The Effect of Cellulose Nanocrystals and Nanoclay on Finger Jointing of Plywood Using the Free Vibration Method

Hamidreza Abbasi,[a] Amirhooman Hemmasi,[a,]* Mohammad Talaeipour,[a]
Esmaeil Ghasemi,[b] and Habibollah Khademi Eslam [a]

Joints are important components of wooden structures that provide continuity to wood and wood products. In this study, a finger joint with two finger lengths of 5 and 10 mm was investigated with two adhesives: epoxy and polyvinyl acetate reinforced with cellulose nanocrystals (CNC) and nanoclay at three levels of 0%, 0.4%, and 1.5% using the free bending vibration method in a free-ended beam on a plywood. The results indicated that except for vibration damping, the values at the 10 mm joint length were significantly higher at the 95% confidence level. The effect of CNC was also significantly higher than that of nanoclay at the 95% confidence level. Both nano-based adhesives at 1.5% had significantly better results. Epoxy adhesive also had significantly better results than polyvinyl acetate adhesive. Overall, the joint with a 10 mm finger length jointed with epoxy adhesive and reinforced with 1.5% CNC yielded the best results.

DOI: 10.15376/biores.21.3.8340-8349

Keywords: Finger joint; Adhesive; Cellulose nanocrystals; Nanoclay; ACE

Contact information: a: Department of Wood and Paper Engineering, Faculty of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran, Iran, P.O. Box 14515/775; b: Iran Polymer and Petrochemical Institute, Tehran, Iran;
** Corresponding author: h_hemmasi@srbiau.ac.ir*

INTRODUCTION

Plywood is one of the most well-known wood-based, multipurpose engineered wood products used in construction projects, decorative structures, and box making. Plywood is made of wood veneers that are bonded together with special adhesives and varnishes. Plywood sheets are a durable, cost-effective, and versatile material that is used for a variety of construction purposes, both interior and exterior (Brožek 2016). Manufacturers produce this product for construction applications, where it is suitable for both wet and dry conditions, including subfloors, single-layer flooring, wall coverings, roof and floor underlayments, structural insulation panels, wood lattice joists and concrete formwork, as an exterior wall and roof covering, and also has high resistance to lateral forces such as loads, wind and earthquakes (Frolovs *et al*. 2017). It may be used both as a structural underlayment and as a final finish surface. Finger jointing is one of the most durable and widely used engineered wood technique. With this joint, wood and wood products of limited length can be jointed with minimum material waste (Ayarkwa *et al*. 2001). This is particularly important given the limited wood resources. Another factor affecting the behavior of finger-jointed wood is the type of adhesive used. Resin-based joints play an important role in the strength of products, and with the increase in the production and consumption of engineered wood products in buildings.

Polyvinyl acetate (PVA) is a thermoplastic resin widely used in the wood-working industry. This adhesive has many advantages, including being relatively inexpensive, non-toxic, and having minimal impact on the environment. It is often used in the form of a water-based emulsion (Kaboorani *et al*. 2013). Polyvinyl acetate creates a strong adhesive bond when used on porous materials such as wood and paper. Therefore, the process of changing the adhesion strength is limited by the mechanical properties of the polymer (Kaboorani and Riedl 2011).

On the other hand, epoxy resin has long been of considerable importance in engineering and is widely used to bond various materials. Components made from epoxy-based materials have developed special mechanical, thermal, and electrical properties. However, the scope of use of epoxy is limited due to its brittleness and poor strength. The introduction of nanotechnology has provided an opportunity to develop a new generation of adhesives with special properties that are not achieved by conventional methods. Much research has been done on improving epoxy adhesives using nanofillers.

In recent years, the use of cellulose nanomaterials and clay nanomaterials has been investigated (Hosseyni *et al*. 2014; Kaboorani *et al*. 2013; Aydemir *et al*. 2016; Ismita and Lokesh 2017; Kashtegar *et al*. 2019, Madhoushi and Kashtegar 2020; Kamboj *et al*. 2022; Ranjbar *et al*. 2024). The use of cellulose nanocrystals (CNCs) as fillers for composites has attracted the attention of researchers due to its suitable specific surface area, high tensile and flexural strength properties, and desirable interfacial adhesion properties (Aydemir *et al*. 2016; Kamboj *et al*. 2022). Nanoclay is also used as a filler in the manufacture of nanocomposites in significant quantities, so that the use of small amounts of it increases the elastic modulus, strength, heat resistance, reduces gas permeability, resistance to ignition, and improves physical properties. Also, this increases in properties in most cases does not cause a decrease in other properties in other cases (Nafchi *et al*. 2015).

