Effects of Intersection Angle on the Nail-holding Performances of *Pinus massoniana* and *Cunninghamia lanceolata* Dimension Lumber

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Self-tapping screws and round steel nails were driven into *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber pieces to explore the influence of intersection angle on nail-holding performance, expecting to provide a more complete scientific basis for the connection of wood structures. The results showed that (1) as the intersection angle declined, the nail-holding strength of self-tapping screws for both *P. massoniana* and *C. lanceolata* dimension lumber gradually decreased. At the intersection angle of 90°, nail-holding strength was the maximum, being 79.8 and 80.5 N/mm, respectively; (2) With the reduction of the intersection angle, the nail-holding strength of round steel nails for both dimension lumber initially increased and then gradually declined. The maximum nail-holding strength (21.0 N/mm) of *P. massoniana* appeared at the intersection angle of 45° while that (22.3 N/mm) of *C. lanceolata* appeared at 60°; (3) No matter for self-tapping screws or round steel nails, the rigidity at the connection point was the greatest at the intersection angles of 90° and 0° (cross-section). If diagonally nailed into lumber, both self-tapping screws and round steel nails can enhance the ductility of connection joints, where the former exerts a more evident effect.

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INTRODUCTION

The design of wood connection joints plays an important role in wood structure splicing. The performance of connective components directly affects the structural strength, service life, stability, and reliability (Li *et al*. 2019; Berwart, *et al*. 2022; Wu *et al*. 2022; Yu 2022; Ren *et al*. 2024; Wang *et al*. 2024), and it generates a significant impact on the building appearance, installation convenience, and structural reasonability. Meanwhile, wood has various shortcomings such as low tensile strength, proneness to splitting, and strength change with water content (Lee *et al*. 2020; Stanciu *et al*. 2020; Nyobe *et al*. 2021). Therefore, the reasonable application of wood structural connection technology is the key to the design result and serves an important link of wood structural construction technology.

The mortise-tenon connection mode is generally adopted for traditional wooden structures, which embodies the unique construction technology of wood structures and is the essence of traditional construction technology in China (Wang and Lee 2018; Yang *et al*. 2020; Zhang *et al*. 2021; Zhang *et al*. 2022). However, mortise-tenon connection faces difficulties in production and processing and it can be hardly formed by mechanically designing molds, accompanied by the stricter workpiece specifications and susceptibility to the loss of wooden raw materials. Additionally, this connection mode fails to meet the requirements of modern engineering wooden structures that specify a high strength and a great rigidity.

Joint connection has become a significant link in the research on wood structures thanks to the design concept of modern timber structural buildings. The round steel nail-self-tapping screw connection is an important connective component most used in wood structures and features, with sufficient tightness and toughness, and considered convenient, fast, safe, and reliable construction when compared with mortise-tenon connection (Celebi and Kilic 2007; Oczifci 2009; Li *et al*. 2023, 2024). In real life, "nail withdrawal" is often observed in nail connected joints, which has a great influence on the sustainable utilization and safety of wood structures. This is mostly attributed to the nail-holding performance of wood-nail connections. Generally, self-tapping nails or round steel nails are driven vertically into the wood at 90°, but in some special connection designs, for example, inclined round steel nails are used to connect the wall columns in light wood structures to the baseplate, or the inclined self-tapping screws are used to connect them to the top beam plate. The nail-holding performance of wood is related to the nail type (Teng *et al*. 2020; Li *et al*. 2023, 2024), nail diameter (Rammer *et al*. 2001; Aytekin 2008), wood density and moisture content (Gehloff 2011; Brander 2019; Gutknecht and Macdougall 2019; Khai and Young 2022), and guide hole (Akyildiz 2014), but the nail connection performance at different nail driving angles has been scarcely studied.

Based on the above analysis, self-tapping screws and round steel nails were driven into *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber at different angles to explore the influence of intersection angle on nail-holding performances, expecting to provide a more complete scientific basis for the connection design of wood structures.

EXPERIMENTAL

Materials

Pinus massoniana and *Cunninghamia lanceolata* dimension lumber pieces were produced in Guiyang, China (106° east longitude, 26° north latitude, and about 1100 km in altitude), with the age of about 25 years. After logging, the dimension lumbers were sawn and processed. According to the standard method of testing nail-holding power of wood GB/T 14018 (2009), *P. massoniana* and *C. lanceolata* were processed into 150 mm × 50 mm × 50 mm specimens, and then they were naturally ventilated and dried. The air-dry density and moisture content of *P. massoniana* dimension lumber were 0.49 g/cm^3 and 11.7%, respectively, while those of *C. lanceolata* dimension lumbers were 0.43 g/cm^3 and 11.5%, respectively. Round steel nails used in this study were commercially available, with 3.5 mm in nail rod diameter, 88.5 mm in nail rod length, and 7.5 mm in nail cap diameter. Commercially available self-tapping screws used were 3.5 mm in nail rod outer diameter, 2.6 mm in nail rod inner diameter, 62 mm in nail rod length, 6.8 mm in nail cap diameter and 1.1 mm in screw pitch (Li *et al*. 2023, 2024).

