Cellulose Nanofiber and Nanoclay's Effect on Acoustic Properties of Oak Wood (*Quercus castaneifolia*) Finger Joint

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Finger joints are one of the most important and widely used joints in the wood and wood products industry. The design, type of construction, and the type of glue used, *etc.*, are the most important things in this joint that determine its final quality. In this research, the effect of cellulose nanofiber and nanoclay in polyvinyl acetate (PVA) glue at levels of 0, 0.4, and 1.5% in finger joints with lengths of two fingers of 5 and 10 mm was investigated by the free vibration in free-free beam method. In joints without nanoparticles, finger joints with a finger length of 10 mm had better acoustic properties than joints with a finger length of 5 mm, except for the acoustic conversion efficiency factor. The results showed that by adding cellulose nanofiber (CNF) and nanoclay in both finger lengths of 5 and 10 mm at both 0.4% and 1.5% levels, the dynamic modulus of elasticity, elastic stiffness, acoustic coefficient, and acoustic conversion efficiency increased significantly, while the damping factor values showed a significant decrease. In general, the effect of CNF on the acoustic properties of both types of joints was better than that of nanoclay.

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INTRODUCTION

One of the main advantages of wood and its composite products as a structural material is that it is easy to join structural components with a wide range of fasteners, including components of a connector jointed to each other (types of adhesives and mechanical fasteners). A joint in a wooden structure, whether wooden buildings or furniture, means jointing two or more members by means of a connector (Custodio *et al*. 2009).

Joints may consist entirely of wooden members, but they may also include wood-to-steel joints or other metallic and non-metallic members (Ayarkwa *et al*. 2001). In addition, due to the limited wood resources in the world, joints reduce the wastage of wood. Adhesive joints have been used for many years in the manufacture of various types of wooden products in different shapes, end to end, edge to edge, and face to face, and have a wide range (such as: mortise and tenon, wood dowel, dovetail, finger joints) (Custodio *et al*. 2009; Vassiliou *et al.* 2016). In 2016, Vassiliou *et al.* investigated mortise and tenon and double dowel joints in beech wood (*Fagus sylvatica* L.) and Black locust (*Robinia pseudoacacia* L.) joined with polyvinyl acetate (PVA) and polyurethane (PUR) adhesives.

The results of this research indicated that PVA glue gave higher strength results than PUR glue in both types of wood studied (Custodio *et al*. 2009; Vassiliou *et al*. 2016).

The finger joint is one of the most important end-to-end adhesive joints in the manufacture of wooden products; with the use of this joint type, it is possible to produce longer wooden parts and in some cases wider plates with different types of glue (Ayarkwa *et al*. 2001). Yavari *et al.* (2015) in two separate articles, investigated the acoustic properties of oak wood (*Quercus castaneifolia*) with finger and scarf joints at different angles using the free vibration in free-free beam method. The results of this research were also similar to their research on joints without the use of nanoparticles in PVA glue. Also, in accordance with the previous research in the manufacture of glulam from pine species (*Pinus sylvestris*), it was found that the number of layers and the direction of the fingers in the finger joints had a significant effect on improving the bending strength of the manufactured glulams. The highest bending strength was achieved in 5-layer beams with finger joints in the vertical direction (İşleyen and Peker 2020).

Much research has been done in the field of producing joints with greater strength using various types of nanoparticles (Kaboorani and Riedl 2011; Kaboorani *et al*. 2014; Hosseyni *et al*. 2014; Ismita and Lokesh 2017; Guo *et al*. 2018). Among the types of these nanoparticles are cellulose nanofiber (CNF) and nanoclay particles. Cellulose, which is a member of the polysaccharide family, is the most abundant biological substance and natural renewable substance. At the submicroscopic scale it consists of filament-like bundles called micro fibrils with a diameter of 3 to 30 nm. In recent years, the demand for plastic and polymeric materials has been increasing, and thus it must be considered in terms of sustainability. Both the producer and the consumer consider plastic and polymeric composites as clean and environmentally friendly engineered materials. (Zor *et al.* 2023).

Among many other sustainable nanomaterials, nanocellulose is drawing increasing interest for use in environmental remediation technologies due to its attractive properties such as excellent mechanical properties, high surface area, rich hydroxyl groups for modification, and natural properties with 100% environmental friendliness (Fidan *et al.* 2022). Nanocellulosic materials allow the design of special materials with high performance that can eliminate present environmental and sustainability problems (Tozluoglu *et al.* 2022). The production method of these particles has a significant effect on the final properties of the product created from it (Poyraz *et al*. 2017). These nanoparticles are generally renewable, low in price, high in specific surface area, and high in strength. The results showed that by increasing the amount of nanographene up to 0.5% by weight, the flexural strength, flexural modulus, and notched impact strength of the composite increased. After adding 2.5 wt.% nanographene, these properties were reduced. (Beigloo *et al*. 2017). Kamboj *et al*. (2022) investigated the effect of using CNF at different concentrations in finger joints jointed with polyvinyl acetate (PVA) glue in two species of spruce (*Picea abies* L.) and beech (*Fagus sylvatica*). The results showed that using a combination of 1% CNF improved the mechanical properties of both species. Nanoclay also has been used as a filler in the manufacture of nanocomposites in a significant volume. The consumption of small amounts causes an increase in modulus of elasticity, strength, and thermal resistance, reduction of gas permeability, resistance to ignition, and improvement of physical properties. Additionally, this increase in properties in most cases does not involve deterioration of other properties (Nafchi *et al*. 2015; Candan *et al.* 2015). Previous research on the use of nanoclay particles in PVA glue concluded that nanoclay particles have a high bonding ability with PVA glue. Polyvinyl acetate creates a strong adhesive bond when used on porous materials such as wood and paper. Therefore, the adhesion strength process is limited by the mechanical properties of the polymer. Also, the results of the research indicated that the presence of CNF and nanoclay in PVA glue creates a higher bonding performance and can be used in applications that require higher bond strength (Kaboorani and Riedl 2011; Aydemir *et al*. 2014; Candan *et al.* 2020).

Considering the importance of adhesive joints in wooden structures and the effect of nanoparticles in increasing the efficiency of adhesives, the purpose of this research was to investigate the effect of using cellulose nanofiber particles (CNF) and nanoclay (nanoclay sodium montmorillonite) at the 2 levels of 0.4 and 1.5% in finger joints with finger lengths of 10 and 5 mm in the oak wood (*Quercus castaneifolia*) with PVA adhesive with the non-destructive test method of free vibration in free-free beam.

