Dynamic Modulus of Wood Containing Water-Resistant Glue Finger Joint after Severe Steaming

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The effect of steaming treatment on the dynamic modulus of oak wood (*Quercus castaneifolia,* C. A. Mey.; Fagaceae) containing a water resistant glue-finger joint was investigated. Sample joints were made with two different types of waterproof adhesives, polyurethane (PU) and epoxy, and the samples were tested by a free flexural vibration method according to flexural and longitudinal free vibration modes. Compared with the epoxy joints, the PU finger-joints retained elastic moduli closer to their initial values. In all three vibration tests, finger-jointed oak wood specimens with either glue retained their moduli of elasticity, after the steaming treatments. In the case of longitudinal-tangential (LT) vibration, some increases were observed for the evaluated elastic moduli. After steaming, the obtained dynamic values decreased. For epoxy-bonded specimens, the correlation coefficient in terms of the elastic modulus before and after steaming were weak. There were some acceptable PU-bonded specimens, but there was a considerable decrease after steaming.

Keywords: Elastic modulus; Finger joint; Polyurethane; Epoxy; Vibration; Flexural; Stress wave

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INTRODUCTION

Water-resistant wood adhesives are used in joineries, carpentries, musical instruments, and outdoor applications where the relative humidity may be high. The water resistance is always a function of duration and temperature in natural or artificial weathering. To be able to effectively test and classify the resistances of different joint types and adhesives, it would not be practical to rely on ambient outdoor conditions due to the slow effects on the testing material. Thus, accelerated exposures are developed for rapid assessments.

Joints and their strengths have been studied using static and dynamic test methods. Tran *et al.* (2014) presented experimental and numerical finite element results on the mechanical behavior of beech timber finger-joints. The finger length, the pitch, and the tip gap were the optimized design variables, and the finger-joint resistance was increased by optimizing its geometry. Kohantorabi *et al.* (2011) examined the effects of different joint types on acoustical properties of the jointed beams. Yavari and Roohnia (2015) studied the joints in terms of the adhesives and the joint types, reporting that the greatest moduli of elasticity occur in finger joints with longer finger lengths and that polyvinyl acetate is a better adhesive than isocyanate glue. In the case of longitudinal finger-jointing wood elements, Obucina *et al.* (2014) studied the influence of layers on the bending strength.

They confirmed the assumption that an excessive increase in the quantity of adhesive impairs the joint strength.

Among the dynamic assessments used in wood and wood-based panels, vibration-based nondestructive tests are the predominant methodology. Roohnia *et al.* (2011) studied the effect of wood beam heterogeneity in shapes of manually drilled holes in controlled orientations and widths. They introduced the *ΔLE%* index to measure differences in evaluated moduli in different vibrational planes and directions and to comment on the clarity of the specimen. Divos and Tanaka (2005) studied the relationship between static and dynamic modulus of elasticity, establishing that greater creep effects are manifested at higher test speeds, and that this falsely increases the elastic moduli values. With or without drilled holes of different diameters, some elastic properties of 13 rectangular clear bars of poplar wood were examined in a "free vibration of a free-free bar" method by Yavari *et al.* (2010). Hossein *et al.* (2011) investigated the influence of knots on modulus of elasticity and on vibration damping factor, using free vibration on a free-free bar method, in comparison with the static bending values of the moduli of elasticity. Pirayeshfar *et al.* (2014) compared a new carbon fiber/epoxy composite with wood in musical instruments using the free vibration on a free-free beam method.

Waterproof adhesives in commercial advertisements are not actually anti-humidity remedies. Their ability to resist water is affected by external parameters, *i.e.*, temperature, air-pressure, duration, *etc*. Wood vibrational behavior in humidity conditions has been studied previously. Kamoun *et al.* (1998) examined the effect of humidity on cross-linked and entanglement networking of formaldehyde-based wood adhesives. Mohebby *et al.* (2007) investigated hydrothermal modifications and vibrational properties of mulberry wood, revealing an increase in specific Young's modulus and quality factor but no significant effect on tan δ. Water absorption and swelling were reduced by the hydrothermal treatment, which also slightly reduced acoustic converting efficiency (ACE). The effects of the finger length and material origination on bending strength of finger-jointed steamed and un-steamed beech wood were studied by Vassiliou *et al.* (2009). The specimens with longer fingers showed higher MOR values in both steamed and un-steamed materials, for both their studied originations in Albania and Greece.

In commercial waterproof adhesives, epoxy systems consist of two components—epoxy resin and the curing agent, or hardener—that react to form a hard inert material. Urethane resins are either aliphatic, aromatic, or a combination of each. Aliphatic resins have a straight chain of carbons (*i.e.*, linear) in the backbone, for example, polyethylene.

