Comparison of Nail-holding Performance of *Pinus massoniana* and *Cunninghamia lanceolata* Dimension Lumber Based on Round Steel Nails

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In this study, the influence of the diameter of round steel nails, the guiding bores, and the wood sections on the nail holding performance of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber was explored. The results showed that the nail-holding power of round steel nails mainly came from their friction with wood fibers, while the radial and tangential sections were also affected by the shearing action of wood fibers. The tangential section reached the largest nail-holding power, followed by the radial section and cross section. Greater wood density was associated with higher nail holding power. Under a large nail diameter, however, high-density wood was prone to plastic cracking, which influenced the nail holding power greatly. Prefabricated guiding bores could prevent plastic cracking in wood to some extent and improve the nail holding power of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber when diameter of round steel nails was more than 3.0 mm. For *Cunninghamia lanceolata* characterized by low density and rigidity, the wood fiber was in close contact with the round steel nail and internal cracking could not be easily generated under a large diameter of round steel nails.

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Keywords: Pinus massoniana; Cunninghamia lanceolata; Dimension lumber; Nail connection; Round steel nail; Nail-holding performance

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INTRODUCTION

Pinus massoniana and *Cunninghamia lanceolata* are widely planted, and they have the characteristics of fast growth, high economic benefit, and strong regeneration ability. Houses built with *Pinus massoniana* and *Cunninghamia lanceolata* can be seen throughout Southern China (Wang *et al*. 2019; Yu *et al*. 2020; Wu *et al*. 2021; Wang *et al*. 2022; Zhang *et al*. 2022a; Zhang *et al*. 2023a). As an important connection mode of wood structure, nail connection is more compact and tougher than mortise-tenon connection, and it is convenient and fast to construct, safe, and reliable, thus becoming the most commonly used connection in wood structures (Tian and Xu 2019; Liu *et al*. 2020; Zheng *et al*. 2022;Berwart*et al*. 2022; Xia *et al*. 2022). At present, the parameters of nail-holding performance of *Pinus massoniana* and *Cunninghamia lanceolata* have been rarely investigated. To ensure the rationality and safety of the nails used by *Pinus massoniana* and *Cunninghamia lanceolata* in buildings and furniture, therefore, it is necessary to study the nail-holding performance of *Pinus massoniana* and *Cunninghamia lanceolata*.

The nail-holding power of wood refers to the resistance when the nail is pulled out of wood, which is an important performance index of wood (Aytekin 2008; Taj *et al*. 2009; Prevatt *et al*. 2014). The nail holding power varies indifferent woods. The nail holding performance of wood generally has been found to be linear with its density; higher density results in higher nail holding power (Brandner 2019; Teng *et al*. 2020). Higher moisture content reduces the nail holding performance of wood (Akyildiz 2014; Gutknecht and MacDougall 2019). The nail holding performance of wood's longitudinal surface is greater than that of its bottom end (Rammer *et al*. 2001; Zhao *et al*. 2010; Barcík *et al*. 2014; Deng *et al*. 2017).

Self-tapping screws and round steel nails are used in wood structure connections. Self-tapping nails work through friction and shearing wood fibers, thus displaying better nail holding performance than round steel nails and are more widely used in practice (Que *et al*. 2014; Ceylan and Girgin 2020; Zhang *et al*. 2022b). Most reports on wood nail holding performance are based on threaded nails, while the basic research on circular steel nail connection is relatively few. In fact, in real life, round steel nails are applied to dimension lumber in quantity, but there are few published studies about the connection of round steel nails. In Method for Testing Nail Holding Power of Wood (GB/T14018-2009), only the nail-holding power of ordinary round steel nails with a diameter of 2.5 mm under static load is specified as an index to measure the wood performance, which is not enough for the stability and reliability of wood structures. In this study, the influence of the diameter of round steel nails, the guiding bores, and the wood sections on the nail-holding performance of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber was explored to provide a scientific basis for the connection design of *Pinus massoniana* and *Cunninghamia lanceolata* balsa dimension lumber pieces.