EXPERIMENTAL

Materials

First, the number of 100 completely healthy and straight-grained samples of oak wood (*Quercus castaneifolia* Pant.) (region of Caspian Forests) without any apparent defects, including knots, cracks, decay, *etc.*, according to the international standard ISO 3129 (2019), with dimensions of 4 × 4 × 36 cm^3 (Radial × Tangential × Longitudinal) were selected to perform the test. The acoustic and physical properties of the beams, including density, dimensions, relative humidity (RH), frequency, and other factors, were measured, and all test stages were run in the climatic chamber with a balanced moisture level of 12%. To further ensure that the samples were free from internal hidden defects, the test samples were subjected to the free flexural vibration in the free-free beam. Based on Timoshenko's beam theory, the samples with the highest correlation between the first to third vibration modes (correlation above 0.98) were selected to continue the test (Roohnia *et al*. 2012). Based on this, 72 samples of the prototypes were qualified to continue the research, and their acoustic characteristics were recorded as control samples.

Sound recording and storage was done using Audacity® software (Muse Group, 3.6, Pennsylvania, America). The audio file was read by the NDT-lab® system with the same sampling frequency (Roohnia 2007). The polyvinyl acetate adhesive used in this research was obtained from Resin & Chasbe Shomal Chemical Industries with the specifications listed in Table 1. Cellulose nanofiber (CNF) and nanoclay were prepared from Negin east trade Corporation Company with specifications listed in Table 2.

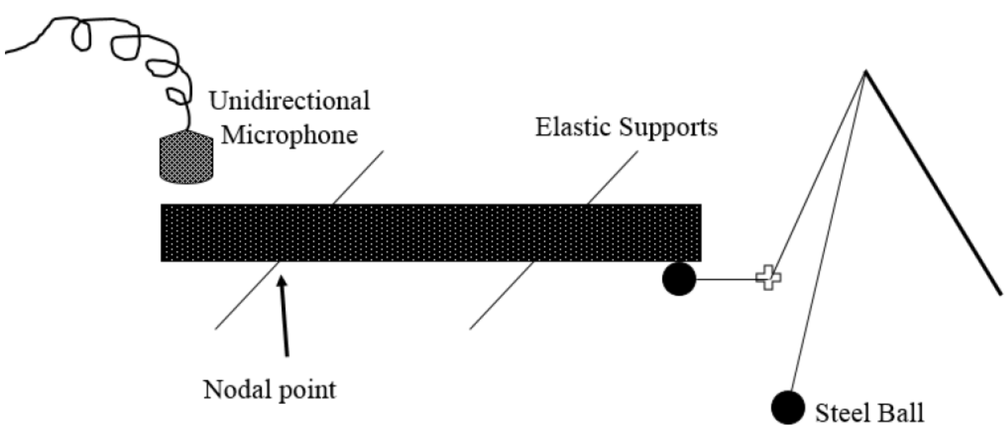

Fig. 1. Schematic view of the beam under flexural vibration

Table 1. Physical and Chemical Properties of PVA Adhesive

Solids Percentage (%)	Density (Kg/m^3)	Time Curing (at 20 °C)	Diluting Base	pH
62 to 66	1/1 to 1/5	10 to 20 min	0.15 to 0.2	6

Table 2. Characteristics of Nanoparticles

Kind	Density	Particles Size (Micrometer)			Specific Surface Area
		Length	Width	Diameter	
Cellose nanofiber (CNF)	0.5 gr/cm^3	20 to 180	20 to 50	32 ± 10	31 to 33 m^2/gr
Nano-clay sodium montmorillonite	0.7 gr/cm^3	10 to 15	4 to 5	1 to 2	220 to 270 m^2/gr

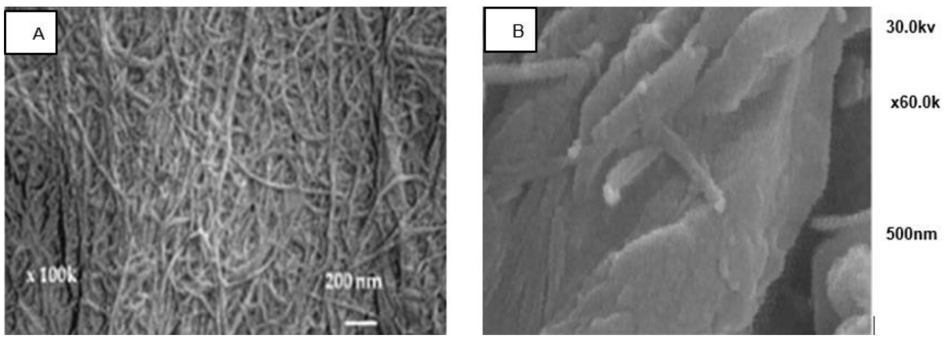

Fig. 2. Cellulose nanofiber (A) Nanoclay (B)

Preparation of PVA Adhesive with CNF and NC

Cellulose nanofibers and nanoclay at two levels of 0.4% and 1.5% based on the total weight of polyvinyl acetate adhesive were stirred with a digital stirrer for 15 min at 2000 rpm to disperse the particles (Keshtegar *et al*. 2019; Najafian Ashrafi *et al*. 2023). For the production of cellulose nanofibers, sawdust, a mixture of beech wood (*Fagus orientalis*), hornbeam wood (*Carpinus betulus*), and walnut species (*Juglans regia*), as well as corn starch, was passed through a 20-mesh sieve and placed in an oven for 24 hours. After that, corn starch was processed with 26 wt% glycerol (as a softener) in a Haake mixer model 90 HBI system made in the United States for 8 minutes at 82 rpm. This machine has a mixing chamber of 55 cm^3. The filling factor is 0.75 (Esmaeilzadeh Saieh *et al*. 2019).

Creating a Finger Joint and Jointing the Sample Tests

The finger joint was formed with a commercial MAKITA® machine in the middle of the specimens (Fig. 3). The initial samples were divided into 12 groups of 6 and glued according to Table 3. The consumption of glue was considered to be 200 g/m^2, and the required amount was calculated after measuring the joint area. After gluing, the samples were placed in a hand gripper for 48 h until the joint was fully established. After that, to reach the moisture balance of 12%, they were placed in an air-conditioned room (with a temperature of 21 ± 1 °C and a relative humidity of 65 ± 5%) for 3 weeks.