The objective of this study was to justify the stability of the mechanical characteristics of the water resistant jointed wooden beams against a sever steaming. The dynamic longitudinal modulus of elasticity values of finger-jointed wooden beams were obtained in longitudinal and flexural free vibrations of a free-free rectangular beam. The jointed specimen quality for both above introduced adhesives, before and after severe steaming were also evaluated with regard to the "*ΔLE%*" parameter.

As it is previously introduced by Roohnia *et al.* (2011), to ensure the clarity of the specimens, the Δ*LE%* index was evaluated (Eq. 1),

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

where LE_{LT} and LE_{LR} represent the longitudinal modulus of elasticity obtained in LT (longitudinal-tangential) and LR (longitudinal-radial) flexural vibration tests, respectively.

Some theories and practical applications were introduced in previous literature. According to Bordonné's solution (1989) for Timoshenko's advanced theory of flexural vibration, the longitudinal modulus of elasticity (E) is determined using the following linear regression,

$$y_n = \left(\frac{E}{\rho}\right) - \left(\frac{E}{K \times G_{ij}}\right)x_n \text{, } R^2 \geq 0.98 \tag{2}$$

$$x_n = \frac{4\pi^2 l^2 f_n^2 F_{2n}}{X_n} \tag{3}$$

$$y_n = \frac{[4\pi^2 l^2 f_n^2 (1 + \alpha F_{1n})]}{\alpha X_n} \tag{4}$$

$$X_n = m_n^4 \tag{5}$$

$$\alpha = \frac{I}{Al^2} \tag{6}$$

where I is the moment of inertia (m^4), A is the cross-sectional area (m^2), l is length of the specimen (m), K is the shape coefficient (the value of 5/6 can be used for a rectangular cross-section), G_{ij} is shear modulus in vibration plane (Pa; G_{LT} or G_{LR} is not discussed here), ρ is the specific gravity (Kg.m^{-3}), f_n is the frequency of the n$^{\mathrm{th}}$ mode of vibration obtained from FFT spectrum (Hz), and m_n is the n$^{\mathrm{th}}$ result from the following equation (Bodig an Jayne 1982):

$$\cos(m_n).\cosh(m_n) = 1 \tag{7}$$

In Eq. 3 and Eq. 4, F_{1k} and F_{2k} can be calculated as follows:

$$F_{1k} = \Theta^2(m_k) + 6\Theta(m_k) \tag{8}$$

$$F_{2k} = \Theta^2(m_k) - 2\Theta(m_k) \tag{9}$$

$$\Theta_{(m_k)} = \frac{[m_k \tan(m_k)\tanh(m_k)]}{[\tan(m_k) - \tanh(m_k)]} \tag{10}$$

In addition to the flexural vibration, the longitudinal stress wave velocity (V) was also evaluated in longitudinal vibration from wavelength (λ) and the 1st modal frequency (f), as follows:

$$V = \lambda f \tag{11}$$

The longitudinal dynamic modulus of elasticity (E, Pa) is calculated through Eq. 11 from velocity (V, m.s^{-1}) and density (ρ, Kg.m^{-3}):

$$E = \rho V^2 \tag{12}$$

EXPERIMENTAL

Materials and Preparation

In accordance with the ISO 3129 (2012) standard, 23 pieces of visually clear specimens of chestnut-leaved oak (*Quercus castaneifolia*, C. A. Mey.; *Fagaceae*) (Panahi *et al.* 2011) with the nominal dimensions of 20 × 20 × 360 mm (radial × tangential × longitudinal) were stabilized at 65 ± 5% relative humidity and 20 ± 1 °C. The average density of the specimens was 789±55 $Kg.m^{-3}$. The samples were made from the mature wood where the average annual ring-width was 3.1±0.4 mm. The specimens were visually straight grain and clear.

Samples with $\Delta LE\%$ (Eq. 1) higher than 5 were eliminated; only 17 absolutely sound and clear specimens remained. The longitudinal modulus of elasticity through LT or LR flexural vibrations were obtained according to the advanced flexural vibration theorem (Timoshenko 1921), while the coefficients of determination in modal decreasing line slope model in Bordonné's solution remained greater than 0.99 for all specimens (Bordonné 1989; Roohnia *et al.* 2011).

After assessing the clear samples (without joint), every specimen was divided into two pieces and re-assembled by a finger joint, as previously described (Hemmasi *et al.* 2014). The length of the fingers was 10 mm, the pitch 4 mm, and the total number of fingers was three in every joint member across the joint width (Fig.1). Using sharp blades (Laguna Tools®, Irvine, USA), the preliminary solid wood was carefully cut to obtain similar and even joint plane surfaces. The separated members were re-assembled; the length of the beams was not significantly reduced during joint preparation. Therefore, the effect of rotary inertia and shear deflection on the evaluated Young's modulus was not relevant.