EXPERIMENTAL

Materials

Pinus massoniana and *Cunninghamia lanceolata* dimension lumber pieces, produced in Guiyang, were from trees that were about 25 years old, with average air-dry densities of 0.49 g/cm^3 and 0.42 g/cm^3, and average moisture content of 11.7% and 11.5%, respectively. According to GB/T14018-(2009), the dimension lumber of *Pinus massoniana* and *Cunninghamia lanceolata* were processed into specifications of 150 mm (radial section) × 50 mm (tangential section) × 50 mm (cross section). Round steel nails, commercially available, with straight ejector pins and no surface rust, defect, or hanger-iron on the tip were used. The detailed specifications are shown in Table 1 and Fig. 1.

Table 1. Detailed Parameters of Round Steel Nails

Diameter of Nail Rod (mm)	Length of Nail (mm)	Diameter of Nail Cap (mm)
2.0	30.0	4.5
2.5	52.5	5.3
3.0	75.0	6.5
3.5	88.5	7.5
4.0	100.0	8.3

Fig. 1. The round steel nails used for nail-holding power test

Test Methods

By reference to GB/T 14018-2009, the specimens were placed under the conditions of 23°C, humidity of 65%, and good ventilation for 6 months to stabilize its water content at about 12%. Then, the specimens without such defects as knots, cracks, decay, or discoloration were selected to measure their density, and 6 nails were nailed into the adjacent cross, radial, and tangential sections of the specimens, as shown in Fig. 2.

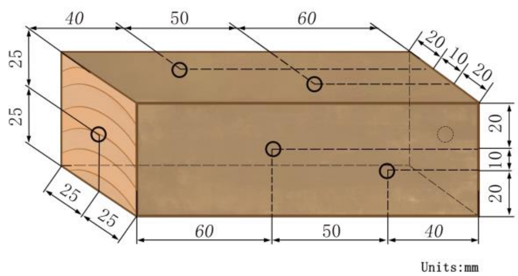

Fig. 2. Diagram for nail-holding power test

Round steel nails were nailed vertically into the wood (the specimen needing guiding bores 1.8 mm in diameter and 20 mm in depth) to a depth of 20 mm with a hammer. Within 10 to60 min after nailing, the nail holding power test was finished using a WDS-50KN universal mechanical testing machine at a uniform speed of 2.5 mm/min (Fig. 3). The final nail-holding power was the average of 8 to 10 specimens.

Fig. 3. The test of nail-holding power

RESULTS AND DISCUSSION

Effect of Diameter of Round Steel Nails on Nail-Holding Performance of *Pinus massoniana* and *Cunninghamia lanceolata* Dimension Lumber

The effect of the diameter of round steel nails on the nail-holding performance of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber is shown in Fig. 4 (taking tangential section as an example). Figure 4 shows that when the diameter of round steel nails was 2.0 to3.5 mm, the nail-holding power of *Pinus massoniana* dimension lumber increased gradually with the increase of nail diameter, from 14.4 to 22.8 N/mm, indicating an increase of 58.3%. This is because the larger the diameter of the round steel nail, the stronger the extrusion on the wood, the greater the friction between the two, and the higher the nail holding power (Bai *et al*. 2023; Chen *et al*. 2023; Zhang *et al*. 2023b). When the diameter of round steel nails was 4.0 mm, the nail holding power (20.3 N/mm) began to decrease, which was 11.0% lower than that at the diameter of 3.5 mm. This is because the excessive extrusion of the larger nail diameter caused wood cracking, resulting in local cracks inside, and the nail-holding power also decreased. The nail holding power of *Cunninghamia lanceolata* was consistent with that of *Pinus massoniana*, reaching the maximum of 24.3 N/mm when the diameter of round steel nails was 3.5 mm, and decreasing to 23.7 N/mm when the diameter was 4 mm, with a decrease of 2.5%.