Processing and Preparation of Materials

According to GB/T 14018 (2009), the dimension lumber specimens were placed under constant temperature, constant humidity, and good ventilation for 6 months to keep their moisture content at about 12%, and the specimens without knots, cracks, decay, and discoloration were selected to determine the density. The nails with straight ejector pin and no rust and no defect on the surface were picked out and driven into the lumbers at the position as shown in Fig. 1. The penetration depth of the nails was 20 mm without pre-drilled holes and the angle of nail insertion was controlled by the device similar to Fig. 2.

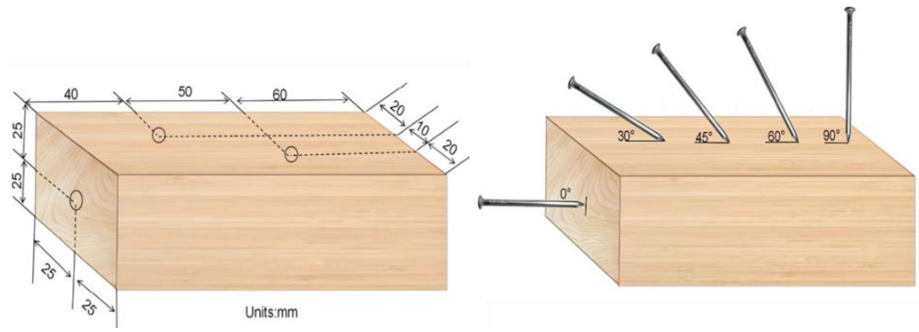

Fig. 1. Schematic diagram of pull-out nail-holding power test

Because only the test method of vertical nailing into wood blocks is provided in GB/T 14018 (2009), the nail-holding power when driving nails at a slant angle cannot be tested. Therefore, 90°, 60°, 45°, and 30° model fixtures were self-designed according to test requirements, as shown in Fig. 2.

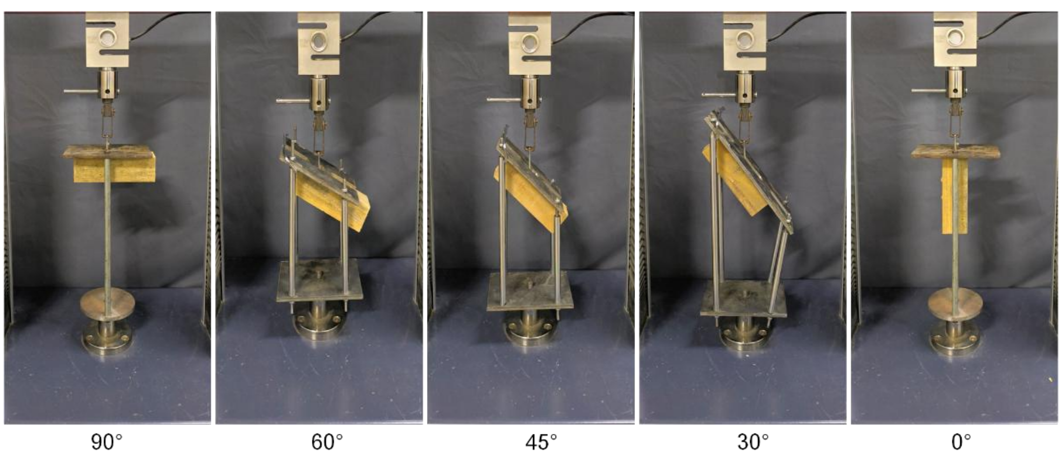

Fig. 2. The device design of the nail-holding performances at different nail intersection angles

Nail-holding Power Test

Round steel nails or self-tapping screws were driven into the radial sections of *P. massoniana* and *C. lanceolata* dimension lumber pieces at 90°, 60°, 45°, and 30°. Then, the test was performed by loading with a WDS-50KN universal mechanical testing machine at a uniform speed of 2.5 mm/min, and the nail-holding strength test was completed within 10 to 60 min. After the test, the maximum load was recorded and the load-displacement curve data was saved. The final nail-holding strength was the mean value of 30 specimens.

Statistical Analysis

The data were processed in Excel and Origin software, and the significance of differences was judged *via* the one-way analysis of variance (ANOVA) ($P < 0.05$).