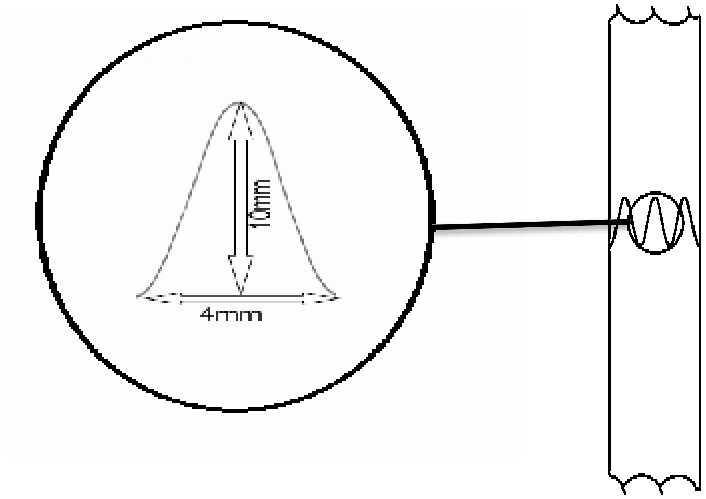

Fig. 1. The 10 mm finger joint was located precisely at the middle of the bars on the radial surface.

Two different glues, a two-componential epoxy and an aromatic polyurethane (PU), were used in the finger joints. The choice of these two adhesives was due to their successive applications in Iranian joineries and the Iranian traditional musical instrument making, where the humidity resistance is important. Both the adhesives were made in Iran (by Jalasanj Company) for water resistant outdoor applications. Eight epoxy samples and nine PU samples were prepared. The concentration of the resin was 1.2 g/cm^3 and 1.1 g/mL for epoxy and polyurethane, respectively. Both adhesives were cured 24 h at 20 °C. The best application temperature range was introduced as -40 to 80 °C for epoxy and -30 to 100 °C for polyurethane by the producer. For both sample sets, 0.5 g of glue was applied equally to both joint faces.

The jointed specimens were exposed to humidity in an autoclave with saturated vapor at 120 °C and 120 kPa for 2 h. Both sets were sensitive to the severe condition; however, high temperature and pressure were used to accelerate the effect of steaming. The specimens were stabilized and subjected to the vibration test before and after steaming to determine the longitudinal dynamic moduli of elasticity.

Dynamic Test

Vibration-based nondestructive testing was used to evaluate the dynamic longitudinal modulus of elasticity through flexural and longitudinal free vibration of a free-free end beam. The specimen leans on soft thin rubber on its nodal points and is excited or recorded on its antinodes (Fig. 2). The node of the longitudinal vibration is at the middle, but the flexural mode is near the ends. For example, the nodal points for the 1st mode of the free flexural vibration of a free-free end beam are located at 0.224 × length from each end (Harris and Piersol 2002).

The beam was excited by a light spherical steel pendulum (mass: 57 g; diameter: 23.97 mm) on an end, while the sound was recorded on the other end by a unidirectional microphone. The sampling frequency was set to 44100 ± 3 Hz. The attenuation of sound was plotted in terms of time (s), amplitude (dB), and frequency (Hz) (Z, Y, and X coordinates, respectively). The fast Fourier transform spectrum was applied to obtain the modal frequencies. In flexural vibration, the frequencies of the three initial flexural modes were used to evaluate the dynamic longitudinal modulus of elasticity in the advanced model of flexural vibration (Timoshenko 1921).

However, Bernoulli's elementary theory was sufficiently appropriate for evaluating the elastic modulus from the transversal vibration test, but the coefficient of determination in Timoshenko's model as a critical clearness index was preferred (Eqs. 2 to 10). This parameter was also re-evaluated in a longitudinal vibration test (Eqs.11 and 12).

The longitudinal moduli of elasticity of specimens from the flexural (LR and LT) or longitudinal vibration tests before and after manipulations were plotted (jointing and steaming). These values were compared to those of clear specimens. The clarity of the jointed (virgin or steamed) specimens was judged based on their $\Delta LE\%$ values (Eq. 1). Changes in Timoshenko's coefficient of determination (Eq. 2) were monitored for every individual test sample.

