considering complex and anisotropic but symmetric structure of wood, its mechanical and elastic properties have become foreseeable using nondestructive methods. Nondestructive tests have recently shown great advantages in this regard [1].

Nondestructive methods were also successful to evaluate the mechanical properties of manipulated, modified or defective wood [2, 3]. In the structural performance of finger-jointed black spruce lumber with different joint configurations, tensile strength of various types of end joints were evaluated by Bustos et al. [4]. It was concluded that structural finger-joints must have relatively longer fingers with thin tips compared to non-structural joints and they must be used when joint strength is the primary concern. In general, those connections with feather configurations showed the most effective one compare to male–female and reverse finger-joint configurations.

In finger-joint designs, Mohammad [5] showed that the critical finger profile parameters to achieve high strength were slope and tip sharpness. The tensile strength of finger-jointed lumber is increased with decreasing slope and increasing tip sharpness. Vassiliou et al. [6] measured the most effective connections on the Hungarian oak specimens, regarding the bending strength properties of some finger-jointed oak wooden beams. The increase of finger length from 4 to 10 and 15 mm caused an increase in mean modulus of rapture values. Modulus of elasticity in all the studied joints was not affected by finger jointing and ranged in the same level values of the control solid wood. Using polyvinyl acetate (PVA) for bonding of finger-jointed Beech wood originating from Albania and Greece, the effects of the finger length (4.5, 6.5 and 9.0 mm), and material origination on bending strength of steamed and un-steamed joints were studied by Vassiliou et al. [7]. Obtained results showed that specimens with 9 mm finger length possess higher values of modulus of rapture compared to the specimens with 4.5 and 6.5 mm finger lengths. The steamed wood specimens showed higher modulus of rapture values than the un-steamed ones. During loading capacity determination of the wooden scarf joints, it was found that the scarfs of 60° and 75° are the bests for the adhesion.

Herák et al. [8] carried out laboratory tests of spruce wood bonding using a disperse adhesive (Herkules brand). They confirmed the presumption regarding the suitability of using the scarf joints. All the results of comparing nondestructive methods for assessing mechanical properties of unjointed and finger-jointed lumber showed that lumbers with finger joints have lower bending stiffness than unjointed lumbers [9].

In terms of the effects of joint types on acoustical properties of jointed beams, the results showed that modulus of elasticity was significantly affected by joint types. Finger-jointed beams showed lower dynamic modulus of elasticity and lower acoustic coefficient values compared to solid beams [3]. The effects of joint slopes on bending strength of finger-joint connection, bonded with polyvinyl adhesive were also studied by Ajdinaj and Habibi [10]. Modulus of rupture and modulus of elasticity were measured in this regard. Modulus of rupture increased 10 % with the slope angle of 30° compared to straight finger-joint connection. Modulus of elasticity was not affected by the fingers slope.

Polyvinyl acetate and isocyanate (ISO) adhesives were previously studied for finger joints [11]. Comparing the elastic properties of solid beams with finger-jointed beams of oak wood in both tangential and radial flexural directions, longer finger lengths with PVA adhesive did not cause any serious change to elastic properties of the beams, while shorter finger lengths with ISO adhesive severely changed the acoustic properties. It was also concluded that, a beam having longer finger lengths may have enhanced acoustical properties similar to solid wood.

Martials and methods

In this survey, 80 clear specimens from *Quercus castaneifolia,* (with the nominal dimensions of 20 × 20 × 360 mm^3, R × T × L) were randomly selected from trees of Hyrcanian forest region, north of Iran.