Table 3. How to Glue the Samples

Finger Length	Type of Nanoparticles		
	Nanoclay Sodium Montmorillonite		Cellulose Nanofiber (CNF)
	Amount Used in Adhesive (%)		
10 mm	0	0.4	1.5
5 mm	0	0.4	1.5

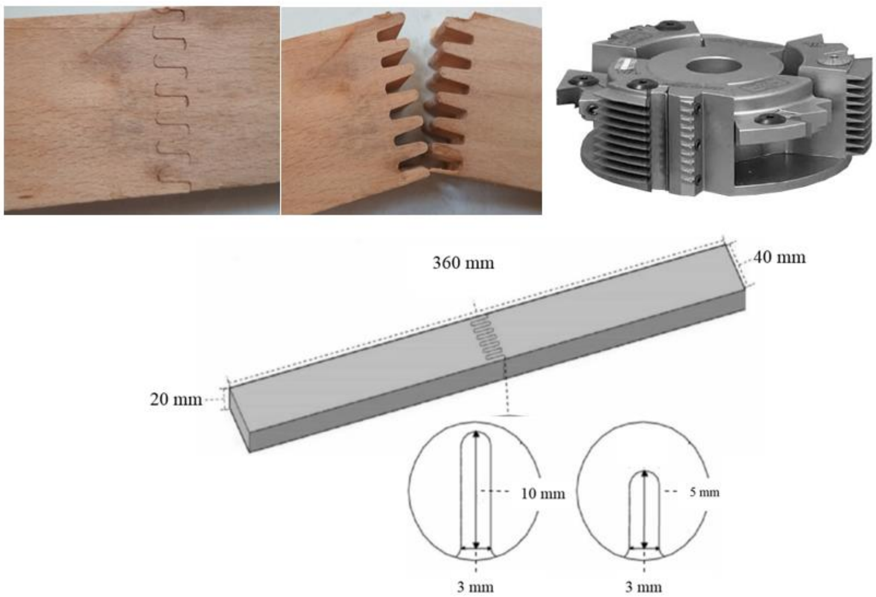

Fig. 3. Schematic view of finger joint, joint in the middle of the beams

Free Flexural Vibration in the Free-Free Beam in Finger Jointed Beams

The free flexural vibration in the free-free beam was carried out again on the finger-jointed specimens. Calculations of the dynamic modulus of elasticity were performed on the joints according to Timoshenko's beam theory, Eq. 1:

$$a_{\mathrm{n}} = \left(\frac{E}{\rho}\right) - \left(\frac{E}{K \times G_{ij}}\right) b_n, R^2 \geq 0.98 (for\ solid\ beams) \tag{1}$$

The damping factor was calculated through Eqs. 2 and 3,

$$\lambda = \frac{1}{n} ln \left|\frac{X_1}{X_{\mathrm{n}\,+\,1}}\right| \tag{2}$$

$$tan\delta = \frac{\lambda}{\pi} \tag{3}$$

where λ is the logarithmic decrement, and tan δ corresponds to the damping of vibration.

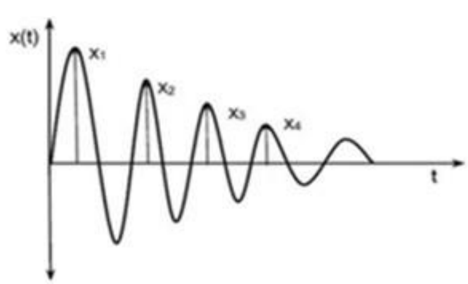

Fig. 4. Expressions of damping capacity in the temporal field through logarithmic decrement λ

The acoustical coefficient (K) and acoustical conversion efficiency (ACE), based on modulus of elasticity, density, and damping factor, are applied in the musical instrument industry as criteria for selecting the proper wood (Ono and Norimoto 1983; Tsoumis 1991; Roohnia 2019). These parameters were calculated through Eqs. 4 and 5,

$$K = \sqrt{\frac{E}{d^3}} \quad (4)$$

$$ACE = \frac{K}{tan\delta} \quad (5)$$

where E is the modulus of elasticity (Pa), K is the acoustic coefficient ($m^4.s^{-1}.kg^{-1}$), d is the density of the wood specimens ($kg.m^3$), and ACE is the acoustical converting efficiency ($m^4.s^{-1}.kg^{-1}$).

Correlation between dynamic properties values of solid beams and jointed beams, jointed with two finger lengths of 10 and 5 mm with three mixing levels of 0, 0.4, and 1.5% by cellulose nanofiber (CNF) and nanoclay was assessed through the Pearson correlation test. A comparison of each one of the mechanical properties obtained from each one of the test stages to that of solid wood was also made using a statistical T-test at the 95% confidence level. The SPSS v.17.5 software (IBM Corp., Armonk, NY, USA) was applied in the statistical tests. Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA) was applied to acoustic characteristics. The data were gathered into tables while their differences were monitored through column and line plots. The comparison was based on the clear qualities of the wood.

RESULTS AND DISCUSSION

Tables 4 and 5 show the calculated acoustic properties values of finger joints with two finger lengths of 10 and 5 mm in different percentages of mixing with CNF and nanoclay nanoparticles. The values of each type of joint are shown compared with the control test group of the same type of joint. Table 6 also shows the percentage difference between the acoustic values of the jointed wood compared to the control sample.

Creating a finger joint with finger length of 10 mm without combining with CNF did not have a significant effect on the values of the dynamic modulus of elasticity compared to the solid beam (decrease: -0.91% compared to the solid beam). As shown in Fig. 5, the addition of 0.4 and 1.5% of CNF caused a significant increase in the dynamic modulus of elasticity in the finger jointed beam compared to the solid beam (8.03% and 25.06%, respectively).

In the finger joints made with finger length of 5 mm, the modulus of elasticity of wood without CNF and containing 0.4% showed a significant decrease compared to the solid beam (decrease: 11.25% and 3.03%, respectively, compared to solid beam). Adding 1.5% of CNF to finger joints made with finger length of 5 mm caused a significant increase in the modulus of elasticity values in the joints, by up to 14.01% compared to solid wood. As the results showed, the presence of CNF in finger joints with both finger lengths was effective. The percentage of changes in joints with a finger length of 10 mm was higher than joints with a finger length of 5 mm. The results of this research were previously reported by Yavari *et al.* in 2015 in finger joints with PVA adhesive without nanoparticles. Kamboj *et al.* (2022) also reported the positive effect of the presence of CNF in PVA glue in different percentages with this research in two species of spruce wood (*Picea abies* L.)

and beech wood (*Fagus sylvatica*). The FTIR analysis of his research indicated a suitable interaction between CNF and PVA adhesive.

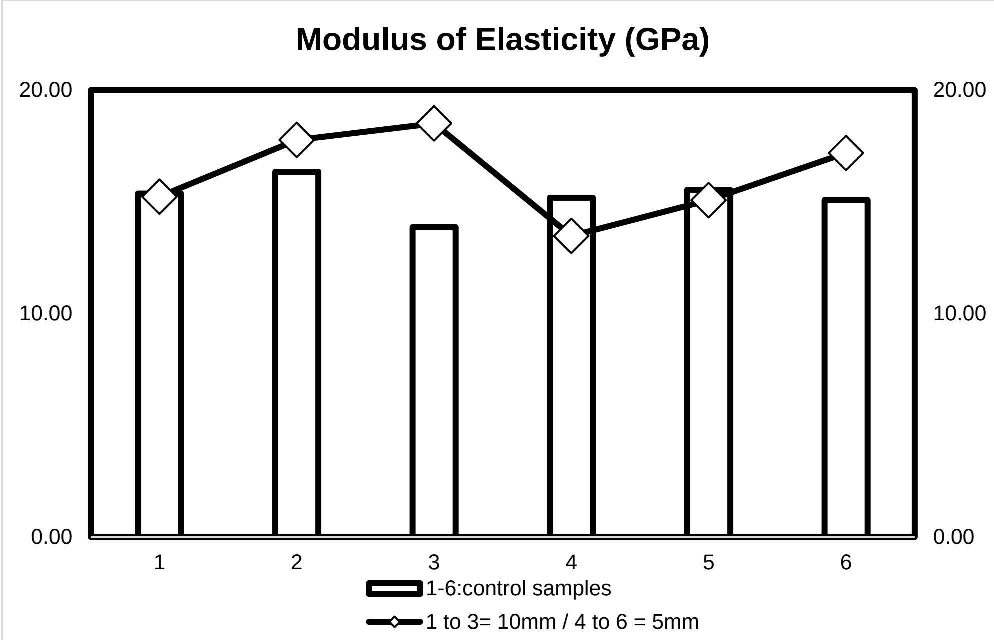

Fig. 5. Comparison of the dynamic modulus of elasticity of solid beams with jointed beams by combining adhesive with CNF