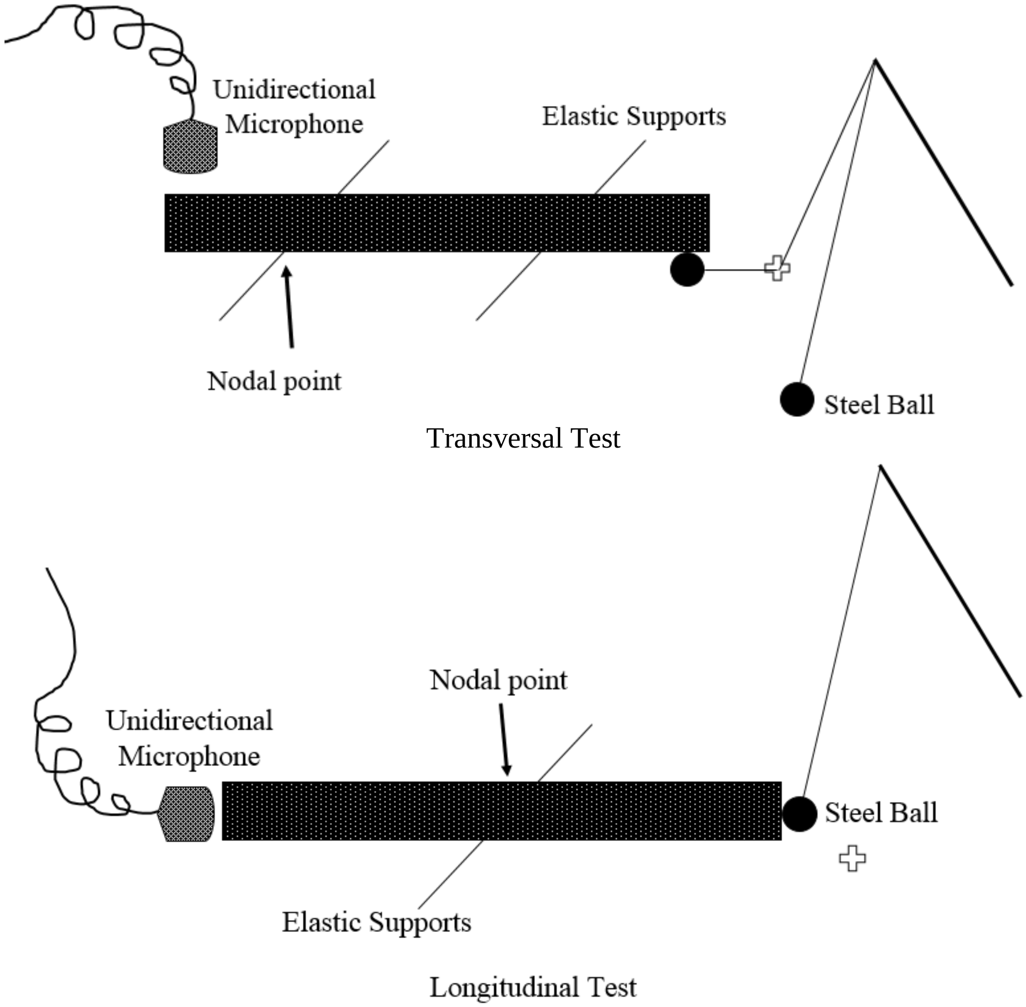

Fig. 2. Experimental setup of flexural (upper) and longitudinal (nether) free vibration test

RESULTS AND DISCUSSION

The Δ*LE%* indexes for epoxy and polyurethane samples before and after joining and steaming are shown in Figs. 3 and 4, respectively. Most epoxy-bonded specimens lost their clarity even before steaming. None of the jointed-virgin and jointed-steamed specimens were comparable to the unaltered controls after jointing and steaming. For polyurethane bonding, there were better results. Only three jointed specimens showed clarity indexes greater than 5%. After severe steaming, there were still a few acceptable specimens. The modulus of elasticity determined by the flexural LR and LT vibration tests are shown in Figs. 5 and 6, respectively.

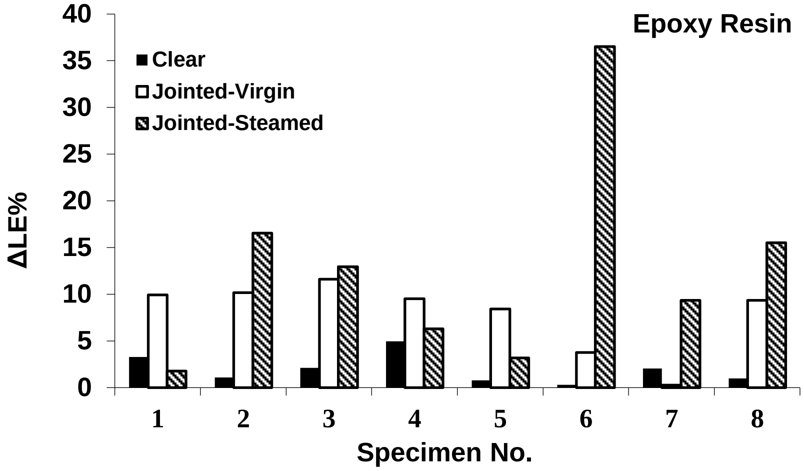

Fig. 3. The clarity index (Δ*LE%*) for epoxy-bonded specimens before and after manipulations