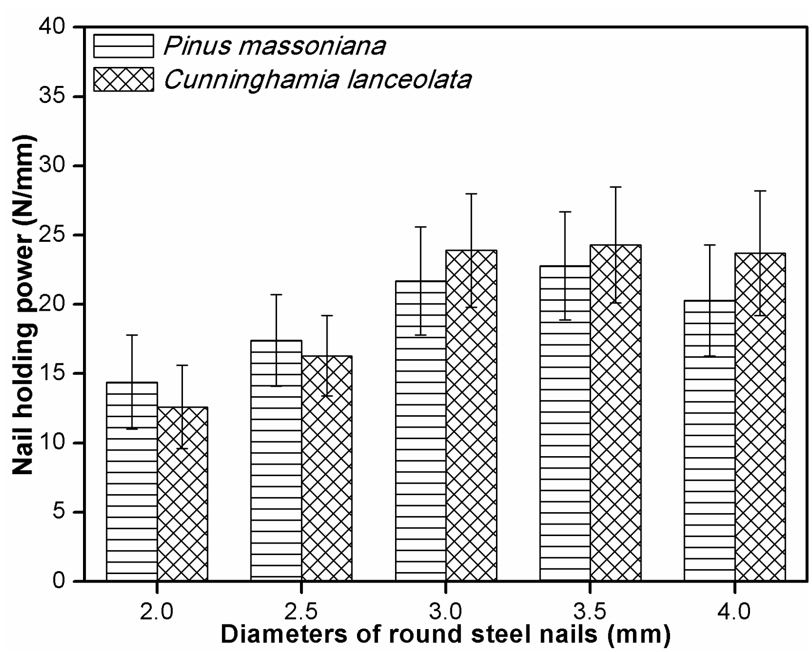

Fig. 4. Effect of the diameters of round steel nails on nail-holding power of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber**. Note**: The standard deviation was less than 5%.

Comparing the nail-holding power of *Pinus massoniana* and *Cunninghamia lanceolata* in Fig. 4, when the diameter of the round steel nail was 2.0 to 3.5 mm, the extrusion of the round steel nail on the two kinds of wood increased nearly linearly, which was an elastic stress-strain stage and could be attributed to elastic deformation. When the diameter of round steel nails was 2.0 and 2.5 mm, the nail-holding power of *Pinus massoniana* dimension lumber was higher than that of *Cunninghamia lanceolata*. At the nail diameter of 3.0 to 4.0 mm, however, the nail holding power of *Pinus massoniana* dimension lumber was weaker than that of *Cunninghamia lanceolata*, which could be ascribed to the high density and rigidity of *Pinus massoniana*. The larger the diameter of round steel nails, the looser the contact between the nails and the wood, and the excessive diameter of the nails would also lead to internal cracking of the wood. For *Cunninghamia lanceolata* with low density and rigidity, the larger the diameter of round steel nails, the closer the wood fiber was in contact with the nail, and the higher the nail holding power. This effect was shown by the different descend ranges of the nail holding power between the two kinds of wood when the nail diameter ranged from 3.5 to 4.0 mm.

Effects of Different Sections on Nail-Holding Performance of *Pinus massoniana* and *Cunninghamia lanceolata* Dimension Lumber

The results of nail-holding performance of *Cunninghamia lanceolata* and *Pinus massoniana* in different sections at the nail diameter of 2.5 mm are shown in Fig. 5. The nail holding power of *Pinus massoniana* dimension lumber in cross section, radial section, and tangential section was 8.3, 14.5, and 17.4 N/mm, respectively, which was sorted as tangential section > radial section > cross section. In the cross section, all microfibrils were arranged vertically in parallel and mainly connected by hydrogen bonds except that the microfibrils of wood ray cells were arranged horizontally. In this case, the nail holding power mainly depended on the friction generated by the extrusion between the longitudinal microfibrils, so the nail-holding power in the cross section was the smallest. The round steel nails driven by radial and tangential sections generated a certain shearing effect on microfibrils (these microfibrils were bonded by C-C and C-O bonds, and their bond energy was much greater than the hydrogen bond of microfibrils in the cross direction), so the nail-holding power of radial and tangential sections depended on the joint action of the nail pressing on microfibrils and the shearing resistance of microfibrils. In the process of pulling out round steel nails, the shear mode of nail shaft and microfibril was different, and the force between nail and wood was different, so the nail-holding power of radial section and tangential section was significantly higher than that of cross section. The nail holding power in radial section was lower than that in tangential section, which was possibly for the following reasons (Gehloff 2011; Dong *et al*. 2021): (1) the difference in the content of early and late wood between radial section and tangential section (the density and shear strength of late wood are higher than those of early wood), (2) the difference in the connection mode between early and late wood in radial section and tangential section (in radial section, early and late wood are connected in series, while in tangential section, early and late wood are connected in parallel), and (3) the difference in lignin content between radial section and tangential section (lignin endows wood with the ability to resist deformation).