RESULTS AND DISCUSSION

Effects of Driving Angle of Self-tapping Screws on Nail-holding Performance of Dimension Lumbers

When the diameter of self-tapping screws was 3.5 mm, the influence of the driving angle into the radial section on nail-holding strength is displayed in Fig. 3. At the driving angle of 90°, the nail-holding strength of *P. massoniana* and *C. lanceolata* specimens was 79.8 and 80.5 N/mm, respectively. With the reduction of the intersection angle, the nail-holding strength of both dimension lumbers presented a gradual declining trend. At the driving angle of 0° (driving into the cross-section), the nail-holding strength of *P. massoniana* and *C. lanceolata* specimens was 61.8 and 57.6 N/mm, respectively. When self-tapping screws were pulled out, the wood fiber embedded into the self-tapping screw threads and the wood fiber around the nail rod experienced shearing action, and the nail-holding strength mainly depended on the anti-shear force. When the driving angle was 90°, the wood fiber between the self-tapping screw threads and the wood fiber around the nail rod went through a failure mode of peeling off; at the driving angle of 0°, the sideslip between fibers became the failure mode. When the driving angle decreased from 90° to 0°, the failure mode of wood fibers was gradually transformed from peeling into sideslip, which was also the source of the nail-holding strength. The sideslip force between wood fibers was smaller than the peeling force; that is, the nail-holding strength gradually declined with the reduction of the intersection angle.

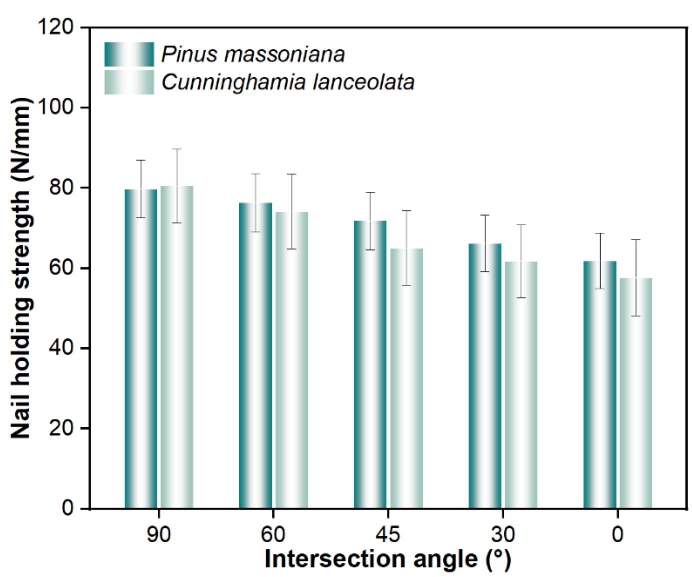

Fig. 3. Effects of intersection angles of self-tabbing screw on the nail holding strength of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber

By comparing the nail-holding strength of the two wood species in Fig. 3, the overall nail-holding strength of *P. massoniana* was higher than that of *C. lanceolata* at the same driving angle. This is because the nail-holding strength of wood is directly proportional to the density, and the nail-holding strength of *P. massoniana* is high due to its high density. The nail-holding capacity of *P. massoniana* was higher than that of *C. lanceolata*. This was because the pre-drilled hole was not used in this work and *P. massoniana* was more likely to experience cracking when nailed at a 90° angle, resulting in reduced nail holding force.

Effects of Driving Angle of Round Steel Nails on Nail-holding Performance of Dimension Lumbers

When the diameter of round steel nails was 3.5 mm, the influence of the driving angle into the radial section on the nail-holding performance is displayed in Fig. 4. At the driving angle of 90°, the nail-holding strength of *P. massoniana* and *C. lanceolata* specimens was 16.6 and 18.7 N/mm, respectively. With the reduction of the intersection angle, the nail-holding strength of these dimension lumber pieces increased at first and then decreased gradually. The maximum nail-holding strength of *P. massoniana* dimension lumber was 21.0 N/mm at the intersection angle of 45°; the maximum nail-holding strength (22.3 N/mm) of *C. lanceolata* dimension lumber appeared at the intersection angle of 60°.