The best and sound samples without any obvious defects were selected in accordance with ISO 3129 international standard [12]. A tighter selection was made based on Timoshenko's trends in advanced flexural theory, highlighted by Bordonné [13], with Pearson correlation coefficients of higher than 0.99. With the decrease in correlation coefficient, the probability for inhomogeneity of samples will increase; where the Timoshenko model has been fitted initially to isotropic materials, or next to the clearest specimens [3]. Absolutely clear and sound beams were chosen by comparing the longitudinal modulus obtained from radial and tangential flexural directions of vibration in a methodology described by Roohnia et al. [3]. Assuming the equality of the longitudinal modulus obtained from LR and LT vibrations for an absolutely clear and sound beam, the observed differences in percentages due to defects was defined as ΔE %. It was demonstrated that a sample with ΔLE >5 % (Eq. 1) can be selected as a homogeny and clear specimen:

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

Here $\mathrm{LE}_{\mathrm{LT}}$ and $\mathrm{LE}_{\mathrm{LR}}$ represent the longitudinal moduli of elasticity obtained in LT and LR flexural vibration tests, respectively.

NDT-lab® portable system setup [14, 15] considering Timoshenko's advanced theory of free flexural vibration of a both-ends free beam [1, 13] was used for evaluating the longitudinal modulus of elasticity from fundamental frequency both in LR and LT flexural excitations.

To simulate the free flexural vibration, the test specimens were placed on a 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 40–12,000 Hz. The sampling rate of sound was 44,100 Hz, with a frequency resolution close to 3 Hz. The three initial modes of vibration were used for Timoshenko's model analyses. The Timoshenko's advanced theory was used since taking into account the effect of shear deflection in consecutive modal frequencies, the shear modulus is also estimated. Although it was not reported here, the shear modulus approach for the studied specimens is still in progress.

After tight selection of the sound beams the 40 of 80 was selected for further experiments. They were categorized in

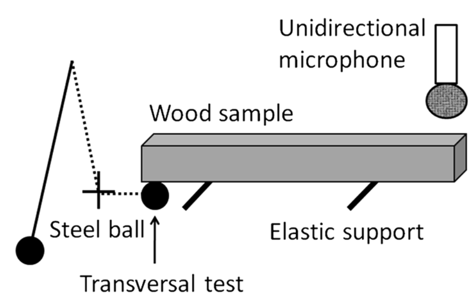


Fig. 1 A beam under flexural vibration

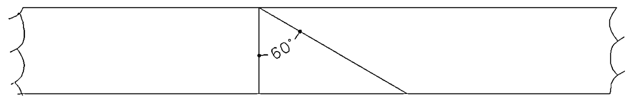


Fig. 2 Scarf of 60° as an example of jointed beams in different scarf angles (scarf-joint connections located exactly in the middle of the beams on tangential face)

4 different controlled pathways (Fig. 2). They were divided into 2 groups of 5 in terms of adhesives; PVA and ISO adhesives were applied individually. The joint production was accomplished in laboratory standard condition (20 ± 1 °C; 65 ± 5 % RH) for 5 h in constant pressure (using a grip mechanism) until the expected curing was achieved. An additional lateral grip was used to prevent the sliding the glued surfaces.

The density of a solid oak beam was approximately 0.75 g/cm^3, while the density in jointed beams can reach 0.81 g/cm^3 (PVA and ISO adhesives are much denser than solid oak wood).

Then the obtained data of longitudinal modulus of elasticity in jointed beams were plotted versus the original solid beams. In plotted data points, shifts of longitudinal moduli of elasticity before and after joinery manipulations were discussed in terms of flexural direction of vibration, i.e., LR or LT, adhesive used and the scarf angle.

A full accidental factorial design was also performed to detect the effect of scarf angle (in five levels of 60, 65, 70, 75 and 0 for original solid beams), adhesive materials (for two types of ISO and PVA) on longitudinal modulus of elasticity.

Results and discussion

At first, the longitudinal modulus of elasticity in LT versus LR directions for both jointed specimens and solid samples were plotted. As the solid beam samples had been selected in a tight procedure to ensure the clearness, the equality of the results of both flexural directions of vibration was confirmed considering the convergence of the data points near the fitted trend line with $R^2 = 0.93$ (square data points in Fig. 3). After the manipulation of the specimens in cutting and jointing scenario, the data points were more far away from the trend line with $R^2 = 0.88$; however, the equality of the results of two perpendicular flexural directions of vibration totally was still controlled in terms of longitudinal modulus of elasticity, while the fitted trend-line slope remained unchanged. (Heed is needed for the coincidence of two different trend lines in a similar slope.)

