Quality Assessment of Scarf Joints Considering the Acoustic Parameters: A Nondestructive Approach

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The present research studied the acoustic properties of 40 oak timber samples (*Quercus castaneifolia*): the acoustic coefficient (*K*) and acoustic conversion efficiency (ACE) in free vibration mode, using the free-free bar method with different planes of vibration, *i.e.*, tangential (*LT*) and radial (*LR*). These acoustic parameters were considered for both primary virgin wooden beams and modified beams carrying a single scarf joint in four different bonding angles (60°, 65°, 70°, and 75°), individually glued with two different adhesives (isocyanate and polyvinyl acetate). Comparing the acoustic properties of primary solid beams with scarf jointed beams of oak wood in *LT* and *LR* planes, the steeper joint angles of 70° and 75° did not result in any serious changes with polyvinyl acetate adhesive. Scarf-jointed beams with smaller joint angles (60° and 65°) had significant effect on the acoustic properties relative to larger angles. Thus, beams having larger joint angles and beams glued using polyvinyl acetate may have enhanced acoustic properties.

Keywords: Acoustic coefficient; Acoustic converting efficiency; Isocyanate; Polyvinyl acetate; Scarf joint

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INTRODUCTION

Various joints are used in places where acoustical properties are considered high priorities (theaters, cinemas, and wood product industries). Hence, perceiving the necessity of applying joints, several studies have been performed in recent years to shed light on some important factors: joints geometry and configuration (Roohnia *et al*. 2012); the influence of commonly used adhesives (Hemmasi *et al*. 2014), considering the advantages of nondestructive methods such as accuracy, portability, *in-situ* assessment capabilities, and desirable correlation coefficient of static and dynamic young modulus, (Divos and Tanaka 2005; Biechele *et al*. 2010) resulting in increased life span of wood products and quality assurance.

Considering the importance of acoustical properties of scarf joints, numerous research studies have been completed and significant progress has been made (Deng *et al.* 2014; Roohnia *et al*. 2014). Herak *et al.* (2009) studied the mechanical properties of scarf joints and evaluated the influence of joint slope on the mechanical properties and found that scarves of 60° and 75° were the most efficient slopes for joints of spruce wood.

Atar *et al*. (2008) studied the influence of polyvinyl acetate (PVAc) on different joint types and found that the highest shear strength occurred with a 78° joint glued with polyvinyl acetate. In a similar study, tensile strength of wooden furniture with numerous adhesives and different joint angles was studied, indicating that European oak with PVAc glue and a joint angle of 84° had the highest tensile strength (Atar *et al*. 2010). Several cutting angles (in a range of 90° to 180°) were investigated regarding the influence of joint angle on mechanical properties of wood, and a 170° cutting angle was found to be the most reliable using PVAc (Karastergiou and Ntalos 2005). The effect of joint angles on mechanical properties of wood has been evaluated by other studies. Roohnia *et al*. (2014) studied the elastic modulus in the acoustic properties of scarf-jointed wooden beams with different cutting angles (60°, 65°, 70°, and 75°); the best performance of studied joints was detected at 75° scarf joints.

Similar studies have been done on the effect of finger length on mechanical properties of joints. Hemassi *et al.* (2014) studied the mechanical and acoustical properties of finger-jointed beams (glued with PVAc and isocyanate adhesives), demonstrating that joints glued with PVAc showed higher mechanical and acoustical properties and concluding that longer finger lengths had higher levels of acoustic and mechanical properties such as MOE, acoustic coefficient (K), and acoustic conversion efficiency (ACE). In another study, the influence of finger length (glued with PVAc) on the bending strength of finger-jointed treated and untreated beech wood was studied by Vassilious *et al.* (2009), showing that longer finger lengths improved the mechanical properties (*e.g.*, the modulus of rupture (MOR)), and demonstrating that steam-treated samples had a higher modulus of elasticity (MOE) compared to un-steamed samples.

Acoustical performance of the joints and impact of commonly used adhesives on acoustical properties of wood products is of great importance for amphitheaters and soundboard producers; hence, taking into account the previous research findings on vibration based methods (as NDT methods), these factors have been considered, and concerns over quality control have been dealt with.