Figure 6 shows the effect of nanoclay (NC) on the values of dynamic modulus of elasticity of finger joints obtained from finger length of 10 mm and 5 mm.

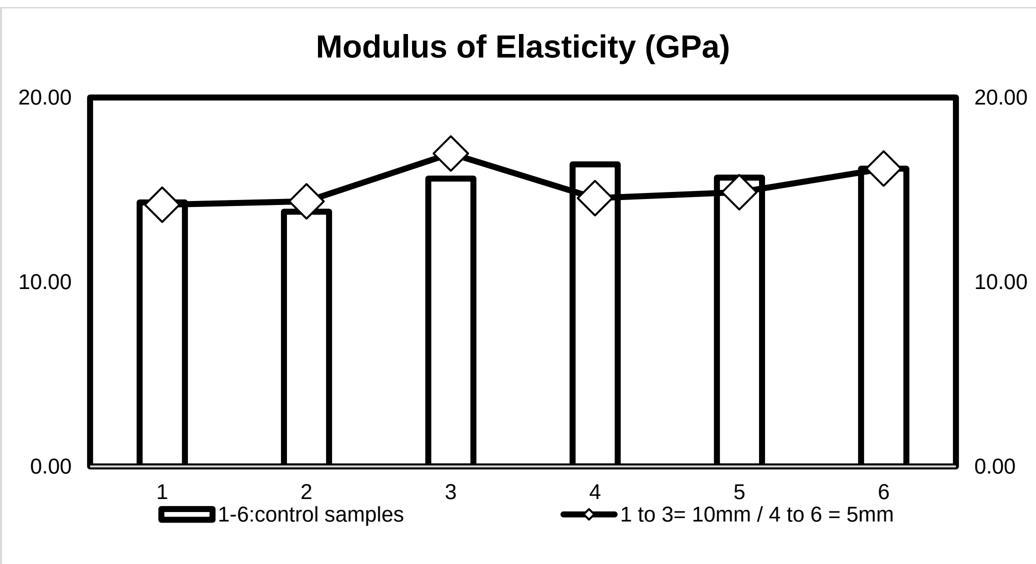

Fig. 6. Comparison of the dynamic modulus of elasticity of solid beams with jointed beams by combining adhesive with NC

As seen in Fig. 6, adding both 0.4% and 1.5% of NC in finger length of 10 mm caused a significant increase in dynamic modulus of elasticity values (respectively: 3.94% and 8.01% compared to solid beam). The addition of 0.4% of nanoclay in 5 mm long finger joints has increased the values of the dynamic elasticity modulus compared to the jointed wood without nanoclay. But the values obtained from the modulus of elasticity in joints containing 0.4% nano resin are still lower compared to solid wood (decrease: 5.04% compared to solid beam). The addition of 1.5% of nanoclay made the values of modulus of elasticity equal in jointed wood compared to solid wood (decrease: 0.26% compared to solid beam). The effect of CNF in the modulus of elasticity values of joints was more than the effect of NC, and the changes in joints with a finger length of 10 mm were more than those with finger length of 5 mm. In previous research on beech wood finger joints, the effect of larger finger length on improving the mechanical properties of the joints was reported (Vassiliou *et al*. 2006).

Before this, the positive effect of the presence of NC in PVA glue was reported by other researchers using the static method (Kaboorani and Riedl 2011; Aydemir *et al*. 2016). The results of this research also show a significant increase in the values of dynamic modulus of elasticity of finger joints in oak species.

Table 4. Measured Quantitative Values of Acoustic Properties of Joints with Finger Length of 10 mm

10 mm		MOE_d (GPa)	Elastic Stiffness ($MPa.m^3/Kg$)	Acoustic Coefficient ($m^4.s^{-1}.kg^{-1}$)	Damping Factor	ACE ($m^4.s^{-1}.kg^{-1}$)
CNF	S1*	15.37	20.14	5.87	0.0107	743.77
	0	15.23	19.95	5.84	0.0189	362.27
	S2*	16.34	22.21	6.41	0.0095	733.17
	0.4	17.77	24.16	6.68	0.0145	488.49
	S3*	13.87	16.99	5.03	0.0159	353.56
	1.5	18.51	22.67	5.82	0.0228	289.71
NC	S1	14.31	18.55	5.57	0.0137	459.85
	0	14.18	18.39	5.54	0.0241	247.03
	S2	13.80	17.47	5.28	0.0138	403.96
	0.4	14.37	18.18	5.39	0.0216	258.68
	S3	15.60	21.07	6.19	0.0105	620.11
	1.5	16.96	22.91	6.46	0.0157	448.46

1: Control test for finger joints without nano particles
2: Control test for finger joints containing 0.4% nano
3: Control test for finger joints containing 1.5% nano

Figure 7 shows the effect of CNF on elastic stiffness in joints with finger lengths of 10 and 5 mm. As shown, creating a joint without CNF did not have a significant effect on the elastic stiffness values (decrease: 0.95% compared to solid beam). With the increase of CNF in both values of 0.4 and 1.5%, the elastic stiffness values increased significantly (respectively: 8.05% and 25.08% compared to solid beam).