The data points being far away from trend of equality might be caused by manipulation of the specimens (triangle data points in Fig. 3).

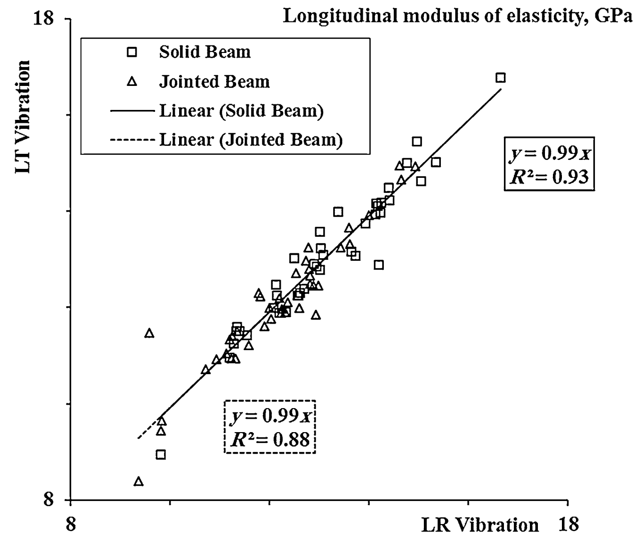


Fig. 3 Relative equality of the longitudinal moduli of elasticity obtained from LR and LT flexural vibration in jointed and original solid beams

As the specimens were cut in 60° and scarf jointed, the results of longitudinal moduli of elasticity (Fig. 4) were not statistically comparable to those of solid beams for both flexural directions of vibration (i.e., LR or LT) and adhesive used (i.e., PVA or ISO). In this case there was no significant Pearson correlation between the vertical and horizontal axis of the chart. However, there seems to be a promising preference of PVA compared to ISO adhesive. This hypothesis was reinforced in 65° scarf-jointed beams (Fig. 5).

In 65° scarf-jointed beams, longitudinal moduli of elasticity were a bit weaker both in LR or LT flexural vibration tests while using PVA adhesive; however, the decrease in longitudinal modulus of elasticity was statistically non-significant. ISO adhesive in 65° scarf-jointed beams did not show any statistically significant correlation between jointed versus original solid beams.

In 70° scarf-jointed beams (Fig. 6), there were significant correlations between jointed versus original solid beams for both PVA and ISO adhesives, suggesting a relative equality of the results.

Again the relative equality trend fades in its value in the 75° scarf-jointed beams while using ISO as the bonding adhesive. PVA adhesive for 75° scarf-jointed beams is still considered as suitable glue to keep the original longitudinal modulus of elasticity (Fig. 7). We have no idea regarding the reason behind the non-similarity of the modulus of elasticity results when using ISO adhesive in Figs. 4, 5, 6 and 7; supposing it not to be accidental, one can recognize an obvious decrease in modulus of elasticity. It would be enough to judge the preference of PVA over ISO adhesive. All the parameters were kept constant during the