The nail-holding power of *Cunninghamia lanceolata* dimension lumber pieces in cross section, radial section, and tangential section was 8.0, 13.9, and 16.3 N/mm, respectively, and the variation trend of nail-holding power in the three sections was consistent with that of *Pinus massoniana* dimension lumber, which was sorted as tangential section > radial section > cross section.

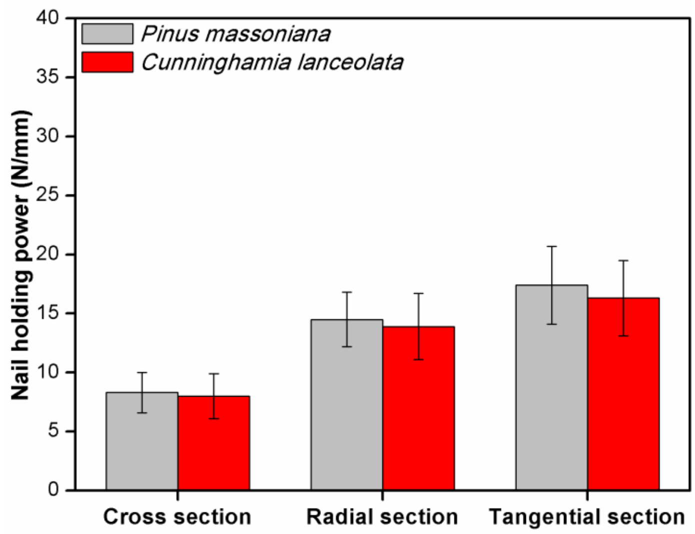

Fig. 5. Effect of different sections on nail-holding power of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber

Effect of Guiding Bores on Nail-holding Performance of *Pinus massoniana* and *Cunninghamia lanceolata* Dimension Lumber

Guiding bores 1.8 mm in diameter and 20 mm in depth were pre-processed at the nail location on the radial section of *Pinus massoniana* and *Cunninghamia lanceolata*, and then the nail holding power was tested, with result displayed in Figs. 6 and 7.

As shown in Fig. 6, when the diameter of round steel nails was 2.0 and 2.5 mm, the nail-holding power of *Pinus massoniana* dimension lumber with guiding bores was smaller than that without guiding bores. At the nail diameter of 3.0, 3.5, and 4.0 mm, the nail-holding power of *Pinus massoniana* dimension lumber without guiding bores was 16.6, 16.9, and 15.8 N/mm, respectively, while that of *Pinus massoniana* dimension lumber with guiding bores was 17.0, 17.3, and 18.2 N/mm respectively. With the increase in the diameter of round steel nails, the nail holding-power of *Pinus massoniana* dimension lumber without guiding bores first increased and then decreased (the maximum value appeared at the nail diameter of 3.5 mm), while that of *Pinus massoniana* dimension lumber with guiding bores gradually increased. At a large diameter of round steel nails, the guiding bore could improve the nail-holding power of *Pinus massoniana* dimension lumber to some extent.

With a small diameter, round steel nails could be easily nailed into wood. Compared with the specimens without guiding bores, those with guiding bores presented insufficient shear and extrusion with wood fibers, and the friction generated towards the surrounding wood when round steel nails were pulled out was relatively small, so the nail-holding power of specimens with guiding bores was lower than that without guiding bores. With the increase of nail diameter, the round steel nail could shear and squeeze wood more sufficiently, and the friction between them increased. The specimens with guiding bores did not crack obviously, when the nail diameter was 3.0, 3.5, and 4.0 mm. When the diameter of the nail was 3.0, 3.5, and 4.0 mm, the specimens without guiding bores cracked to different degrees, which further reduced the nail-holding power. The above results showed that when the diameter of round steel nail was large, the decrease of nail-holding power was attributed to the plastic cracking in wood, so the guiding bore could reduce plastic cracking and thus reduce the impact on nail-holding power.