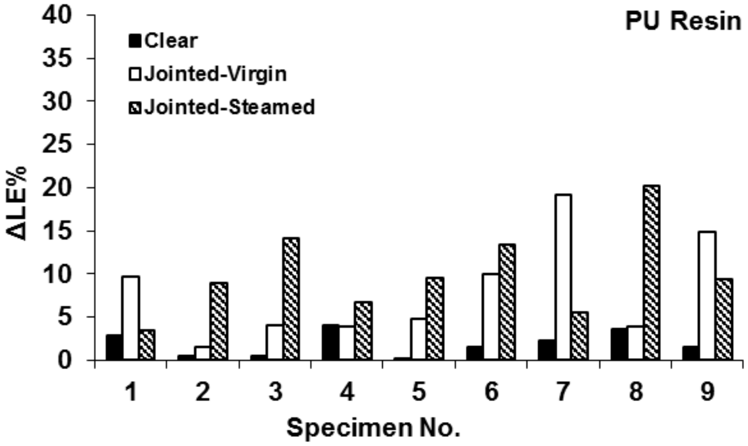

Fig. 4. The clarity index (Δ*LE%*) for polyurethane-bonded specimens before and after manipulations

Based on the concepts described by Roohnia *et al.* (2011) and considering the advanced theory of flexural vibration introduced by Timoshenko (1921) and Bordonné (1989), the longitudinal dynamic values of modulus of elasticity evaluated through LT or LR flexural vibrations must be theoretically the same. The factors that might affect this theory are shear deflection and rotary inertia variations due to the dimensional variations in height and width of the cross-section in different flexural planes of vibration. Local or global heterogeneities that coincide with the flexural nodes or antinodes also cause discrepancies.

Figures 5 and 6 show that for the initial clear specimens, the values obtained from both LR and LT flexural tests were similar. This was expected because they have been chosen by this criteria as previously introduced in the Materials section.

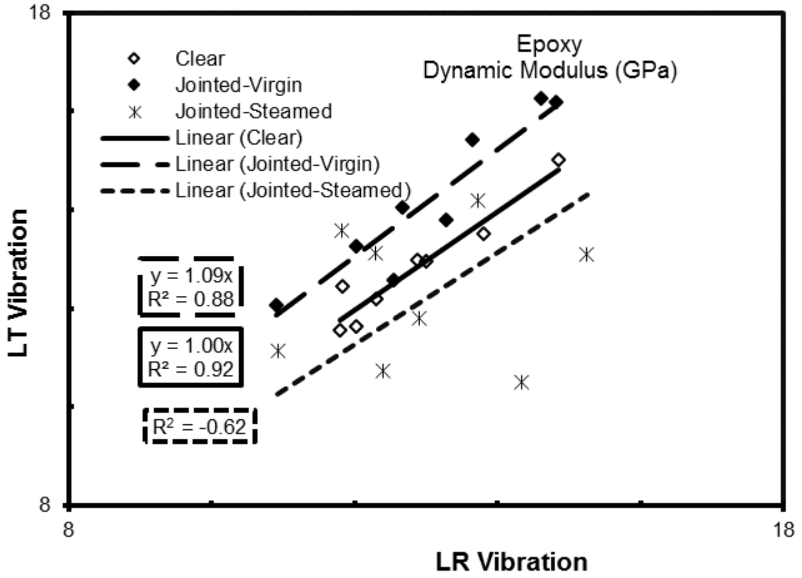

Fig. 5. LT *vs*. LR flexural vibration before and after jointing and steaming of epoxy-bonded specimens

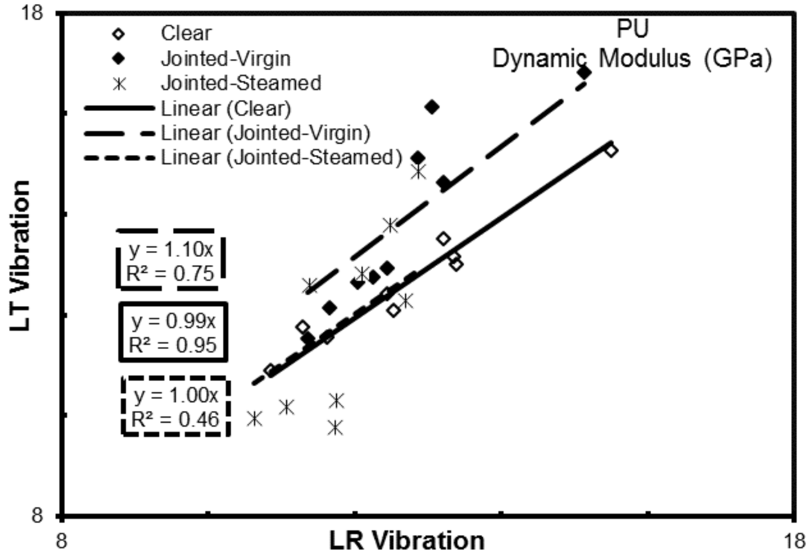

Fig. 6. LT *vs*. LR flexural vibration before and after jointing and steaming of PU-bonded specimens