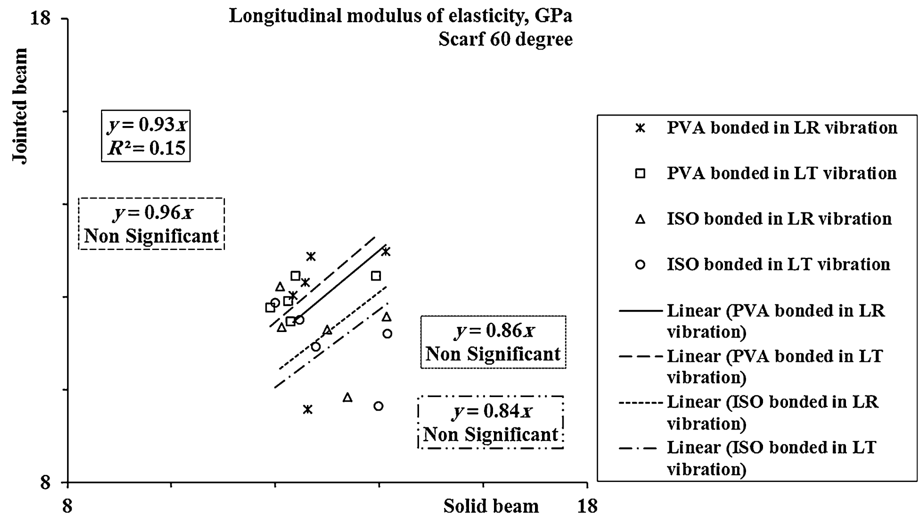


Fig. 4 Longitudinal moduli of elasticity obtained from LR and LT flexural vibration in 60° scarf-jointed versus their original solid beams using polyvinyl acetate (PVA) and isocyanate (ISO) adhesives

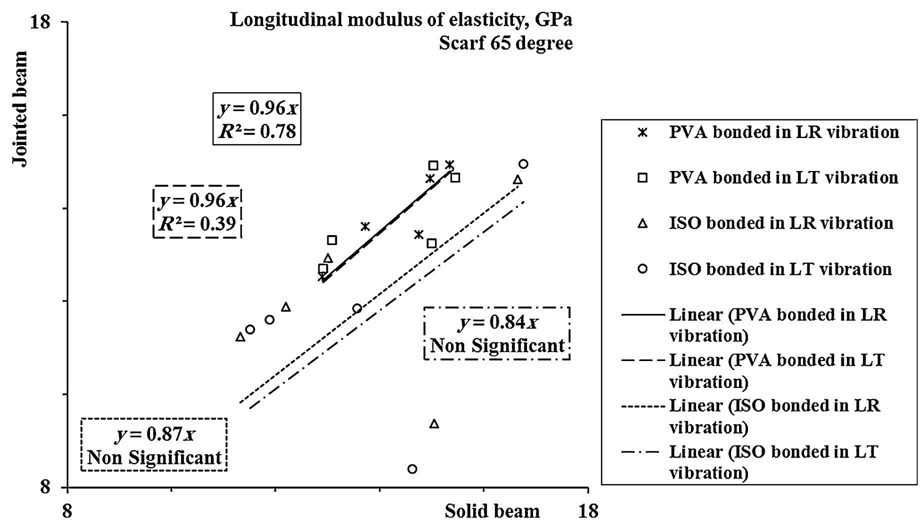


Fig. 5 Longitudinal moduli of elasticity obtained from LR and LT flexural vibration in 65° scarf-jointed versus their original solid beams using polyvinyl acetate (PVA) and isocyanate (ISO) adhesives