Method

Oak logs (*Quercus castaneifolia*) were obtained from Nowshahr–Mazandaran province, Iran, where high quality oak wood is abundant and could be easily obtained. The best and clear samples (120) with nominal dimensions of 20 mm ×20 mm ×360 mm (width×height×length, R×T×L) were randomly collected from trees (pith to bark). The samples were selected in accordance with ISO 3129 (2012) and did not have any obvious defects. Nondestructive evaluation was formulated according to Timoshenko’s improved flexural equations (Bordonné 1989; Brancheriau and Bailleres 2002). Timoshenko’s correlation coefficients (greater than 0.99) were the criteria for sample selection. Thus, 40 clean rectangular samples were chosen for further experimentations. Samples were kept in room condition (22 ˚C and 65% relative humidity until their moisture content was stabilized (9%)). Using a linear equation, longitudinal modulus of elasticity, acoustic coefficient, and acoustic conversion efficiency were determined. The Timoshenko model was initially fitted to isotropic materials (Roohnia *et al.* 2010, 2011). Thus, any decrease in the Timoshenko’s correlation coefficient might have been strongly related to a defect or to an unacceptable sample.

One of the most important elements specifying the acoustical properties of wood is the acoustic coefficient which is influenced by the modulus of elasticity and density. Acoustic properties of oak wood (K and ACE) are derived from the following formulas:

$$K = \sqrt{\frac{E}{\rho^3}} \tag{1}$$

In Eq. 1, E is the longitudinal modulus of elasticity (Pa), ρ is the density of air-dried wood samples (kg/m^3), and K is the acoustic coefficient (m^4/kg·s).

Damping can be driven from a logarithmic decrease in the acoustic coefficient (tan δ) or internal friction (Bodig and Jayne 1989) (Eq. 2), where a combination would result in acoustic converting efficiency (Eq. 3). Damping is given by,

$$Tan\ \delta = \frac{\lambda}{\pi} \tag{2}$$

where λ is the logarithmic decrement and tan δ corresponds to the damping of vibration (Bremaud 2008).

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

SPSS V16.0 software (IBM, USA) was used. Analysis of variance (ANOVA) and Duncan tests were used for comparing different means of analyzed parameters.

The longitudinal modulus, obtained from LR (parallel to radial surface) compared to LT (parallel to tangential surface) flexural vibration, was also applied for a tighter selection of the best samples according to Eq. 1 (Roohnia *et al.* 2011). Specimens with ΔLE values higher than 5%, calculated using Eq. 1, were eliminated,

$$\Delta LE\ (\%) = \left| \frac{LE_{LT} - LE_{LR}}{LE_{LT}} \right| \times 100 \tag{4}$$

where LE_{LT} and LE_{LR} represent the longitudinal modulus of elasticity obtained from LT and LR flexural vibration tests, respectively. An NDT-lab® (Iranian portable system setup that can evaluate the mechanical properties of wood, developed at the Islamic Azad University Karaj Branch) (Roohnia *et al.* 2006), was used to evaluate the mechanical properties.

The scarf joints (40 scarf-jointed beams) were categorized in various controlled path ways; they were divided into two groups of four in terms of adhesives; polyvinyl acetate and isocyanate were applied independently (Table 1).

Fabricating scarf joints, four different cutting angles (60°, 65°, 70°, and 75°) on the tangential surface of the beams were created, facing the tangential surface (Fig. 3).

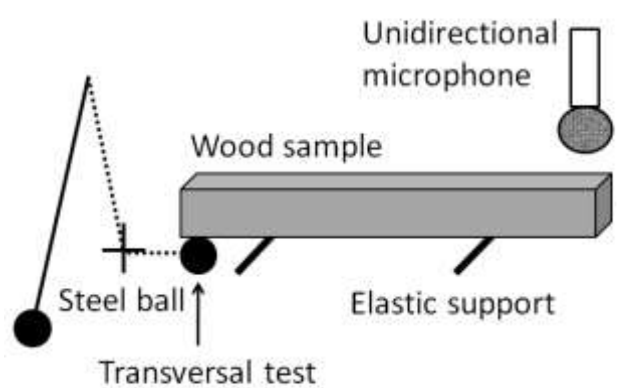

Fig. 1. Schematic view of the beam under flexural vibration

Table 1. Patterns Used for Creation of Scarf-jointed Beams

Scarf joints							
Isocyanate				Polyvinyl acetate			
60^0 (5 specimens)	65^0 (5 specimens)	70^0 (5 specimens)	75^0 (5 specimens)	60^0 (5 specimens)	65^0 (5 specimens)	70^0 (5 specimens)	75^0 (5 specimens)