The LT flexural vibration test produced slightly higher values (9% and 10% in Figs. 5 and 6, respectively) for the modulus of elasticity of the jointed beams. As this phenomenon was similar for both adhesives, it might be attributed to the finger joint orientation in radial and tangential directions. The correlation coefficient between the results obtained in LT and LR vibration tests is decreased. After steaming no significant correlation coefficient was considered for the steamed specimens within the epoxy collection. Thus, finger joints with polyurethane glue were stronger.

Figures 7 to 10 show the step-wise jointing and steaming in terms of the obtained moduli of elasticity separately for the epoxy and the polyurethane bonding.

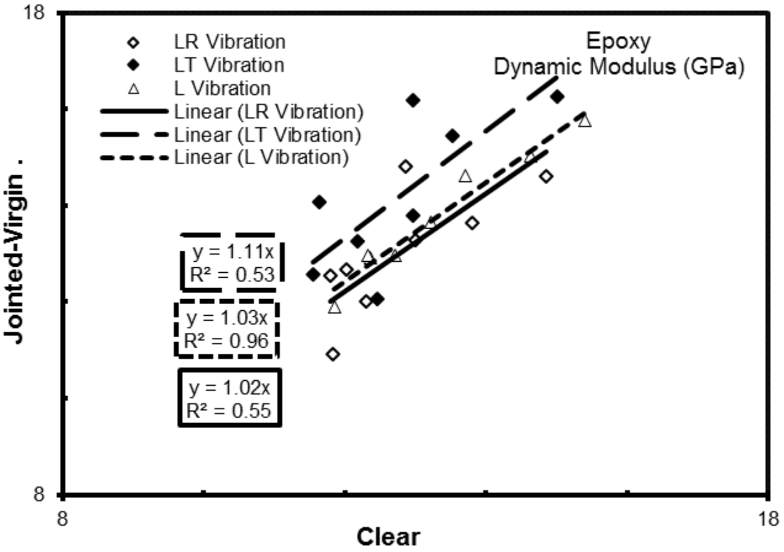

Fig. 7. Epoxy-jointed specimens before steaming *vs*. initial clear un-jointed specimens

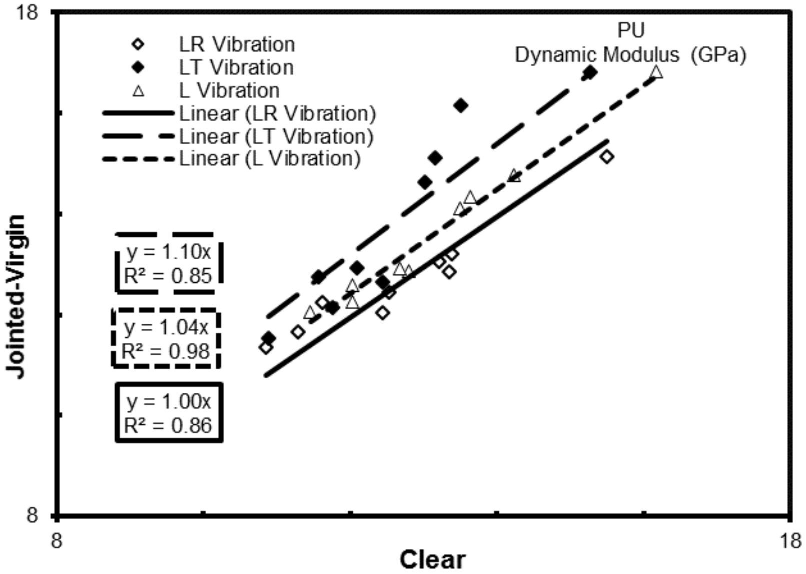

Fig. 8. Polyurethane-jointed specimens before steaming *vs*. initial clear un-jointed specimens

The goal was to find out that what happened to the moduli of elasticity of the jointed steamed specimens during the introduced manipulation steps. Both the flexural (LT and LR) and longitudinal vibration are demonstrated.

In all three vibration tests, finger-jointed oak wood specimens maintained their moduli of elasticity with both glues. For LT vibration, some increases were observed for the elastic moduli. After steaming, the obtained dynamic value decreased. There was no noticeable difference in epoxy-bonded specimens after steaming. There were some acceptable specimens within the polyurethane-bonded set; however, there was a significant decrease in the steamed *versus* jointed-virgin values.