Figure 7 shows that the impact trend of guiding bores on the nail-holding power of *Cunninghamia lanceolata* dimension lumber was basically the same as that of *Pinus massoniana*, but the nail-holding power of *Cunninghamia lanceolata* dimension lumber was improved by guiding bores more significantly (when the diameter of round steel nails was 3.5 and 4.0 mm, the nail-holding power of *Cunninghamia lanceolata* dimension lumber with guiding bores was significantly greater than that without guiding bores). The possible reason is that *Cunninghamia lanceolata* is soft in texture, the nail shaft squeezes the wood fully and cracking fails, and the compactness reaches the critical point, so that the friction between round steel nails and wood increases rapidly.

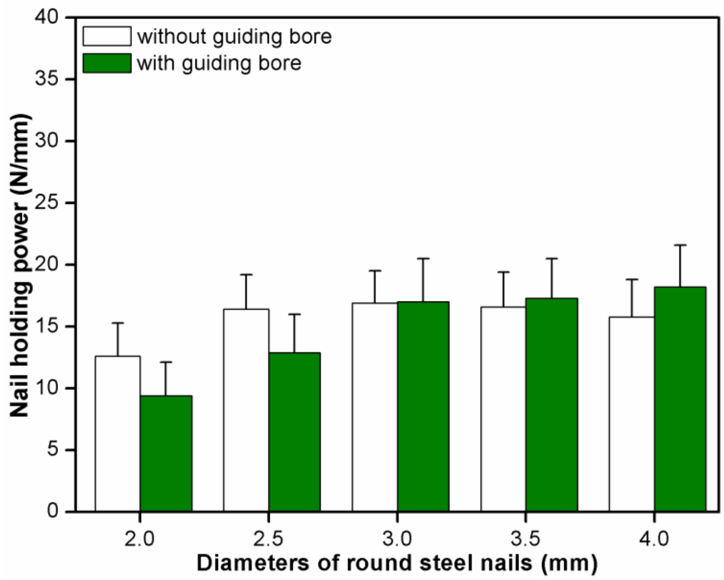

Fig. 6. Effect of guiding bores on nail holding power of *Pinus massoniana* dimension lumber

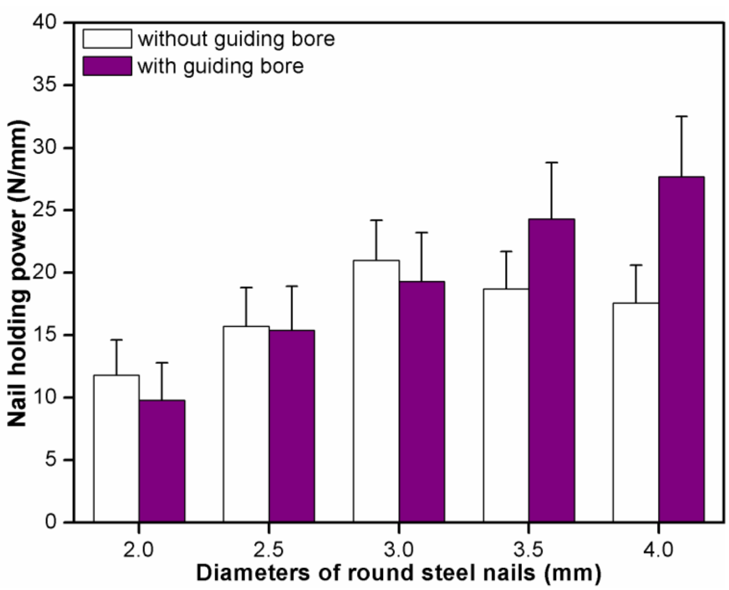

Fig. 7. Effect of guiding bores on nail-holding power of *Cunninghamia lanceolata* dimension lumber

Load-displacement Curves of Nail Holding Test

Figure 8 shows a load-displacement curve of nail-holding power of *Cunninghamia lanceolata* and *Pinus massoniana* dimension lumber in cross section, radial section, and tangential section. The load-displacement curves of the *Pinus massoniana* specimen in each section first rose slowly to reach the peak, and then they fell rapidly to form a big peak and fell slowly. The curve of the cross section dropped slowly after the peak. At the nail diameter of 2.0, 2.5, and 3.0 mm, the radial section and tangential section decreased in the form of repeated yield (they decreased to a certain value and then increased, showing a fluctuation phenomenon, but the amplitude gradually declined), but this phenomenon did not occur at large nail diameters (3.5 and 4.0 mm).