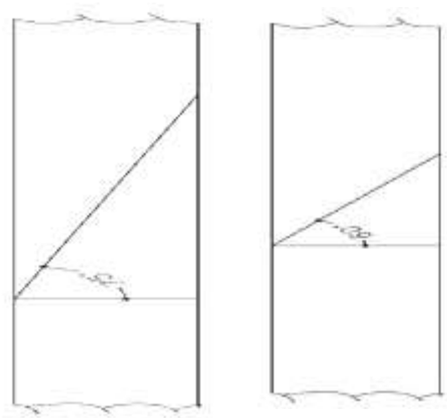

Fig. 2. The 60° and 75o scarves as an example of beams jointed with different scarf angles

RESULTS AND DISCUSSION

The purpose of this research study was to determine the influence of adhesives (PVAc and isocyanate) and scarf joints cutting angles (60°, 65°, 70°, and 75°) on acoustic parameters (i.e., acoustic coefficient and acoustic conversion efficiency) using the flexural vibration method.

Considering the flexural vibration planes (LT and LR) of both jointed and solid samples, it was revealed that the cutting angles, plane of vibration, and adhesives had significant effects on the acoustic properties of samples (Tables 2 and 3).

Taking into account the previous findings regarding the influence of adhesives on elastic properties of joints (Hemmasi *et al.* 2014; Roohnia *et al.* 2014), it was confirmed that the flexural vibration method is sensitive enough for evaluating the acoustical performance of scarf joints. The best performance of the joints was found to be at scarf of 75°.

Considering the acoustical properties of small cutting angles (60° and 65°), gluing scarf joints with isocyanate (in comparison with PVAc), the combination of joints angles (60° and 65°), and applying isocyanate resulted in the weakest acoustical performance of the joints (Figs. 3 and 4); thus, the superiority of acoustical properties of jointed beams glued with polyvinyl acetate was clearly indicated.

Bearing in mind that the acoustic conversion efficiency influenced by both kinds of adhesives (PVAc and isocyanate; in 65° scarf joints), the significant influence of adhesives on acoustic conversion efficiency was observed. Samples glued with isocyanate had a positive effect on the acoustic conversion efficiency (especially in the LT plane of vibration), while PVAc adhesive did not have any significant effect on the acoustic conversion efficiency, and the influence on the LR plane of vibration weakened the correlation between the jointed *versus* reference solid beams (Fig. 4).

Regarding 70° cutting angles, the impact of isocyanate and PVAc adhesives on the acoustic properties of the beams was examined. With respect to PVAc adhesive application (rather than isocyanate adhesive), both acoustic coefficients (Fig. 5) and acoustic conversion efficiency (Fig. 6) remained unchanged, and PVAc adhesive did not show any significant effect on the acoustical properties. Samples glued with isocyanate adhesive had considerably weaker acoustical properties.

As theoretically assumed and confirmed by previous research findings (Herak *et al.* 2009; Hemmasi *et al.* 2014; Roohnia *et al.* 2014), considering the steepest angle (75°), the same trend was observed: a significant difference in the performance of PVAc and isocyanate glued samples in different planes of vibration, comparing the acoustical properties of the solid and jointed samples.

The acoustical properties of jointed beams glued with polyvinyl acetate were considerable in the LR plane of vibration, emphasizing the presumption that applying PVAc increases the acoustical properties. The acoustical properties of jointed beams glued with polyvinyl acetate were similar to reference samples in the LR plane of vibration. The consistent trend was obvious in all joints, and a significant correlation between the jointed beams glued with PVAc and the solid samples was found (Figs. 5 and 6).

As it is seen in Eq. 3, ACE is influenced by two factors: (1) the acoustic coefficient of damping due to radiation (K); and (2) damping ($\tan\delta$).

Damping ($\tan\delta$) is one the chief factors forming ACE (due to internal friction), so any variation in damping would lead to a drastic change in the acoustic conversion efficiency. The damping comparison of solid beams and jointed beams is depicted in Fig. 7.