The wood cell wall is mainly composed of primary wall, secondary wall, and middle layer (ML) between two cells, and the secondary wall accounts for 95% or more of the cell wall thickness at most. The secondary wall is divided into secondary wall outer layer (S1), secondary wall middle layer (S2), and secondary wall inner layer (S3), in which the thickness of S2 layer reaches 70% to 90% of the cell wall thickness, and the microfibril arrangement forms an included angle of 10° to 30° with the longitudinal axis (Brandner 2019; Teng *et al*. 2020; Li *et al*. 2023, 2024). The nail-holding strength of round steel nails in the radial section depends on the joint action of the nail's extrusion on microfibril and the microfibril's shear resistance. In the process of pulling out the round steel nails, the nail-wood interactive force varied with the shear angle between the nail rod and microfibrils. Theoretically speaking, therefore, relatively high nail-holding strength could be achieved within the range of driving angle from 60° to 80°. The maximum nail-holding power of *P. massoniana* dimension lumbers appeared at the intersection angle of 45°, which might be affected by the wood extractives contained therein. In addition, this might also result from the difference in springwood and summerwood content of the radial section, the difference in the springwood and summerwood connection mode, and the difference in lignose content. At the driving angle of 0°, both *P. massoniana* and *C. lanceolata* dimension lumber reached the minimum nail-holding strength, being 15.1 and 14.7 N/mm, respectively. This is because when driving into the cross-section the microfibrils of wood ray cells on the cross-section presented a horizontal arrangement while others basically showed a longitudinal parallel arrangement, and they were connected through hydrogen bonding. Under this circumstance, the nail-holding strength is mainly decided by the frictional force generated by the extrusion between longitudinal microfibrils. Hence, the nail-holding strength on the cross-section is the minimum.

Comparing the nail-holding strength of *P. massoniana* and *C. lanceolata* as shown in Fig. 4, it could be known that the nail-holding strength of the latter was higher than that of the former overall at the same driving angle. This is because the density of *C. lanceolata* is slightly smaller than that of *P. massoniana*, and round steel nails can form a close contact with *C. lanceolata* wood fibers, endowing *C. lanceolata* with greater nail-holding strength.

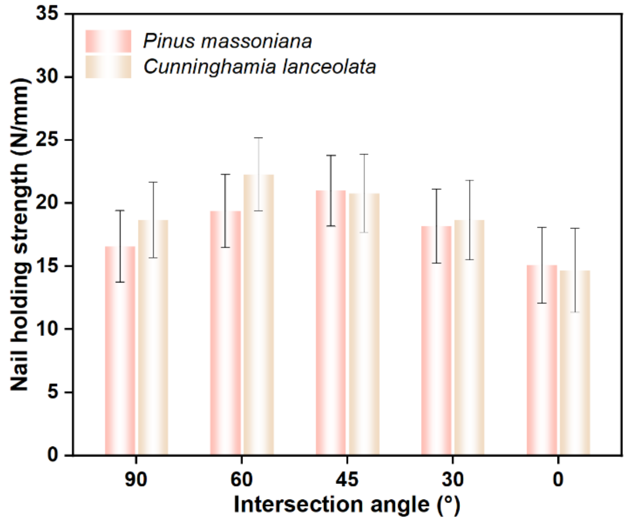

Fig. 4. Effects of intersection angles of round steel nail on the nail holding strength of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber

Load-displacement Curves of Nail Holding Test

Figures 5(a) and 5(b), respectively, show the load-displacement curves of the nail-holding strength tests of *P. massoniana* and *C. lanceolata* at different driving angles of self-tapping screws. At the driving angle of 0°, the load-displacement curves of the test specimens had multiple peaks and were generally short. With the increase of the displacement, the curve first increased and then decreased, and then a continuous round and blunt short peak with gradually decreasing strength was formed. At the driving angle of 0° when screws were driven in from the cross-section, the nail-holding strength was mainly derived from the extrusion between wood fibers, *i.e.*, the static frictional force between self-tapping screws and fibers; so, the curve was short. When the self-tapping screw was pulled out, the wood fibers embedded into the thread part and the adjacent fibers gradually went through breakage and sideslip after the nail-holding strength reached the limit, the static friction force was turned into dynamic friction force, which gradually declined to a certain extent and then was transformed into static frictional force again. During the whole process, the static friction and dynamic friction forces were constantly transformed, and the load-displacement curve fluctuated up and down, forming more short peaks. As the self-tapping screw was gradually pulled out, however, the contact area between the nail rod and wood fibers decreased gradually, and the short peak strength decreased gradually as a whole. When the driving angle was 90°, 60°, 45°, and 30°, the load-displacement curves of *P. massoniana* and *C. lanceolata* specimens were single-peak curves. This is because when the angle was 30° to 90°, the screw was driven in from the radial section. In this case, the nail-holding strength was mainly attributed to the shear force of wood fibers. After the self-tapping screw was pulled out, the nail-holding strength peaked, and wood fibers were cut off. The failure displacement was the minimum at the intersection angle of 90°, along with the maximum slope of the curve and the great rigidity. When the intersection angle was 60°, 45°, and 30°, the slope of the curve evidently decreased, indicating that the ductility of connection joints could be enhanced to some extent by driving in self-tapping screws.