Table 5. Measured Quantitative Values of Acoustic Properties of Joints with Finger Length of 5 mm

5 mm		MOE_d (GPa)	Elastic Stiffness ($MPa.m^3/Kg$)	Acoustic Coefficient ($m^4.s^{-1}.kg^{-1}$)	Damping Factor	ACE ($m^4.s^{-1}.kg^{-1}$)
CNF	S1	15.19	19.72	5.76	0.01310	509.04
	0	13.47	17.51	5.43	0.01859	327.09
	S2	15.54	20.32	5.90	0.01081	569.26
	0.4	15.08	19.72	5.81	0.01537	406.79
	S3	15.08	19.64	5.75	0.01300	528.55
	1.5	17.19	22.39	6.14	0.01741	421.43
NC	S1	16.38	22.49	6.52	0.00966	675.80
	0	14.54	19.98	6.14	0.01402	439.21
	S2	15.66	20.76	6.03	0.01115	581.46
	0.4	14.87	19.71	5.88	0.01583	390.41
	S3	16.14	22.12	6.44	0.01079	628.24
	1.5	16.14	22.17	6.43	0.01541	451.69

1: Control test for finger joints without nano particles
2: Control test for finger joints containing 0.4% nano
3: Control test for finger joints containing 1.5% nano

Table 6. Percentage of Changes in Jointed Beams Compared to Solid Beams

Addition Percentage	MOE_d (GPa)	Elastic Stiffness ($MPa.m^3/Kg$)	Acoustic Coefficient ($m^4.s^{-1}.kg^{-1}$)	Damping Factor	ACE ($m^4.s^{-1}.kg^{-1}$)
10 mm with 0% CNF	-0.91	-0.95	-0.46	+42.23	-105.31
10 mm with 0.4% CNF	+8.03	+8.05	+4.13	+35.00	-50.09
10 mm with1.5% CNF	+25.06	+25.08	+13.47	+30.50	-22.04
5 mm with 0% CNF	-11.23	-11.25	-5.76	+45.03	-35.74
5 mm with 0.4% CNF	-3.03	-2.95	-1.49	+40.25	-28.54
5 mm with 1.5% CNF	+14.01	+13.99	+6.79	+35.02	-20.27
10 mm with 0% NC	-0.99	-0.86	-0.46	+43.08	-106.83
10 mm with 0.4% NC	+3.94	+3.94	+2.02	+36.10	-56.16
10 mm with 1.5% NC	+8.01	+7.99	+4.09	+33.05	-38.28
5 mm with 0% NC	-11.20	-11.18	-5.74	+45.05	-35.01
5 mm with 0.4% NC	-5.04	-5.06	-2.54	+43.98	-32.86
5 mm with 1.5% NC	-0.26	+0.24	-0.23	+42.05	-28.10

In finger lengths of 5 mm, elastic stiffness results were obtained, including the dynamic modulus of elasticity. Without adding CNF, there was a significant drop in elastic stiffness values (decrease: 11.25% compared to solid beam). Adding amounts of 0.4 and 1.5% of CNF in finger joints resulted in a significant increase of the mentioned factor (respectively: increase from -11.25% compared to solid beam to -2.95% and +13.99% compared to solid beam). The results of the elastic stiffness factor in finger lengths of 5 mm were also affected by the results of its modulus of elasticity due to the constant density factor. No similar research was observed regarding elastic stiffness in joints containing CNF and other wood products. However, with increasing values of dynamic modulus of elasticity and keeping density constant, such a result was not far from expected.

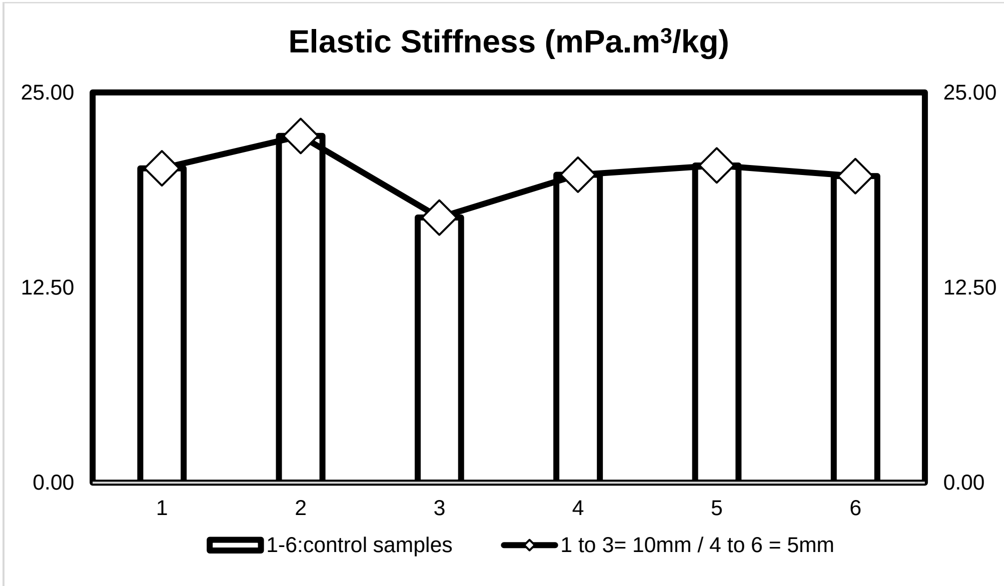

Fig. 7. Comparison of the elastic stiffness of solid beams with jointed beams by combining adhesive with CNF

Figure 8 also shows the effect of adding NC on the elastic stiffness of joints obtained from both joints with finger lengths of 10 and 5 mm. The addition of nanoclay to joints with both 10 and 5 mm finger lengths resulted in similar dynamic modulus elasticity results for elastic stiffness. In finger joints with finger lengths of 10, there was no significant change in dynamic elastic stiffness (decrease: 0.86% compared to solid beam). The addition of 0.4% and 1.5% of NC caused a significant increase in the values of this factor (respectively 3.9% and 8.0% compared to solid beam). In the case of finger lengths of 5 mm, the elastic stiffness values without the presence of NC showed a significant decrease of 11.2%.

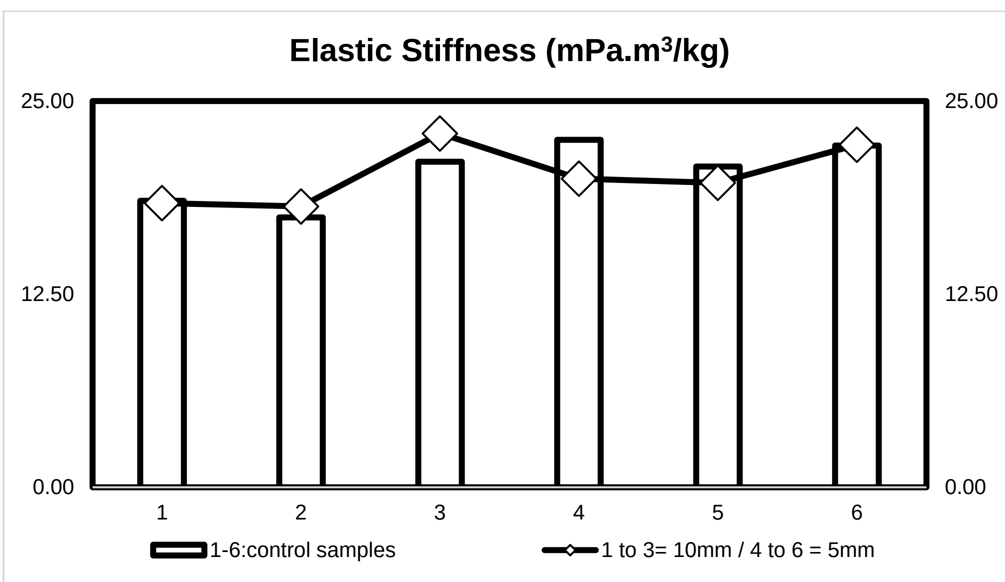

Fig. 8. Comparison of the elastic stiffness of solid beams with jointed beams by combining adhesive with NC

Adding 0.4% of nanoclay significantly increased the stiffness modulus values compared to joints without nanoclay, but the results are still lower than solid wood (decrease: 5.1% compared to solid beam). Through addition of 1.5% of nanoclay, the stiffness modulus values were equal to that of solid wood (increase numerically: 5.1% compared to solid beam).