Epoxy and polyvinyl acetate adhesives are widely used in the wood and wood products industries. Considering the remarkable features stated for using CNC and nano-clay sodium montmorillonite in enhancing the strength properties of polymer adhesives, the aim of this study was to investigate the effect of using epoxy resin and PVA-reinforced with CNC and nano-clay sodium montmorillonite at 3 levels of 0%, 0.4%, and 1.5% on the dynamic properties using the free vibration method in a free-free beam with finger joints with finger lengths of 5 and 10 mm in plywood, so that steps can be taken to maintain the quality and increase the useful life of the product. No research has been conducted on finger joints on plywood so far. Therefore, in this research, the aim was to investigate the role of this joint on acoustic properties for panel board with the mentioned adhesives and nanomaterials.

EXPERIMENTAL

Materials

First, plywood (5 layers) with a thickness of 2 cm and a density of 0.98 g/cm^3 made of ulmus wood (*Ulmus glabra*) from hyrcanian forests was bonded with phenol formaldehyde adhesive (Part, Isfahan, Iran). Epoxy adhesive with the trademark Ren Lam M 950 with technical specifications: colorless, viscosity of 1600 to 1250 centipoise at 50 °C, density 1.1 g/cm^2, use time with hardener 30 min, setting time of 4 h with colorless amine hardener with density 1.2 g/cm^2, and viscosity of 370 to 470 centipoise at 25 °C, which can be mixed with the adhesive at a ratio of 1 to 2, was used (from Resin & Chasbe

Shomal Chemical Industries, Mazandaran, Iran). The properties of polyvinyl acetate (PVA) adhesive are also listed in Table 1 (from Resin & Chasbe Shomal Chemical Industries, Mazandaran, Iran, grade 3). The cellulose nanocrystals and nanoclay required in this study were obtained from Negin Tejarat Shargh Company (Tehran, Iran) (Table 2).

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	10 to 20 min	0.15 to 0.2	6

Table 2. Characteristics of Nanoparticles

Type	Density (g/cm^3)	Particles Size (µm)			Specific Surface Area (m^2/g)
		Length	Width	Diameter	
Cellulose nanocrystal (CNC)	0.5	50 to 170	50 to 70	70 ± 10	25 to 30
Nano-clay sodium montmorillonite (NC)	0.7	10 to 15	4 to 5	1 to 2	220 to 270

Preparing Plywood Beams

The plywood beams were cut to 20 × 40 × 360 mm dimensions with a panel saw (Fig. 1). About 144 beams were selected for the test and divided into 2 groups of 72 for joint with two finger lengths. Then each group was divided into 2 groups of 12 with 6 repetitions for jointing and mixing with nano fillers at three levels of 0%, 0.4%, and 1.5%.

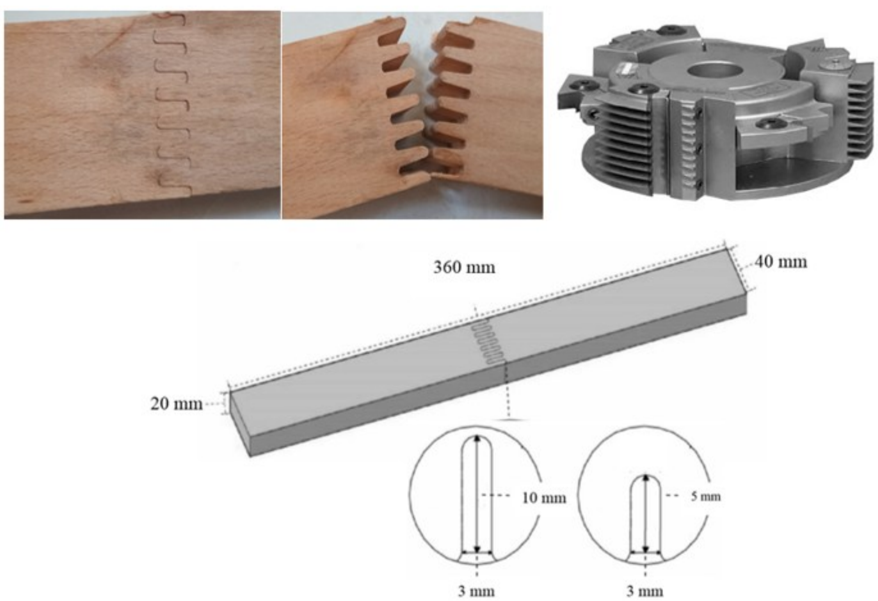

Fig. 1. Schematic view of finger joint in the middle of plywood beams (Ranjbar *et al.* 2024)