Figures 5(c) and 5(d) respectively display the load-displacement curves of the nail-holding strength tests on *P. massoniana* and *C. lanceolata* at different driving angles of round steel nails. The greatest difference of round steel nails from self-tapping screws was that the curve showed obvious reciprocal yield and presented a linear declining trend after reaching the highest point. The reason for the yield was the same as the load-displacement curve of self-tapping screws on the cross-section; *i.e.*, the nail-holding strength mainly came from the static friction force between nails and fibers. The pull-out process of nails was accompanied by the continuous mutual transformation of static friction and dynamic friction forces. When the intersection angle of round steel nails was 90° and 0°, the failure displacement was the minimum, the slope of the curve was the maximum, and the rigidity was great. At the intersection angle of 60°, 45°, and 30°, the failure displacement apparently increased, and the slope of the curve obviously declined, manifesting that the ductility of connection joints could be evidently strengthened by diagonally driving in round steel nails.

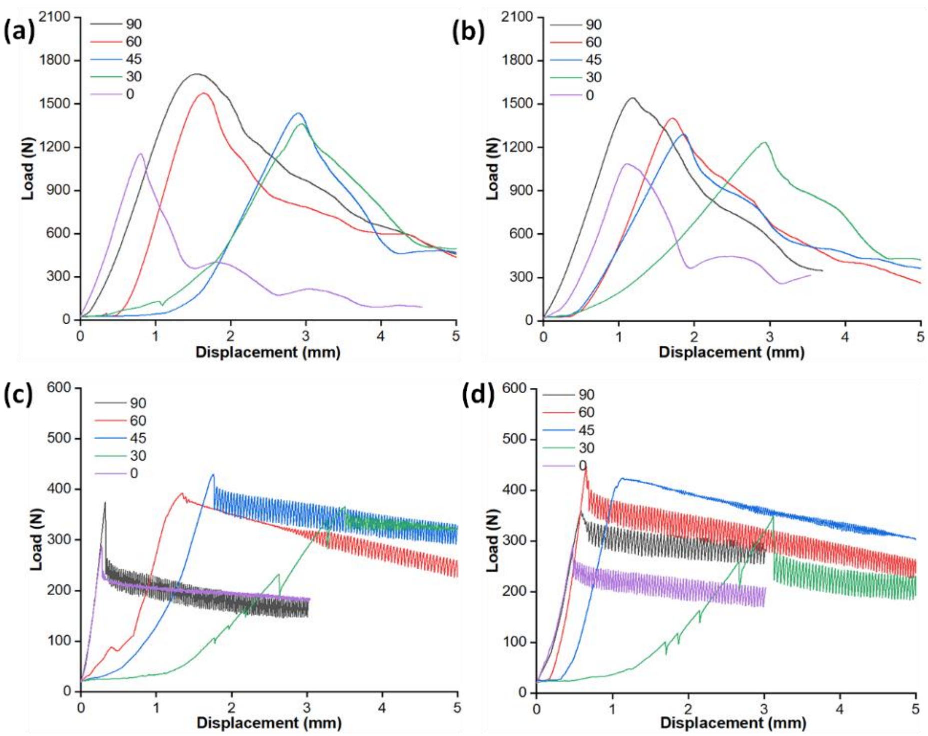

Fig. 5. Load-displacement curves of nail holding performance tests: a: *Pinus massoniana*-self tabbing screw; b: *Cunninghamia lanceolata*-self tabbing screw; c: *Pinus massoniana*-round steel nail; d: *Cunninghamia lanceolata*-round steel nail

The Phenomenon of the Test

Figure 6 shows the profile map of the connection positions of *P. massoniana* and *C. lanceolata* and the state of the specimens when the self-tapping nails were driven in at different angles. From the overall state of the specimens, when self-tapping screws were pulled out, the wood fibers around the nail hole were not evidently deformed, but obvious thread marks were left in the nail grooves. As observed from the profile map, when the driving angle was 90°, because the length direction of wood fibers was perpendicular to the self-tapping screw threads, wood fibers could be better embedded and extruded into threads in the process of driving in self-tapping screws. When self-tapping screws were pulled out, a shear force perpendicular to the length direction of wood fibers was generated. Self-tapping screws experienced the bite with wood so that the wood fibers around the nail rod experienced peeling, tear, and deformation, the wood surface bulged, and saw dust was brought out from the range of failure. With the reduction of the intersection angle, it was harder for wood fibers to be embedded between threads. The anti-pullout and shear force direction gradually turned from horizontal direction into longitudinal direction, and the bulging phenomenon on the wood surface gradually became unobvious. At the intersection angle of 0°, the shear force leading to failure in the anti-pullout process occurred in the longitudinal direction of wood, the hydrogen bond between wood fibers was prone to breakage and sideslip, and the wood fibers between threads and those around the nail rod were cut off, separated, and pulled out together with the nail rod. These changes were similar in *P. massoniana* and *C. lanceolata* species.