The acoustic coefficient is one of the most important acoustic factors of a wood species (Roohnia 2019). Figures 9 and 10 show the effect of adding CNF and NC particles in joints with finger lengths of 10 and 5 mm. Jointing with finger lengths of 10 mm in two control test groups of each group did not have a significant effect on the acoustic coefficient values (decrease: 0.46% compared to solid beam). Adding both nanoparticles at two levels of 0.4% and 1.5% caused a significant increase in the acoustic coefficient values (respectively: +4.1 and +13.5% in CNF and +2.0 and +4.1% in NC compared to solid beam).

In finger lengths of 5 mm, without the presence of both nanoparticles, the acoustic coefficient values had a significant drop compared to the solid wood (-5.8% and -5.7% in the jointed samples compared to their solid beams). Through addition of 0.4% and 1.5% of CNF, the acoustic coefficient values showed a significant increase (respectively: from -5.8% and -5.7% in finger joint without CNF to -1.5% and an increase of +6.8% compared to solid beam). With the addition of 0.4% NC, the acoustic coefficient values increased significantly compared to joints without NC, but the values were still lower than solid wood (numerical drop: 2.5% compared to solid beam). Adding 1.5% of NC increased the acoustic coefficient values to the level of acoustic coefficient values in solid wood (numerical drop: 0.23% compared to solid beam).There has been no research on the effect of adding CNF and NC particles in both finger lengths of 10 mm and 5 mm on the acoustic coefficient factor. The results show that the mentioned factor is influenced by the changes in the values of the dynamic modulus of elasticity and the stability of the density values in the samples.

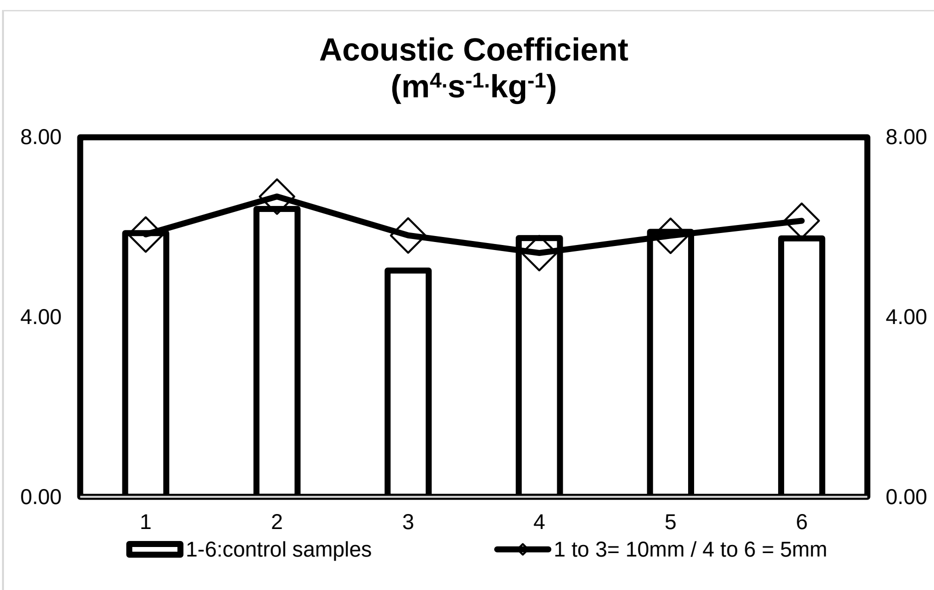

Fig. 9. Comparison of the acoustic coefficient of solid beams with jointed beams by combining adhesive with CNF

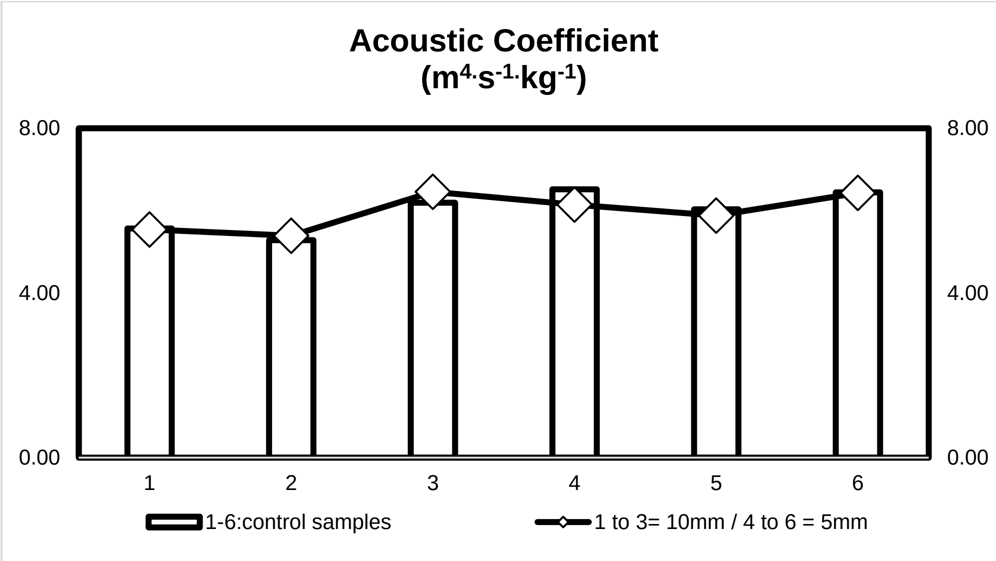

Fig. 10. Comparison of the acoustic coefficient of solid beams with jointed beams by combining adhesive with NC

In Figs. 11 and 12, the changes in damping factor due to jointing with lengths of 10 and 5 mm without mixing and with mixing by CNF and NC particles at two levels of 0.4% and 1.5% are shown. As the results show, creating a finger joint with a finger length of 10 mm caused a significant increase in the damping factor values of the jointed specimens compared to the control samples of each group (increase: 42.2% and 43.1% compared to solid beam, respectively). With the increase of 0.4% and 1.5% of CNF and NC in PVA glue, the damping factor values showed a significant decrease (respectively from 42.2% and 43.1% increase in samples without CNF and NC compared to solid beam to 35.0 and 30.5% in samples with 0.4% and 1.5% CNF, and to 36.1 and 33.0% in samples with NC compared to the solid beams of each group).