Adhesive and Nanomaterial Preparation

Cellulose nanocrystals and nanoclay were prepared at two levels of 0.4% and 1.5% based on the wet weight of two epoxy and PVA resins and were added to each of the resins according to the method of Zhou *et al*. (2006). The resulting mixture was stirred using an ultrasonic device at a temperature of 20 to 35 °C, power of 90 W, and frequency of 30 Hz for 30 min to disperse the particles. After that, hardener was added to it at a ratio of 50% by weight of the epoxy resin and stirred at high speed for 10 min using a magnetic stirrer.

Gluing the Test Specimens

The test samples of each group were glued with brush at a rate of 200 g/cm^3 and placed in a hand clamp under laboratory conditions (22 °C ±2 °C and 65 ±5% relative humidity) for two weeks until the joint was fully established.

Free Bending Vibration Test in a Free-Free Beam

After that, the specimens were removed from the hand clamp and placed in a climate-controlled room with a humidity of 65±5% and a temperature of 21±2 °C for 2 weeks to equalize the humidity. After that period, a free bending vibration in free-free beam test was performed on them (Fig. 2). The distance from the edges was 0.224 of the length and the impact was made at the end of the specimen.

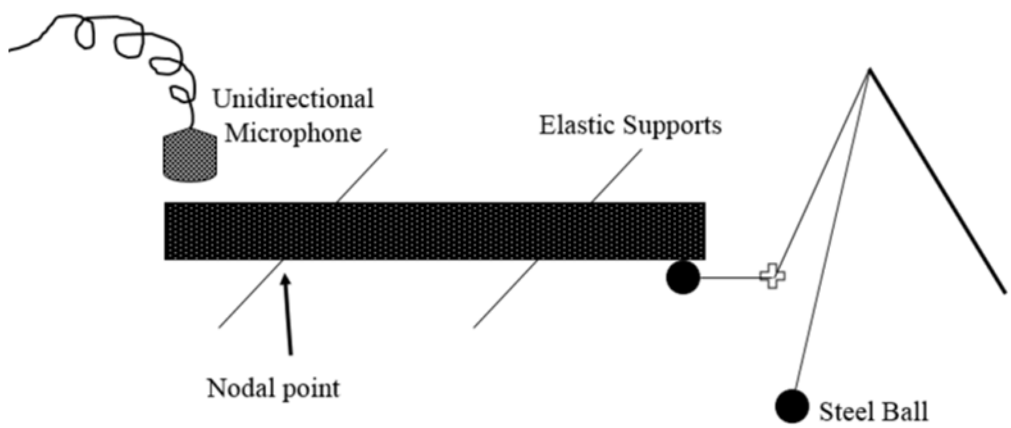

Fig. 2. Schematic view of the beam under flexural vibration

Calculations of the dynamic modulus of elasticity were performed on the joints according to Timoshenko's beam theory as in Eq. 1:

$$a_{\mathrm{n}} = \left(\frac{E}{\rho}\right) - \left(\frac{E}{K \times G_{ij}}\right) b_n \tag{1}$$

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 tanδ corresponds to the damping of vibration.

The 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; Roohnia 2019). This parameter was calculated through Eq. 4,

$$\mathrm{ACE} = \frac{\frac{E}{\rho^3}}{d} \tag{4}$$

where E is the modulus of elasticity (Pa), d is the density of the wood specimens (kg/m^3), tanδ is damping factor, and ACE is the acoustical converting efficiency (m^4.s^{-1}.kg^{-1}).