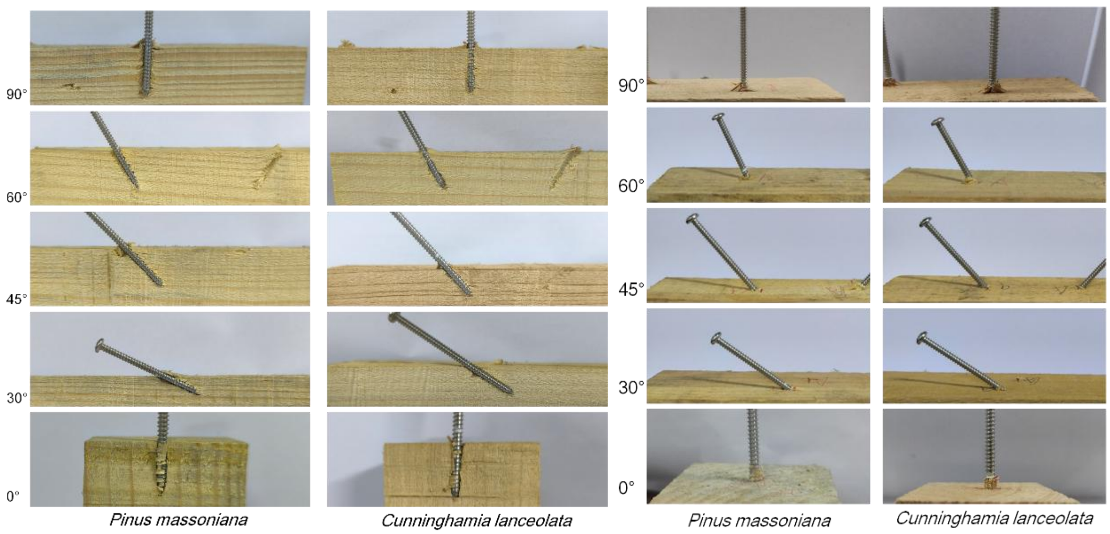

Fig. 6. Test profile and state for nail holding power of self-tapping nails with different screwing angles

Figure 7 shows the profile map of the connection position of *P. massoniana* and *C. lanceolata* and the state of the specimens when the round steel nails were driven at different angles. From the overall state of the specimens, in the process of pulling out the round steel nails, neither *P. massoniana* nor *C. lanceolata* adhered to wood fibers, the surface remained relatively intact, and the inner wall of the nail groove was smooth. From the profile map, when the intersection angle was 90°, the wood fibers collapsed at every junction of springwood and summerwood, and a small gap was produced near the nail rod, which was related to the great difference in density at the junction. When the round steel nails were driven in at 90°, part of the wood broke, and the extrusion force on the nail decreased, which further affected the nail-holding strength, being consistent with the conclusion presented earlier. Theoretically, high nail-holding strength could be obtained at the intersection angles of 60° to 80°, and the maximum nail-holding strength of *C. lanceolata* dimension lumbers appeared at 60°, which basically was in accord with this conclusion. However, the maximum nail-holding strength of *P. massoniana* dimension lumber appeared at 45°. Through a comparison in Fig. 7, the failure degree of *P. massoniana* was greater than that of *C. lanceolata* at the intersection angle of 60°, while at 45°, an opposite situation appeared, and relative intactness was kept around the nail rod of round steel nails, explaining the reason well. When the intersection angle of round steel nails was 45°-0°, with the reduction of the intersection angle, the round steel nails gradually shifted towards a direction parallel to wood fibers, the phenomena of collapse and cracking were gradually mitigated, and the nail-holding strength declined accordingly.