Regarding the fact that K (acoustic coefficient) is derived from E (longitudinal modulus of elasticity) and ρ (density of air-dried wood samples), the acoustic coefficient and acoustic conversion efficiency were greatly affected by the scarf joints (the density of solid oak beam is approximately 0.71 to 0.77 g/cm^3), while the density in jointed beams is as high as 0.81g/cm^3 which is affected by gluing and has higher density (PVAc is 1.19 g/cm3 and ISO is 1.10 g/cm3) (Tables 4 and 5).

Table 2. Duncan Multiple Comparisons Test for the K

Direction	N	Subset for alpha=.05	
		1	2
R	40	1.64947E2	
T	40		1.30261E3
L	40	1.71956E2	
Sig		.924	1.000

Table 3. Duncan Multiple Comparisons Test for ACE

Direction	N	Subset for alpha=.05	
		1	2
R	40	1.02327E4	
L	40		1.13482E4
T	40	1.13482E4	
Sig		0.203	1.000

Table 4. Physical and Chemical Properties of Isocyanate Adhesive

Ingredients(w/w)	CASNo.	EINECSNo.	Conc. (%)	Classification
Methylenediphenyl-diisocyanate Isomers homologues	101-68-8	202-966-0	2.5-4.5%	Xn;R40-42/43
Benzoyl Chloride	98-88-48	202-710-	2.5-10%	Xi;R36/38
Form and color	Density (water=1)		Solubility	
Liquid, light brown	1.10g/mL(10,43–		Not miscible with water	