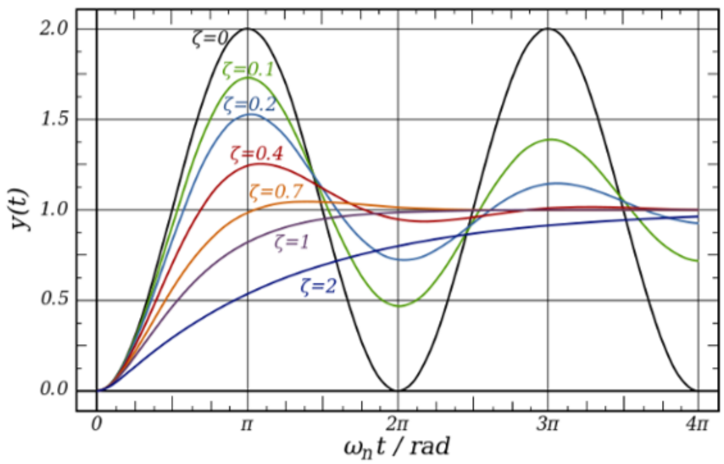

Fig. 3. Expressions of damping capacity in the temporal field through logarithmic decrement λ

In this study, the effect of different treatments was evaluated using factorial test in a completely randomized design using SPSS version 20 software to identify the effective factors statistically (IBM Corp., Armonk, NY, USA). Additionally, comparison of means was performed using Duncan's multiple range test to examine the significance of the effect of variables at a 95% confidence level.

RESULTS AND DISCUSSION

Figures 4 and 5 show the effect of adhesive and nano-bonding on the dynamic elastic modulus for 10 and 5 mm joints.

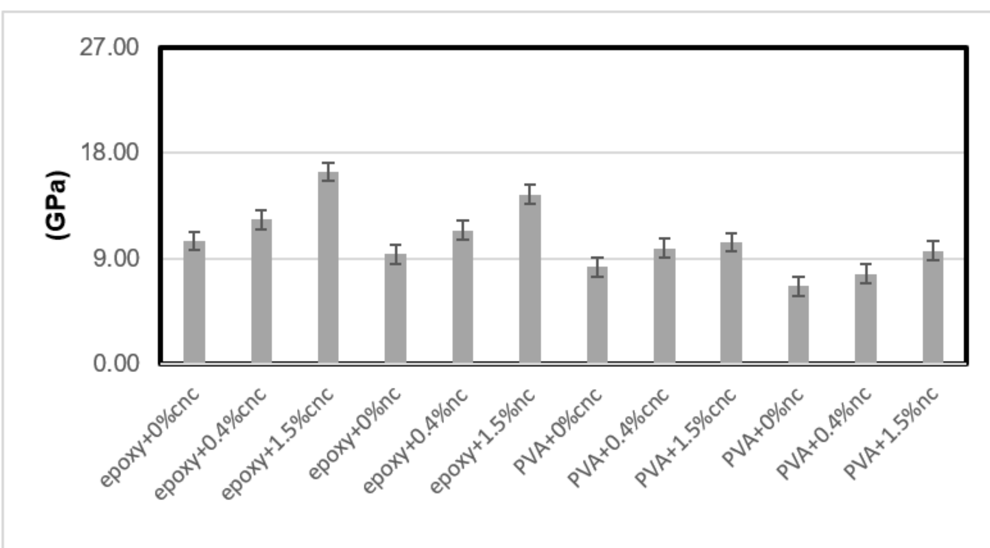

Fig. 4. Changes in dynamic elastic modulus due to adhesive and nano-bonding at a finger length of 10 mm