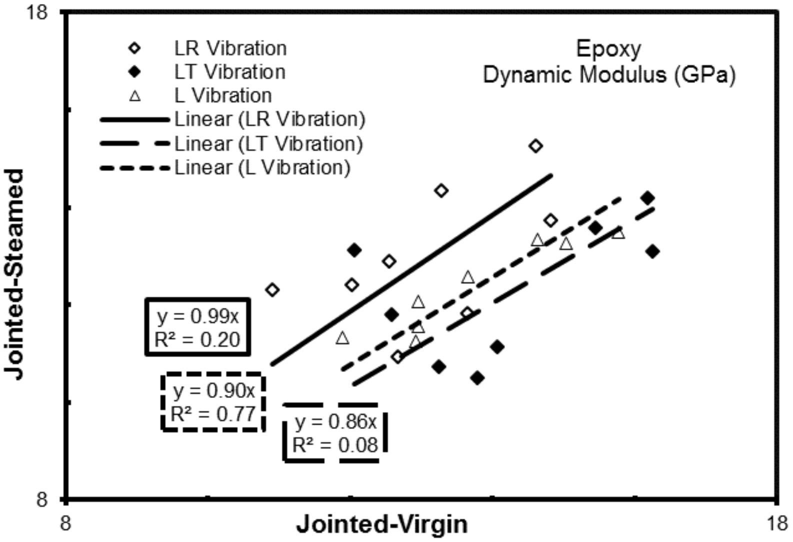

Fig. 9. Epoxy jointed specimens after steaming *vs*. the jointed-virgin specimens

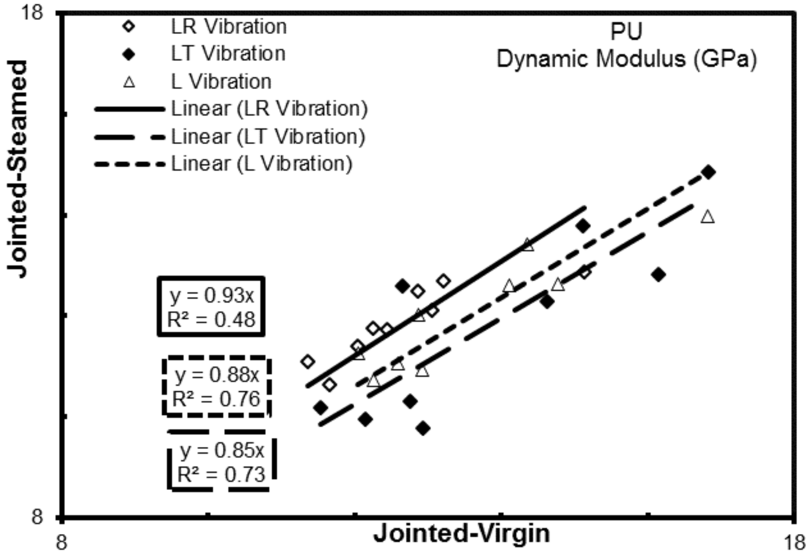

Fig. 10. Polyurethane jointed specimens after steaming *vs*. the jointed-virgin specimens

Timoshenko’s advance theory of the flexural vibration was preferred here because of its ability to calculate a linear coefficient of determination (R^2 in Eq. 2) that correlates the points obtained from the consecutive modal frequencies in a linear decreasing slope (Roohnia *et al.* 2010). The provided model of the evaluation is valid for the clearest specimens, and any heterogeneity might break the linearity of the introduced decreasing slope (Roohnia and Tajdini 2014). Thus, the fitted trend line may show lower coefficients of determination (R^2).