Table 5. Technological Properties of PVA Adhesive

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

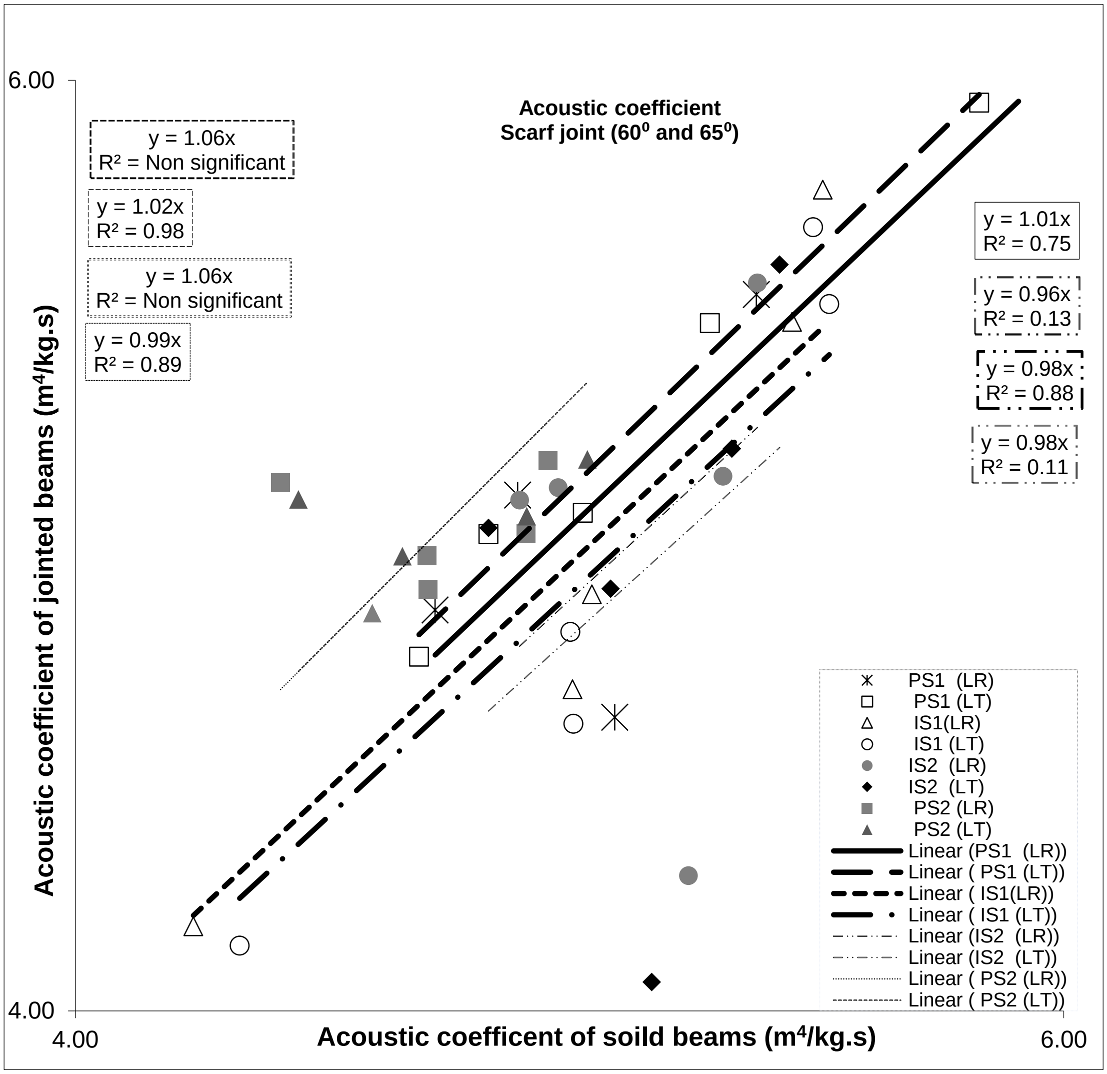

Fig. 3. The acoustic coefficient (m⁴/kg·s) obtained from *LR* and *LT* flexural vibration for 60° and 65° scarf jointed beams *versus* reference solid beams