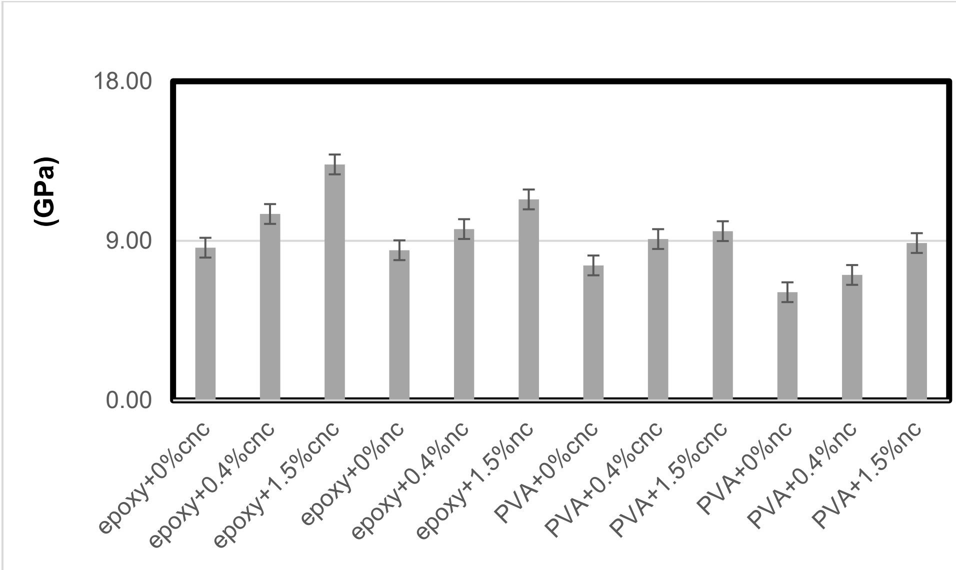

Fig. 5. Changes in dynamic elastic modulus due to adhesive and nano-bonding at a finger length of 5 mm

As is clear from these figures, nano at two levels of 0.4% and 1.5% in both joints resulted in a significant increase in the dynamic elastic modulus at a 95% confidence level. The increase in the 10 mm joint was significantly greater than the 5 mm joint at the 95% confidence level. The effect of epoxy adhesive and CNC was also significantly greater than that of PVA and nanoclay (NC). Furthermore, Yavari *et al*. (2015) and Ranjbar *et al*. (2024) reported a greater effect of a 10 mm finger length on the modulus of elasticity compared to a 5 mm finger length in wood, which in this study also occurred in plywood. The greater effect of CNC compared to nanoclay were also reported by Kamboj *et al*. (2022), and Aydemir *et al*. (2016) in which a similar result occurred on plywood.

Figures 6 and 7 show the damping factor results for joints with tooth lengths of 10 and 5 mm.

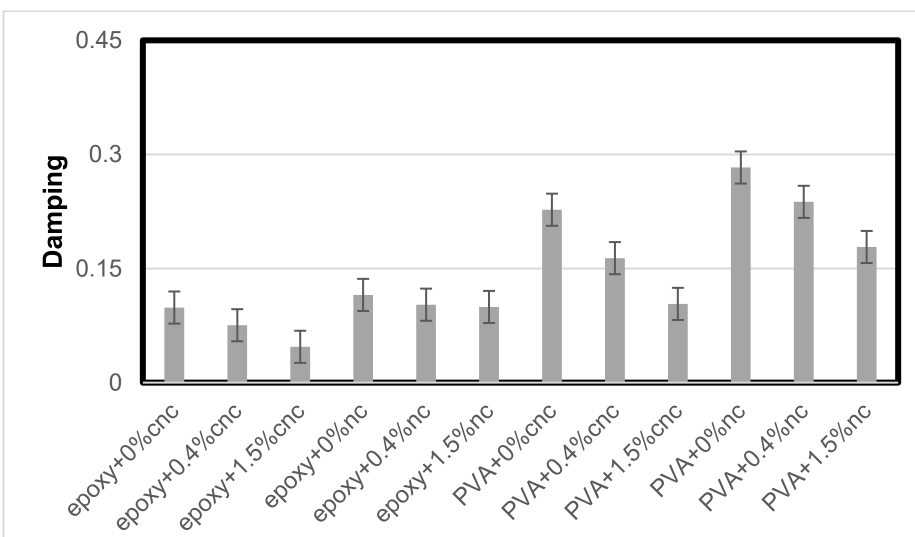

Fig. 6. Changes in damping factor due to adhesive and nano-bonding in a 10 mm finger length joints