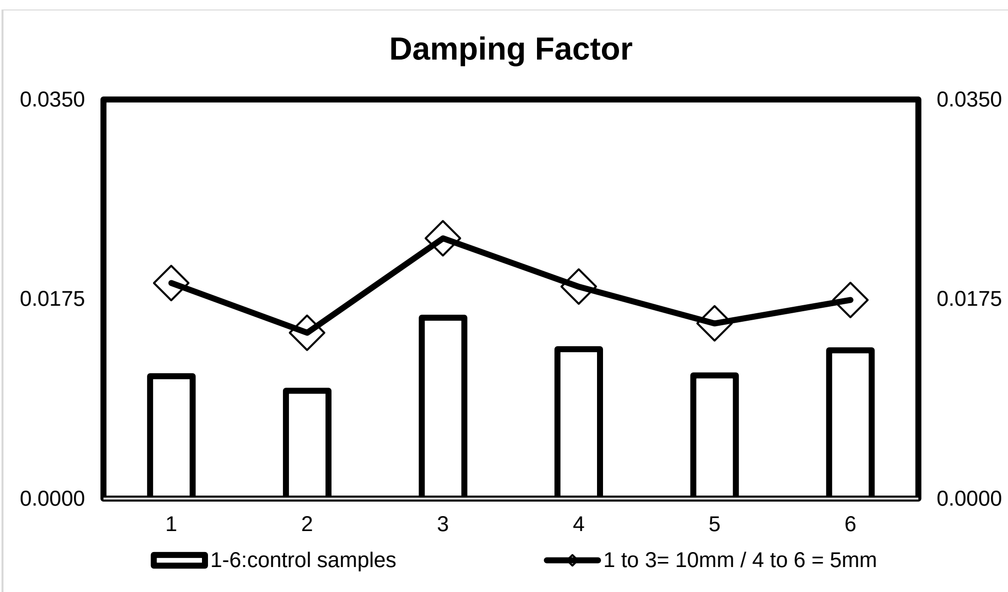

Fig. 11. Comparison of the damping factor of solid beams with jointed beams by combining adhesive with CNF

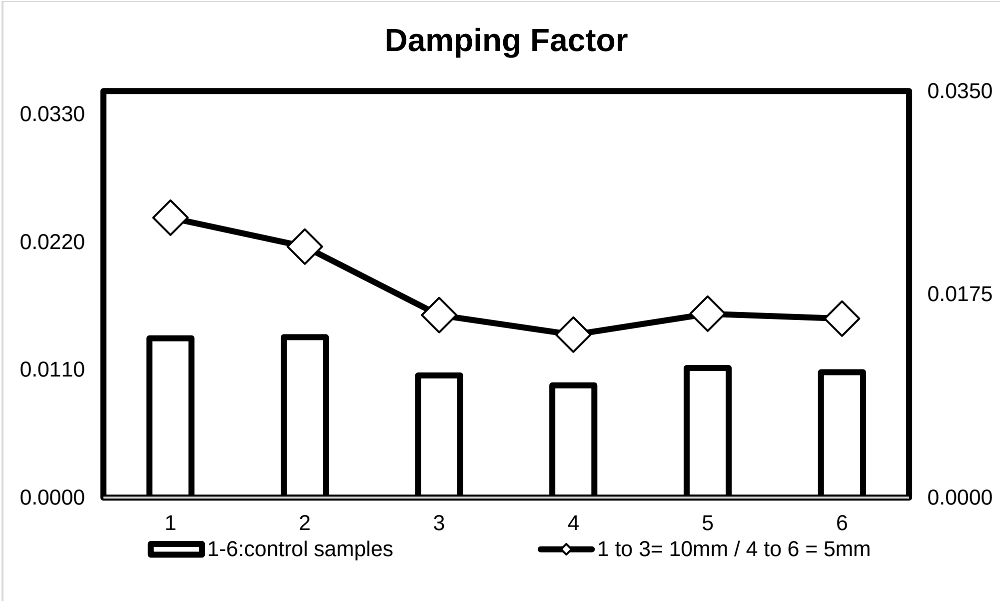

Fig. 12. Comparison of the damping factor of solid beams with jointed beams by combining adhesive with nanoclay (NC)

In the 5-mm-long finger joint, the damping factor values in the joint specimens without CNF and NC particles showed a significant increase (both 45.0% increase in the specimens without nano particles in each group of control samples compared to the solid beams). Through mixing the amounts of both nanoparticles at two levels of 0.4% and 1.5%, the damping factor values in both groups of nanoparticles showed a significant decrease (both 45.0% increase in samples without CNF and NC, in each group of control sample, respectively) to 40.2 and 35.0% in samples with CNF and to 44.0 and 42.0% in samples with NC compared to solid beams of each group.

Kohntorabi *et al*. (2011) and Yavari *et al*. (2015) reported an increase in damping factor values due to the creation of finger joints in oak wood with PVA glue. The results of this research were similar to the results of their research. Thus far, similar research has not been done on the effect of adding CNF and NC particles on damping factor values, but the result can be attributed to the good connection between PVA glue and CNF and NC particles (Kaboorani and Riedl 2011; Aydemir *et al*. 2016; Kamboj *et al*. 2022).

The changes in acoustic conversion efficiency (ACE) in finger lengths of 10 and 5 mm at three levels of 0, 0.4, and 1.5% of CNF and NC are shown in Figs. 13 and 14. Creating a finger joint with finger lengths of 10 mm without adding CNF and NC particles caused a decrease of 105% and 107% in the control samples of each group, respectively. With the increase of 0.4% and 1.5% of CNF and NC in PVA glue, the acoustic conversion efficiency values showed a significant increase; from 105% and 107% decrease in samples without CNF and NC, respectively, compared to solid wood to -50.1 and -22.0% in samples with 0.4 and 1.5% of CNF and -56.2 and to -38.3% in samples with NC compared to the solid beams of each group.

In finger length of 5 mm, creating the finger joint without CNF and NC caused a reduction of -35.7 and -35.0% of the acoustic conversion efficiency compared to the control samples of each group. In this finger length, with the increase of 0.4% and 1.5% of CNF and NC, the values of acoustic conversion efficiency showed a significant increase. The values went from -35.7 and a -35.0% reduction in samples without CNF and NC compared to solid wood to 28.5 and 20.3% in samples with 0.4% and 1.5% of CNF and to 32.9 and 28.1% in samples with NC compared to the solid beams of each group, respectively. In the finger joints created with both finger lengths, the effect of CNF was greater than that of NC.