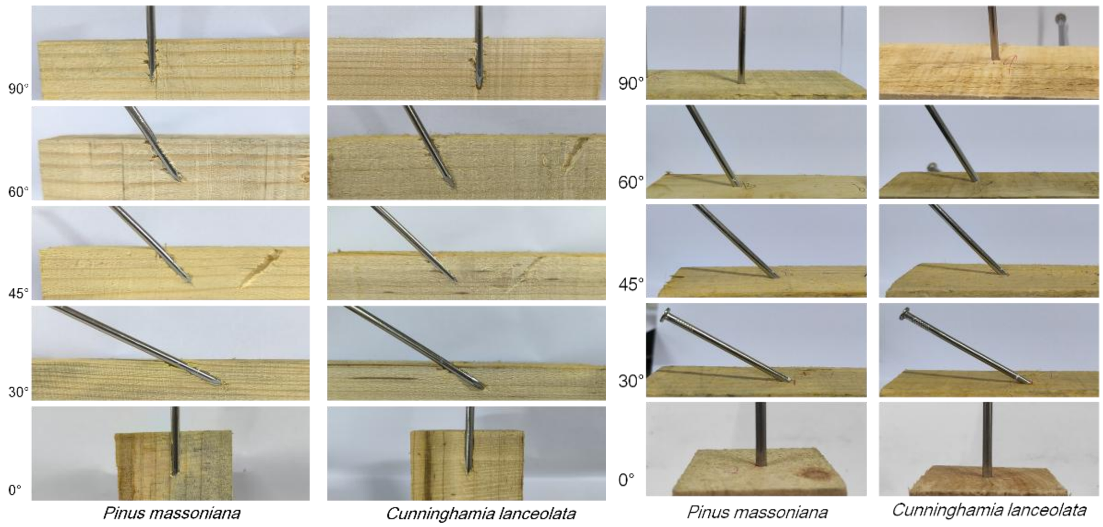

Fig. 7. Test profile and state for nail holding power of round steel nails with different insertion angles

CONCLUSIONS

1. Effects of intersection angles on the nail-holding performances of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumbers were evaluated. The results showed that: As the intersection angle declined, the nail-holding strength of self-tapping screws for both *P. massoniana* and *C. lanceolata* dimension lumber pieces gradually decreased. At the intersection angle of 90°, nail-holding strength was the maximum, being 79.8 and 80.5 N/mm, respectively, for the two species of wood.
2. With the reduction of the intersection angle, the nail-holding strength of round steel nails for both dimension lumbers firstly increased and then gradually declined. The maximum nail-holding strength of *P. massoniana* appeared at the intersection angle of 45° while that of *C. lanceolata* appeared at 60°.
3. No matter for self-tapping screws or round steel nails, the rigidity at the connection point was the greatest at the intersection angles of 90° and 0°. If diagonally nailed into lumber, both self-tapping screws and round steel nails can enhance the ductility of connection joints, where the former exerts a more evident effect.

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REFERENCES CITED

Aytekin, A. (2008). “Determination of screw and nail withdrawal resistance of some important wood species,” *International Journal of Molecular Sciences* 9(4), 626-637. DOI: 10.3390/ijms9040626

Akyildiz, M. H. (2014). “Screw-nail withdrawal and bonding strength of paulownia (*Paulownia tomentosa* Steud.) wood,” *Journal of Wood Science* 60(3), 201-206. DOI 10.1007/s10086-014-1391-5

Berwart, S., Estrella, X., Montaño, J., Santa-María, H., Almazán, J. L., and Guindos, P. (2022). “A simplified approach to assess the technical prefeasibility of multistory wood-frame buildings in high seismic zones,” *Engineering Structures* 257, article ID 114035. DOI: 10.1016/j.engstruct.2022.114035

Brandner, R. (2019). “Properties of axially loaded self-tapping screws with focus on application in hardwood,” *Wood Material Science and Engineering* 14(5), 254-268. DOI: 10.1080/17480272.2019.1635204

Celebi, G., and Kilic, M. (2007). “Nail and screw withdrawal strength of laminated veneer lumber made up hardwood and softwood layers,” *Construction and Building Materials* 21(4), 894-900. DOI: 10.1016/j.conbuildmat.2005.12.015

GB/T 14018-2009 (2009). “Method of testing nail holding power of wood,” Standardization Administration of China, Beijing, China.

Gehloff, M. (2011). *Pull-out Resistance of Self-Tapping Wood Screws with Continuous Thread*, Master’s Thesis, The University of British Columbia, Canada.

Gutknecht, M. P., and MacDougall, C. (2019). “Withdrawal resistance of structural self-tapping screws parallel-to-grain in common Canadian timber species,” *Canadian Journal of Civil Engineering* 46(10), 952-962. DOI: 10.1139/cjce-2018-037

Khai, T. D., and Young, J. G. (2022). “Withdrawal capacity and strength of self-tapping screws on cross-laminated timber,” *Structures* 37, 772-786. DOI: 10.1016/j.istruc.2022.01.033

Lee, J. S., Sokhansanj, S., Lau, A. K., and Lim, C. J. (2020). “Physical properties of wood pellets exposed to liquid water,” *Biomass and Bioenergy* 142, article ID 105748. DOI: 10.1016/j.biombioe.2020.105748