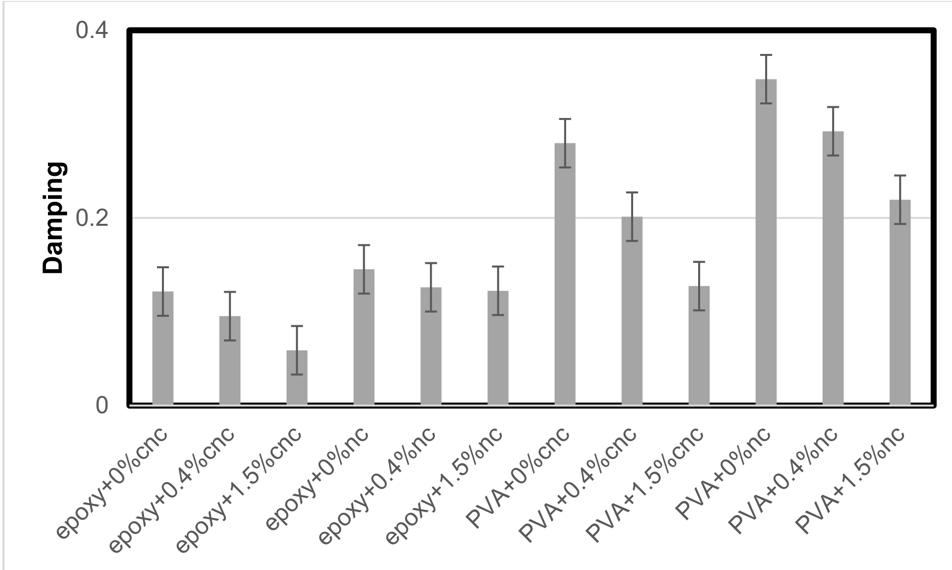

Fig. 7. Changes in damping factor due to adhesive and nano-bonding in a 5 mm finger length joints

As can be seen in the two figures, the 10 mm finger length significantly reduced damping factor in all treatments at the 95% confidence level. This is because of the greater uniformity of joints with a 10 mm finger length compared to 5 mm at the joint. Cellulose nanocrystals exhibited significantly lower attenuation at the 95% confidence level. Meanwhile, Yavari *et al*. (2015) and Ranjbar *et al*. (2024) presented similar results for wood. The efficiency of epoxy and CNC adhesives is also significantly higher than PVA and NC at the 95% level. The result was obtained by Kambog *et al*. (2022) on wood, which was obtained in the present study on multilayer plywood.

Figures 8 and 9 show the results of the ACE for joints of 10 and 5 mm lengths.

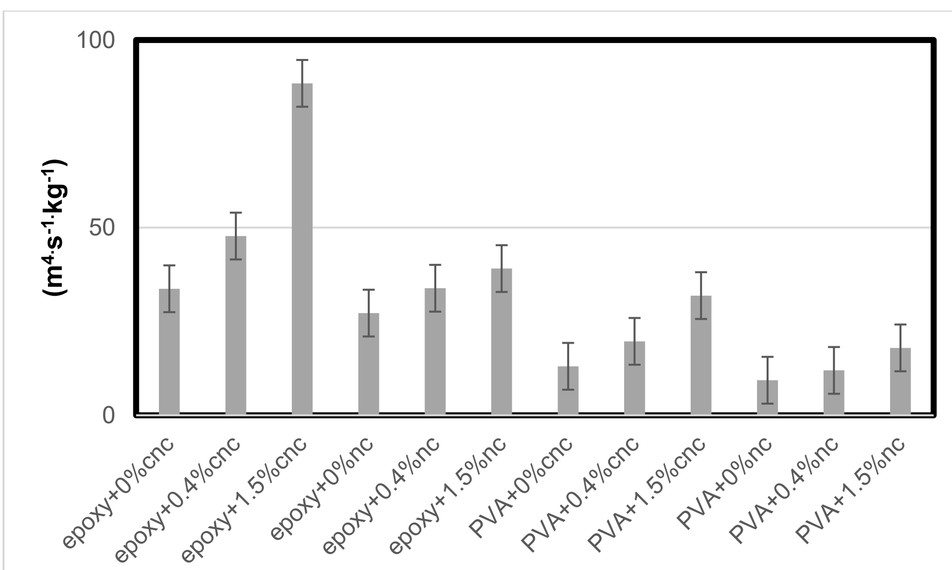

Fig. 8. Changes in acoustic conversion efficiency due to adhesive and nano-bonding at a finger length of 10 mm