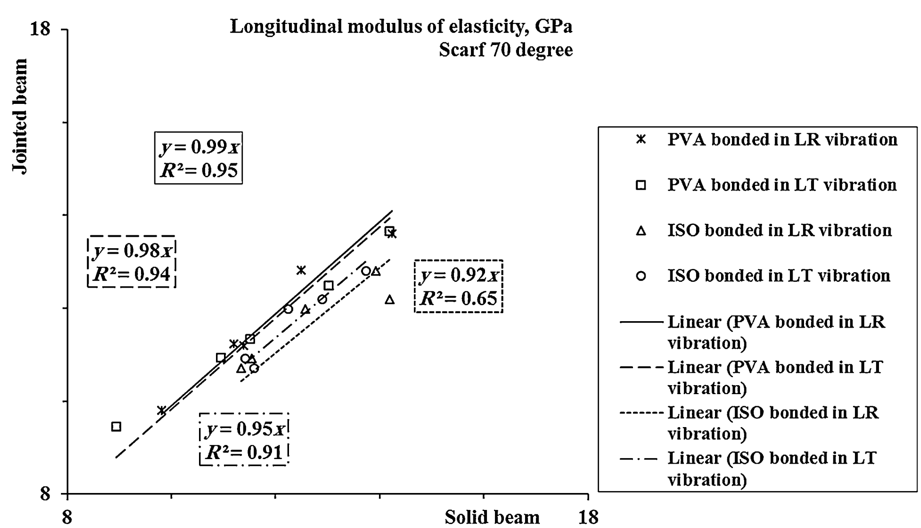
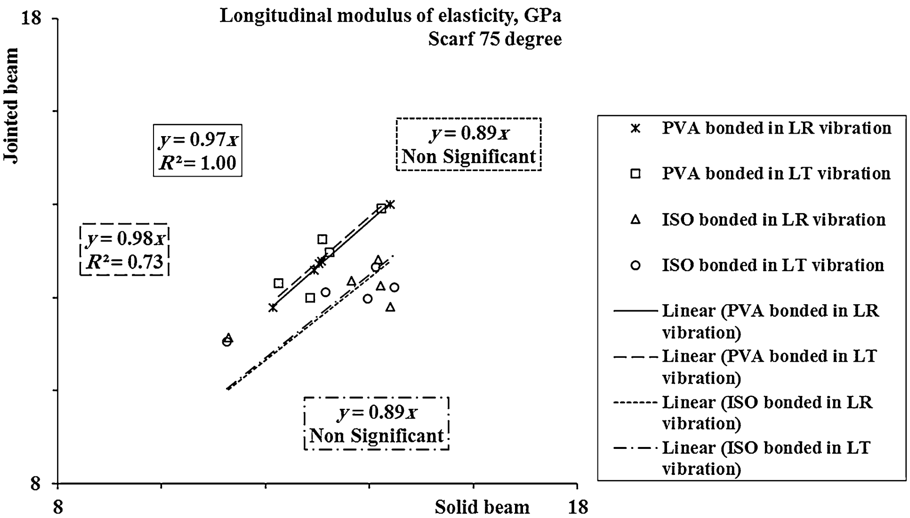


Fig. 6 Longitudinal moduli of elasticity obtained from LR and LT flexural vibration in 70° scarf-jointed versus their original solid beams using polyvinyl acetate (PVA) and isocyanate (ISO) adhesives

Fig. 7 Longitudinal moduli of elasticity obtained from LR and LT flexural vibration in 75° scarf-jointed versus their original solid beams using polyvinyl acetate (PVA) and isocyanate (ISO) adhesives



experiments on ISO adhesive except that of the adhesive spread area. As the angels of connection increase (from 60 to 75°), the surface of connection increases and subsequently the amount of used adhesives will increase too, and logically this would lead to change in bonding quality. Any justification might be related to this variable.

To test the significance of the observed shifts in longitudinal moduli of elasticity before and after cutting and jointing the beams, a full accidental factorial design was performed to statistically analyze of the effects of scarf angle and adhesive used in joints. It was statistically revealed that adhesive type was a significant and effective factor to change the longitudinal moduli of elasticity in manipulated beams, while the effect of scarf angle was not significant.

Regarding the above discussion, it is suggested to study the performance of joints in different temperatures and on firing conditions. It would be interesting to study more different scarf angles (40°, 45°, 80° and 85°) with different types of natural or synthetic adhesives and resins. It is also suggested to study and compare the effect of joints in solid wood samples and structural wood-based materials (e.g., wood plastic composites or wood panels where scarf joints are applied).

Conclusions

The influence of different joint configurations on the mechanical properties of wooden beams has been in the focus of attention since using various types of connections are mandatory in some applications and structures, e.g., resonators. So, monitoring the changes in mechanical properties of joints seems to be important.

Considering different types of joints and two types of applied adhesives, the following results obtained:

- In scarf joints (all four scarf angles) elastic properties of beams remained constant or sometimes decreased compared to their original solid clear beams.
- Escalating trend of elastic modulus was much more considerable and obvious in radial direction of vibration.
- Samples with PVA as the applied adhesive for the scarf joints, showed better modulus of elasticity.
- Scarf-jointed beams with higher angels of joints (70° and 75° angles) are considerably more reliable in keeping the mechanical properties of original solid beams.
- The best performance in the studied interval of joints (comparable with clear beams) was detected at 75° scarf joints.
- Regardless of the joint type, different applied adhesives proved to be an important factor affecting the mechanical performance of the beams.

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