Li, H., Wang, B., Wei, P., and Wang, L. (2019). “Cross-laminated timber (CLT) in China: A state-of-the-art,” *Journal of Bioresources and Bioproducts* 4(1), 22-31. DOI 10.21967/jbb.v4i1.190

Li, D., Zhang, B., Tu, Y., Xiao, G., Tian, M., Xu, X., Zhong, X., Zhang, Q., Wu, Z., and Liang, J. (2023). “Nail holding performance of self-tapping screws on Masson pine and Chinese fir dimension lumbers,” *Journal of Renewable Materials* 11(10), 3725-3738. DOI: 10.32604/jrm.2023.027895

Li, D., Yu, L., Li, L., Liang, J., Wu, Z., Yang, G., Yin, S., and Gong, F. (2024). “Comparison of nail-holding performance of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber based on round steel nails,” *BioResources* 19(1), 670-682. DOI: 10.15376/biores.19.1.670-682

Nyobe, C. J., Lissouck, R. O., Ohandja, L., and Emmanuel, Y. (2021). “Variability of the mechanical strength of Congo basin timbers,” *Wood Material Science and Engineering* 17(3), 210-220. DOI: 10.1080/17480272.2021.1912173

Ozcifci, A. (2009). “The effects of pilot hole, screw types and layer thickness on the withdrawal strength of screws in laminated veneer lumber,” *Materials in Engineering* 30(7), 2355-2358. DOI: 10.1016/j.matdes.2008.11.001

Rammer, D. R., Winistorfer, S. G., and Bender, D. A. (2001). "Withdrawal strength of threaded nails," *Journal of Structural Engineering* 127(4), 442-449. DOI: 10.1061/(asce)0733-9445(2001)127:4(442)

Ren, A., Zhao, Y., Wang, X., Xu, Z., Yu, C., and Pan, B. (2024). "Effect of high-temperature heat treatment on the physical and mechanical properties of *Taxodium* hybrid 'Zhongshanshan' wood," *Journal of Forestry Engineering* 9(4), 25-33. DOI: 10.13360/j.issn.2096-1359.202309031

Stanciu, M. D., Teodorescu, H. D., and Vlase, S. (2020). "Degradation of mechanical properties of pine wood under symmetric axial cyclic loading parallel to grain," *Polymers* 12(10), article ID 2176. DOI: 10.3390/polym12102176

Teng, Q. C., Wang, F. B., Que, Z. L., and Zeng, N. (2020). "Effects of angles on the screw and nail withdrawal strength in dimension lumber," *Scientia Silvae Sinicae* 56(1), 154-161. DOI: 10.11707/j.1001-7488.20200115

Wang, Y., and Lee, S. H. (2018). "A theoretical model developed for predicting nail withdrawal load from wood by mechanics," *European Journal of Wood and Wood Products* 76, 973-978. DOI: 10.1007/s00107-017-1227-2

Wang, Z., He, S., Zhang, X., Li, W., and Leng, W. (2024). "Physical and chemical properties of *Pinus massoniana* synergic modified with furfuryl alcohol-caprolactam," *Journal of Forestry Engineering* 9(4), 40-47. DOI: 10.13360/j.issn.2096-1359.202308024

Wu, G., Zhong, Y., Gong, Y., and Ren, H. (2022). "The calculation method of stability coefficient of CLT members in axial compression based on the effective slenderness ratio," *Journal of Forestry Engineering* 7(1), 59-65. DOI: 10.13360/j.issn.2096-1359.202105008

Yang, Z., Xia, H., Tan, J., Feng, Y., and Huang, Y. (2020). "Selection of superior families of *Pinus massoniana* in southern China for large-diameter construction timber," *Journal of Forestry Research* 31, 475-484. DOI:10.1007/s11676-018-0815-2

Yu, Y. (2022). *Research on Detection Methods of Looseness Properties of Bolted Connections in Timber Structures based on Deep Learning*, Master's Thesis, Nanjing Forestry University, Nanjing, China.

Zhang, L., Chen, Z., Dong, H., Fu, S., Ma, L., and Yang, X. (2021). "Wood plastic composites-based wood wall's structure and thermal insulation performance," *Journal of Bioresources and Bioproducts* 6(1), 65-74. DOI: 10.1016/j.jobab.2021.01.005

Zhang, B., Wu, Z., Liang, J., Yu, L., Xi, X., Lei, H., and Du, G. (2022). "Effects of polyethylene glycol on the flexibility of cold-setting melamine-urea-formaldehyde resin," *European Journal of Wood and Wood Products* 80, 975-984. DOI: 10.1007/s00107-022-01801-x

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