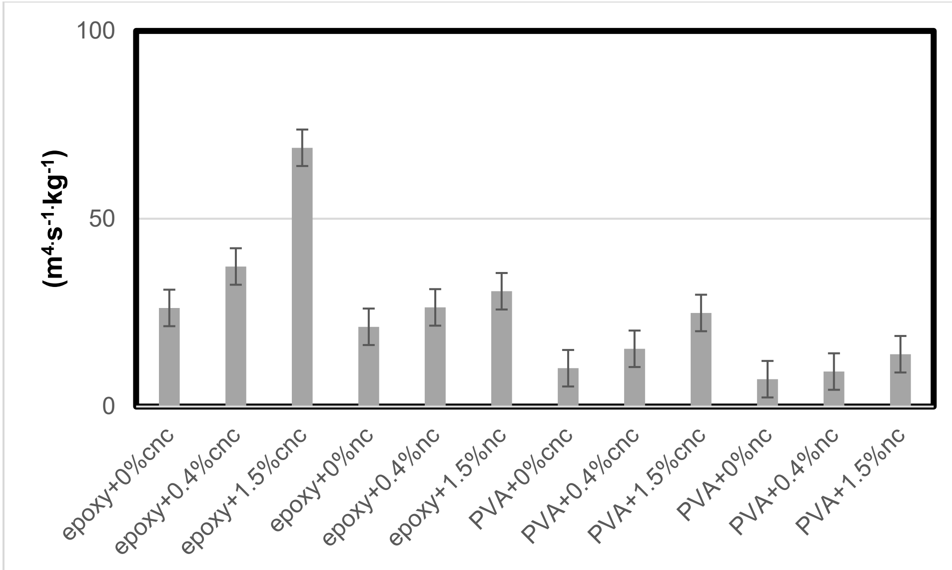

Fig. 9. Changes in acoustic conversion efficiency due to adhesive and nano-bonding at a finger length of 5 mm

As can be seen, the results for joints with a length of 10 mm were significantly higher at the 95% confidence level than for joints with a length of 5 mm. The above result was not unexpected, when considering Eq. 4. In addition, Yavari *et al*. (2015) and Ranjbar *et al*. (2024) obtained similar results to this research on wood. The effect of epoxy adhesive and CNC was greater than that of PVA adhesive and NC in increasing the ACE values at a 95% confidence level.

CNCs contain high densities of surface hydroxyl groups (–OH) that establish dense hydrogen bonding with the polymer matrix and the timber cell wall, enhancing dynamic modulus and decreasing internal friction. Nanoclays also reinforce polyvinyl acetate and epoxy adhesives as matrix materials due to their high tensile strength and also exhibit favorable resistance and flexibility to changes in matrix materials.

CONCLUSIONS

1. The dynamic modulus of elasticity in the joints with a finger length of 10 mm was significantly higher than that of 5 mm at the 95% confidence level.
2. Damping factor due to the 5 mm joint showed a significantly greater increase at the 95% confidence level than the 10 mm connection.
3. The acoustic conversion efficiency in the joints with a finger length of 10 mm was significantly increased compared to the joints with a tooth length of 5 mm.
4. Epoxy adhesive showed significantly better resistance than polyvinyl acetate adhesive at a 95% confidence level.
5. Both nanomaterials, CNC and NC, significantly improved the performance of joints with two finger lengths at the 95% confidence level.

6. The application of 1.5% of both CNC and NC caused a significant increase at the 95% confidence level in most of the measured properties.
7. Cellulose nanocrystals performed significantly better than nanoclay at a 95% confidence level

ACKNOWLEDGMENTS

This article is derived from a doctoral thesis by Hamidreza Abbasi (Ph.D. Student of Islamic Azad University, Science and Research Branch – Tehran, Iran) entitled, "Evaluation of strength in adhesive joints in wood composite products with epoxy and polyvinyl acetate reinforced with nanoclay and cellulose nanocrystals (CNCs)". The authors appreciate the support received from the Islamic Azad University, Science and Research Branch-Tehran, Iran.

Conflict of Interest

Authors must make clear any personal interest or relationship that could potentially be affected by the publication of their manuscript.

REFERENCES CITED

Ayarkwa, J., Hirashima, Y., and Sasaki, Y. (2001). "Predicting modulus of rupture of solid and finger jointed tropical African hardwoods using longitudinal vibration," *Forest Products Journal* 51(1), 85-92.