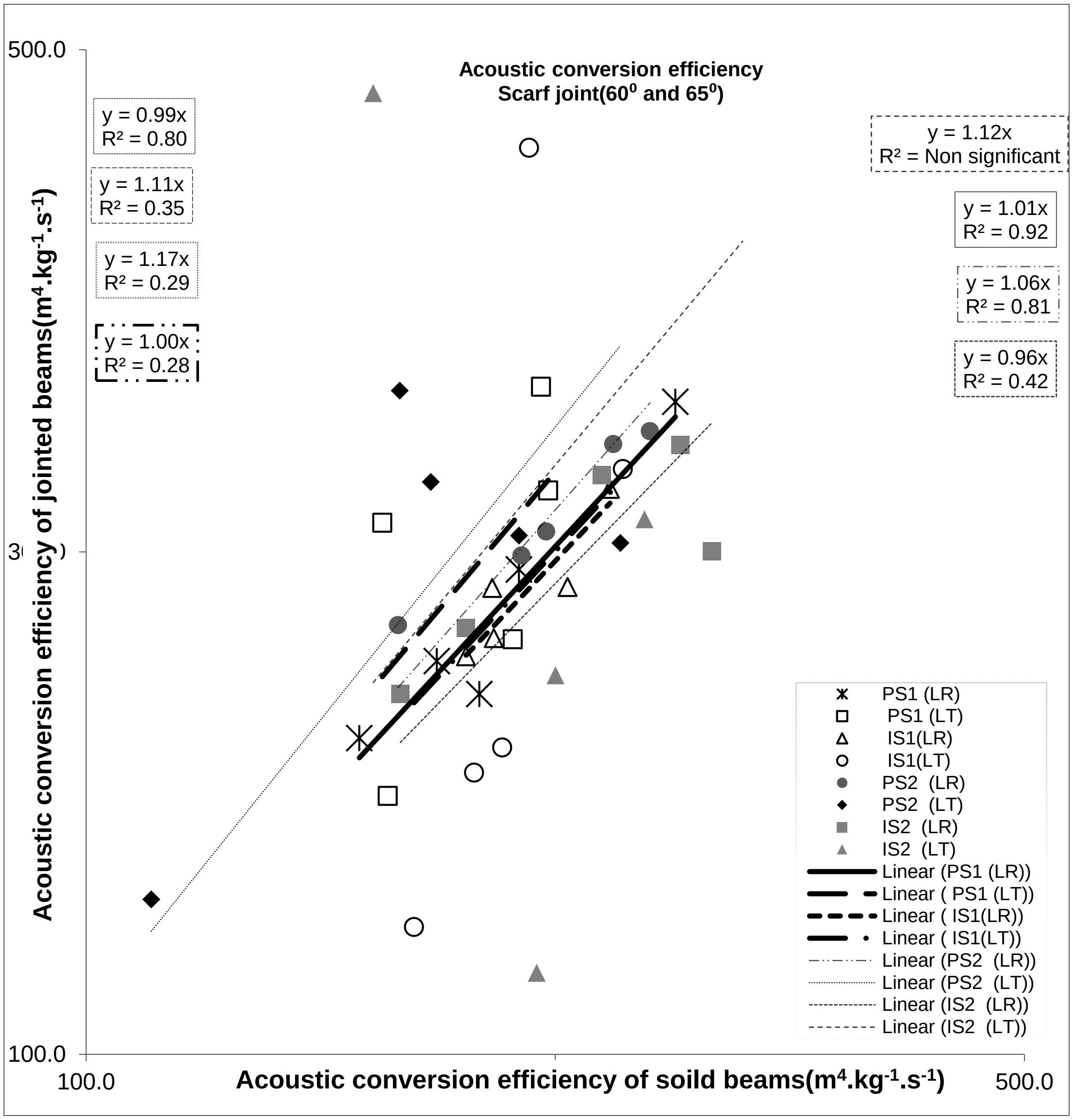

Fig. 4. The acoustic conversion efficiency obtained from LR and LT flexural vibration for 60°and 65° scarf jointed beams *versus* reference solid beams