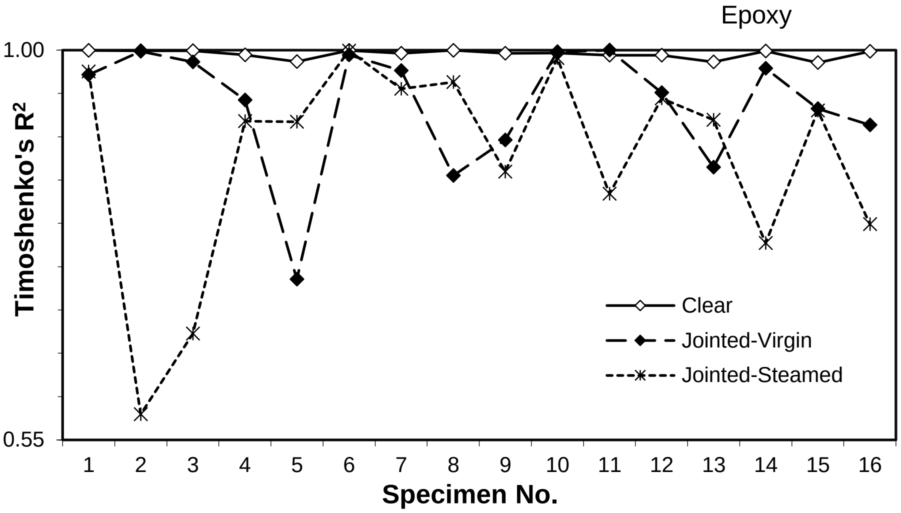

Fig. 11. Timoshenko's coefficient of determination decreased obviously for the epoxy- bonded specimens after steaming. Specimens 1 to 8 are LR, while specimens 9 to 16 are the LT flexural test.

Regarding the number of individuals that remained acceptable after finger jointing and steaming, the R^2 = 0.95 (instead of 0.98 in Eq. 2) was considered as the optimistic threshold of the heterogeneity. As it was firstly formulated, all initial clear specimens are above this threshold. So they were acceptable (Figs. 11 and 12).

Regarding the coefficients of determination in LT or LR tests, specimens 1, 4, 5, 7, and 8 lost their homogeneity after epoxy bonding. The remaining three acceptable individuals within this collection were also rejected after the severe steaming in the autoclave. Based on other concepts discussed above, PU bonding of the studied finger-joints improved. The R^2 approach also certified this finding as an important point of discussion.

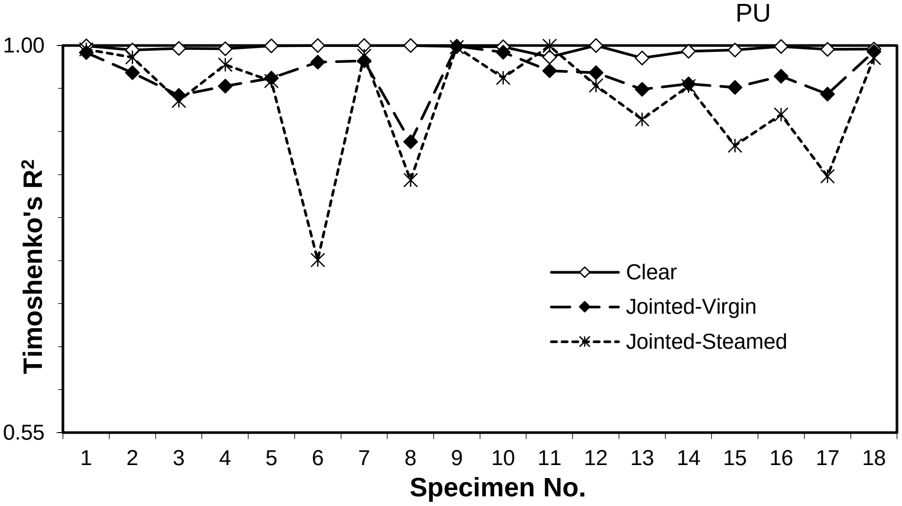

Fig. 12. Timoshenko's coefficient of determination decreased obviously for the PU-bonded specimens after steaming, but not with the same intensity as epoxy bonds. Specimens 1 to 9 are LR, while 10 to 18 are the LT flexural test.

Considering the threshold for heterogeneity, specimens no. 3 and 8 were rejected after polyurethane finger-jointing. Specimens 1, 2, 5, and 9 remained acceptable after steaming either in LT or LR flexural vibration tests. Four accepted *vs*. five rejected steamed specimens is a promising statistic for a meaningful test of polyurethane finger bonding. While it is encouraging that it was possible to differentiate between superior and inferior joints, it is also worth noting that the severe steaming program in autoclave was purposely selected much higher than the temperature tolerance for the glue specifications.

CONCLUSIONS

1. Vibration-based, nondestructive testing was applied to assess the finger-jointed beams of oak wood using two water resistant glues and their residual efficiencies after severe steaming. The clarity criteria were monitored *via* the relative differences in evaluated moduli of elasticity from different vibration planes. The steady decreasing values attributed to modal frequencies were monitored in terms of Timoshenko's coefficient of determination, after manipulating the clear (without joint) specimens by adhesive jointing and steaming.
2. Both approaches showed that compared with the epoxy joints, the polyurethane finger-joints were better in maintaining their initial (clear un-jointed) elastic moduli.
3. After severe steaming, both collections were influenced, but there were still some acceptable specimens among the *PU* joints. All epoxy joints were rejected due to their significant decreases in the evaluated elastic moduli.
4. The $\Delta LE\%$ index and Timoshenko's coefficient of determination exceeded their critical thresholds after dividing, jointing, and steaming the initial clear specimens; however, before these manipulations, both introduced clarity indexes were laid in an acceptable interval.

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