Aydemir, D., Gunduz, G., Aşık, N., and Wang, A (2016). "The effects of poly (vinyl acetate) filled with nanoclay and cellulose nanofibrils on adhesion strength of poplar and Scots pine wood," *Drvna Industrija* 67(1) 17-24. https://doi.org/10.5552/drind.2016.1441

Brožek, M. (2016). "Bonding of plywood," *Research in Agricultural Engineering* 62(4), 198-204. https://doi.org/10.17221/ 39/2015-RAE

Frolovs, G., Rocens, K., and Sliseris, J. (2017). "Shear and tensile strength of narrow glued joint depending on the grain direction of plywood plies," *Procedia Engineering* 172, 292-299. https://doi.org/10.1016/j.proeng.2017.02.117

Hosseyni, M. J., Rahimi, S., Rahimi, S., and Faezipour, M. M. (2014). "Effect of nanoclay particles on the properties of particleboards," *Journal of Basic and Applied Scientific Research* 4(3), 280-287.

Ismita, N., and Lokesh, C. (2017). "Effects of different nanoclay loadings on the physical and mechanical properties of *Melia composita* particleboard," *Bois and Forets des Tropiques* 334(4), 7-12. https://doi.org/10.19182/bft2017.334.a31487

Kaboorani, A., and Riedl, B. (2011). "Effects of adding nano-clay on performance of polyvinyl acetate (PVA) as a wood adhesive," *Composites Part A: Applied Science and Manufacturing* 42(8), 1031-1039. https://doi.org/10.1016/j.compositesa.2011.04.007

Kaboorani, A., Riedl, B., and Blanchet, P. (2013). "Ultrasonication technique: A method for dispersing nanoclay in wood adhesives," *Journal of Nanomaterials* 2013(4), 1-9. https://doi.org/10.1155/2013/341897

Kamboj, G., Gaff, M., Smardzewski, J., Haviarov, E. Hui, D., Rezaei, R., and Kumar, A. (2022). "Effect of cellulose nanofiber and cellulose nanocrystals reinforcement on the strength and stiffness of PVAc bonded joints," *Composite Structures* 295(1), 1-9. https://doi.org/10.1016/j.compstruct.2022.115821

Madhoushi, M., and Keshtegar, B. (2020). "Study of the effect of carbon nanofiber reinforced epoxy adhesive on the flexural moment capacity of corner joints in furniture," *Iranian Journal of Wood and Paper Science Research* 36(4), 305-316. https://doi.org/10.22092/ijwpr.2021.354572.1681

Nafchi, H. R., Abdouss, M., Najafi, S. K., Gargari, R. M., and Mazhar, M. (2015). "Effects of nano-clay particles and oxidized polypropylene polymers on improvement of the thermal properties of wood plastic composite," *Maderas. Ciencia y Tecnología* 17(1), 45-54. https://doi.org/10.4067/S0718-221X2015005000005

Ono, T., and Norimoto, M. (1983). "Study on Young's modulus and internal friction of wood in relation to the evaluation of wood for musical instruments," *Japanese Journal of Applied Physics* 22(4), 611-614. https://doi.org/10.1143/JJAP.22.611

Ranjbar, B., Lashgari, A., Jahan-Latibari, A., and Tajdini, A. (2024). "Cellulose nanofiber and nanoclay's effect on acoustic properties of oak wood (*Quercus castaneifolia*) finger joint," *BioResources* 19(4), 7619-7636. https://doi.org/10.15376/biores.19.4.7619-7636

Roohnia, M. (2019). "Wood: Vibration and acoustic properties," in: *Reference Module in Materials Science and Materials Engineering*, 19th Ed., Elsevier Inc., Amsterdam, Netherlands. https://doi.org/10.1016/B978-0-12-803581-8.01996-2

Yavari, A., Hemmasi, A., Roohnia, M., and Marušák, R. (2015). "Dynamic Young's modulus of scarf- and finger-jointed beams using longitudinal vibration method," *BioResources* 10(4), 6886-6895. https://doi.org/10.15376/biores.10.4.6886-6895

Zhou, Y., Pervin, F., Rangari, V. K. and Jeelani, S. (2006). "Fabrication and evaluation of carbon nano fiber filled carbon/epoxy composite," *Materials Science and Engineering: A* 426(1-2), 221-228. https://doi.org/10.1016/j.msea.2006.04.031

Article submitted: June 2, 2026; Peer review completed: July 4, 2026; Revised version received: July 5, 2026; Further revised version accepted: July 6, 2026; Published: July 17, 2026.
DOI: 10.15376/biores.21.3. 8340-8349