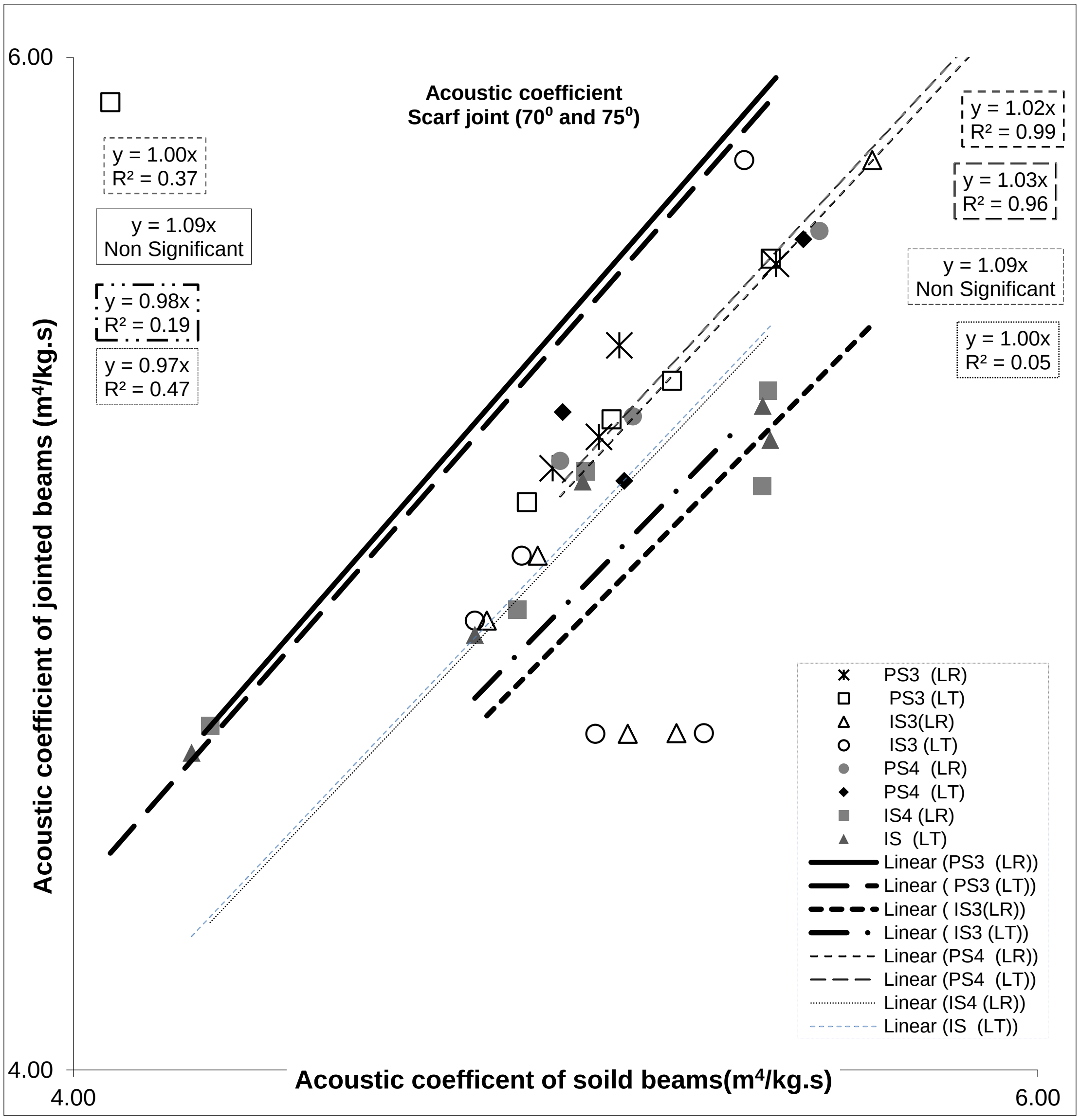

Fig. 5. The acoustic coefficient (m⁴⁄kg·s) obtained from *LR* and *LT* flexural vibration for 70° and 75 ° scarf jointed beams *versus* reference solid beams