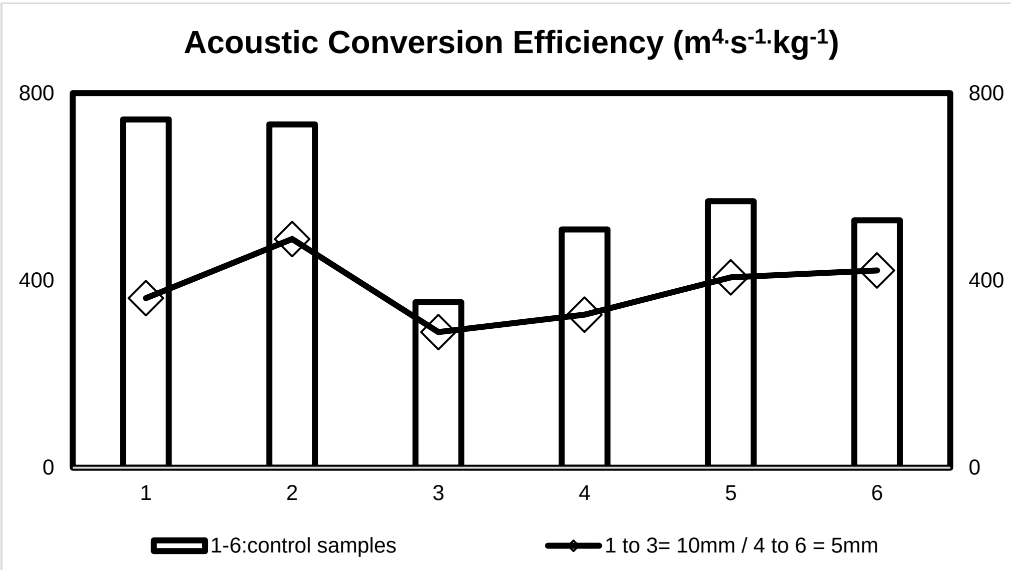

Fig. 13. Comparison of the ACE of solid beams with jointed beams by combining adhesive with CNF

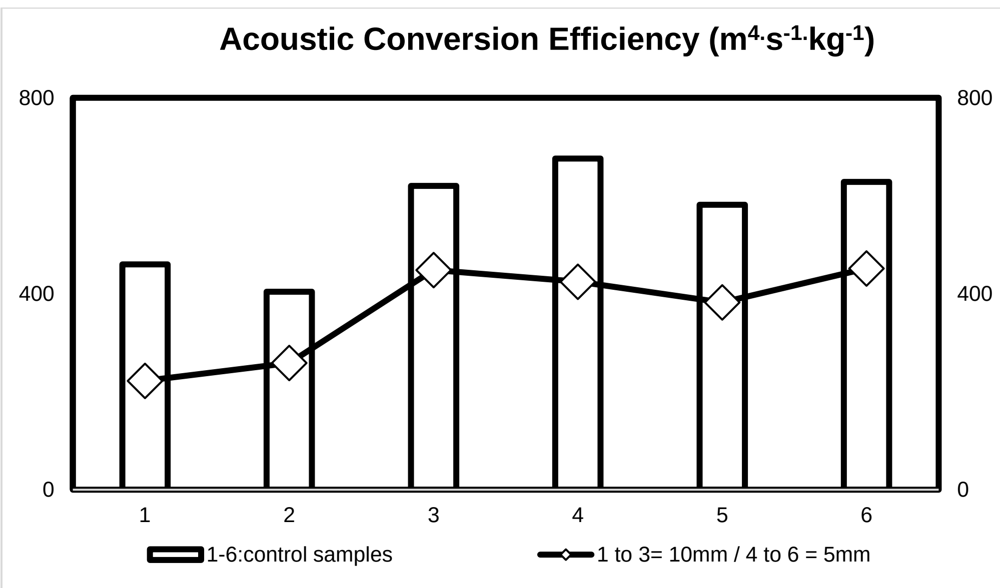

Fig. 14. Comparison of the ACE of solid beams with jointed beams by combining adhesive with NC

The acoustic conversion efficiency has been mentioned as the main criterion in the selection of wood instruments for the use of wood used in vibrating plates for musical purposes (Roohnia 2019). The results of Yavari *et al.*'s research on finger jointing oak wood with PVA adhesive in 2015 were in accordance with the results of this research. In addition, in 2015 and 2020, Kohantorabi *et al.* used this factor to track the heterogeneity in spruce wood (*Populus nigra*) and oak wood, which was made heterogeneous by jointing with spruce wood (*Populus nigra*) by PVA glue. In addition to the inverse relationship between damping factor and acoustic conversion efficiency, the result can be attributed to the creation of greater homogeneity in the joint area due to the presence of CNF and NC in the finger joints made by the two adhesives.

CONCLUSIONS

1. Finger jointing with finger length of 10 mm did not cause a significant change in modulus of elasticity values compared to solid wood. Through adding either cellulose nanofibers (CNF) and nanoclay particles to the polyl(vinyl acetate) (PVA) adhesive, the dynamic modulus of elasticity increased significantly, and the effect of CNF was higher than that of nanoclay.
2. Finger jointing with finger length of 5 mm caused a significant decrease in dynamic modulus of elasticity values. The addition of two levels of 0.4 and 1.5% CNF and nanoclay significantly increased the values of dynamic modulus of elasticity values.
3. The values of elastic stiffness and acoustic coefficient in the joint created in both finger lengths (5, 10 mm) were affected by the values of dynamic modulus of elasticity values. In the joint with a finger length of 10 mm, no significant change was observed in the values of elastic stiffness and acoustic coefficient of the samples compared to solid wood, but with the addition of 0.4% and 1.5% CNF and nanoclay levels, the values of both factors increased significantly compared to solid wood.
4. In the finger joint with finger length of 5 mm without nanoparticles, the values of elastic stiffness and acoustic coefficient showed a significant decrease compared to solid wood, but with the addition of 0.4% and 1.5% CNF and nanoclay, the values of both factors increased significantly compared to solid wood.
5. The values of damping factor in the finger joints obtained from both finger lengths of 10 and 5mm increased significantly compared to solid wood. The amount of this increase in the 5 mm finger length was more than that of the finger length of 10 mm. The presence of 0.4% and 1.5% of CNF and nanoclay caused a significant decrease in the damping factor values in the finger joints made by both finger lengths compared to solid wood, and the effect of CNF was more than that of nanoclay.
6. The values of acoustic conversion efficiency in the finger joints obtained from both finger lengths of 10 and 5 mm decreased significantly compared to solid wood. The amount of this drop in finger lengths of 10 mm was more than that of finger lengths of 5 mm. The presence of 0.4% and 1.5% of CNF and nanoclay caused a significant increase in the acoustic conversion efficiency values in the joints made of both finger lengths of 10 and 5 mm, and the effect of CNF was greater than nanoclay.

7. In general, the results indicate that the Free Flexural Vibration in the Free-Free Beam method in the double-ended beam can be highly effective in detecting the quality of joints.

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This article presents some of the achievements of a series of research studies in the wood-NDT laboratory at Islamic Azad University, Karaj Branch, in particular, this manuscript reports a Ph.D. thesis by the 1st author, entitled: "Evaluation of the bending properties of finger joints reinforced with nanoclay and nano cellulose particles in finger joints of oak (*Quercus castaneifolia*) and pine wood (*Pinus sylvestris*)".

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