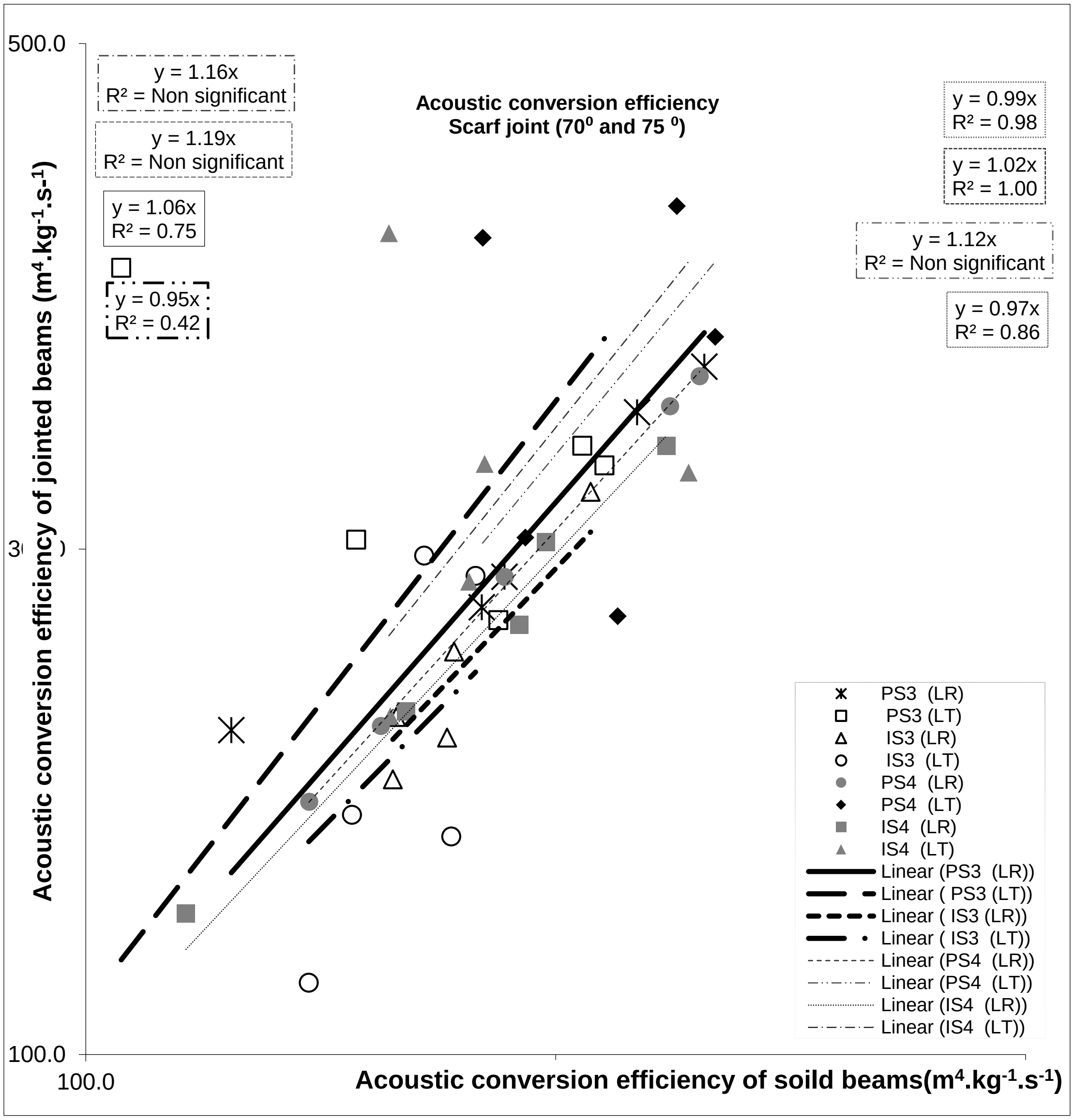

Fig. 6. The acoustic conversion efficiency obtained from *LR* and *LT* flexural vibration for 70° and 75° scarf jointed beams *versus* reference solid beams

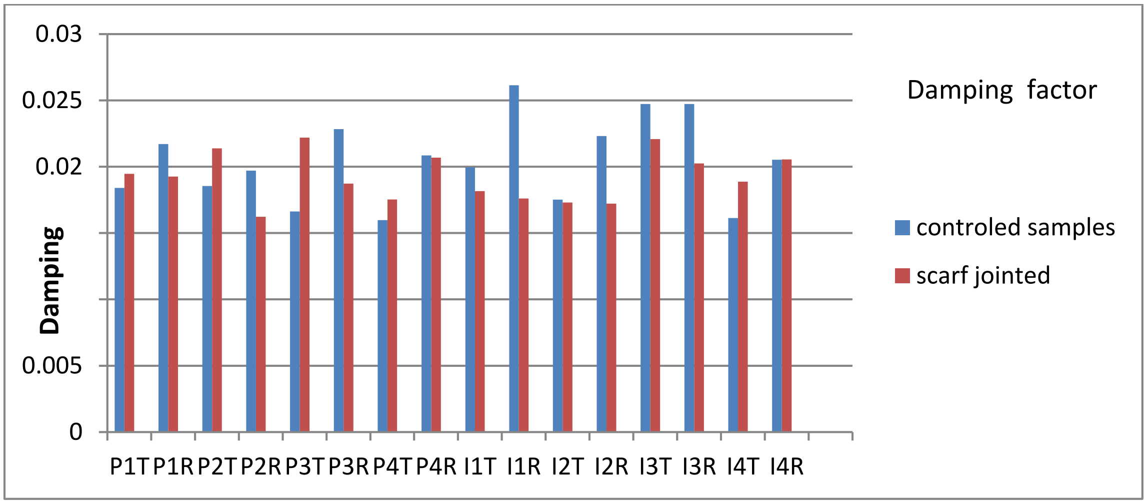

Fig. 7. Damping comparison obtained from *LR* and *LT* flexural vibration for scarf jointed beams *versus* reference solid beams. (Adhesive used: I=Isocyanate, P=Polyvinyl acetate, Angle: 1=60°, 2=65°, 3=70°, and 4=75°)

CONCLUSION

The significance of joint acoustic properties in wood products engineering like resonators is undeniable; therefore, the investigation of factors such as joint angles and adhesive types is crucial. Considering scarf joint angles (0°, 60°, 65°, 70°, and 75°) and joint adhesives (isocyanate and polyvinyl acetate), the following are summarized:

1. Polyvinyl acetate adhesive did not significantly affect the acoustic properties of the samples (*i.e.*, K, ACE), so polyvinyl acetate enhanced the acoustical properties of beams. Therefore, the samples glued with polyvinyl acetate had acoustic properties analogous to the solid beams (*i.e.*, control).
2. Considering joint types, isocyanate glued joints had significant effects on the acoustic efficiency of the samples and notably decreased the acoustic coefficient and acoustic conversion efficiency of the joined beams.
3. The trend of acoustical factors was significant in the radial direction of vibration compared to tangential direction.
4. Lower joint angles (60° and 65°) considerably affected the acoustic properties of beams.
5. Considering the correlation coefficient of the first, second, and third mode of vibration in free-free bars, the flexural vibration seems to be sensitive enough for evaluating the strength performance of scarf joints.
6. The best performance of joints (comparable with clean beams) was detected at 75° glued with polyvinyl acetate.
7. The small jointed angles using isocyanate adhesive (rather than PVA) resulted in the weakest joint.

8. Regardless of the jointed angle and the adhesive used, the flexural vibration seems to be sensitive enough for evaluating the strength performance of scarf joints.

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