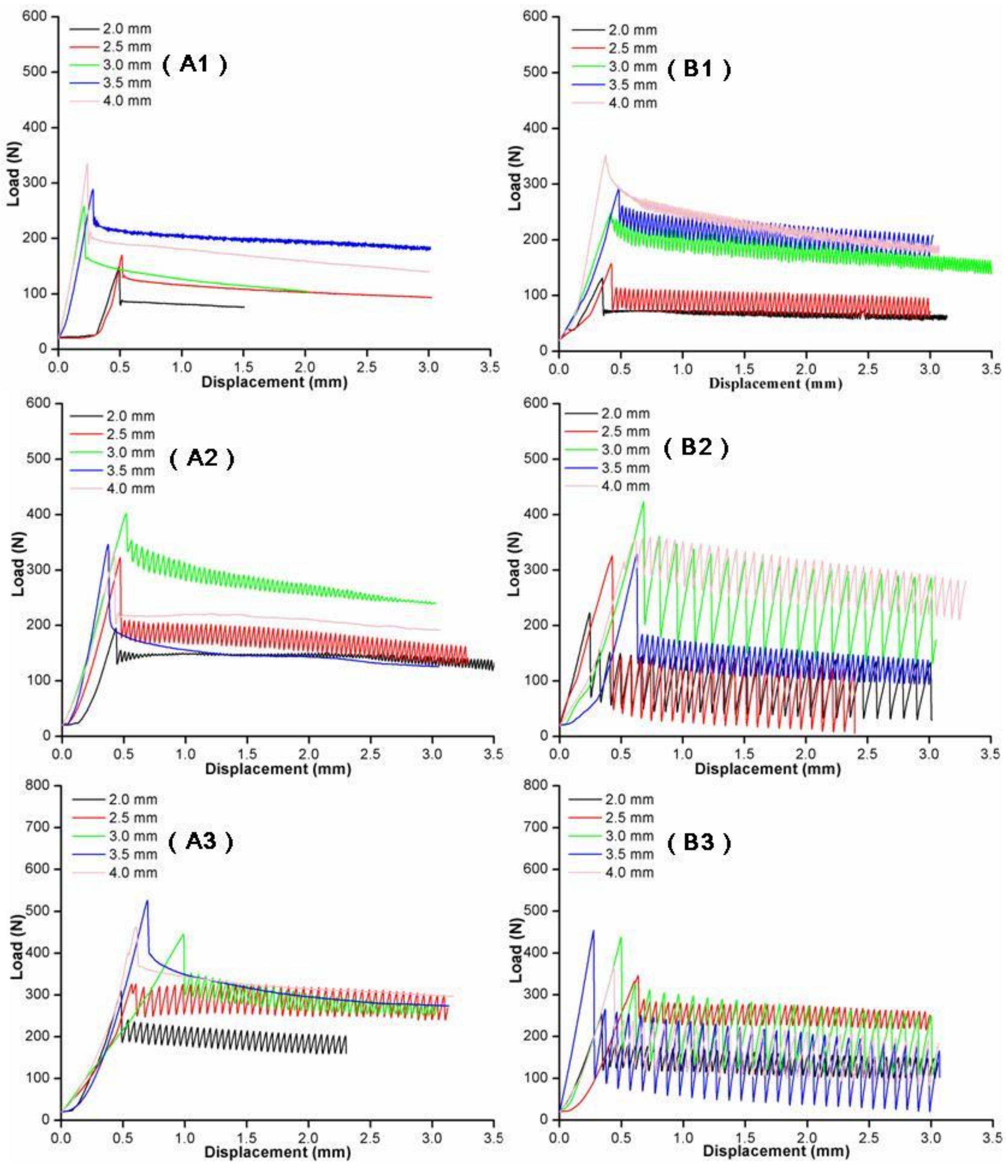

Fig. 8. Load-displacement curves of nail-holding test of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber. Note: A1. Cross section of *Pinus massoniana*; A2. Radial section of *Pinus massoniana*; A3. Tangential section of *Pinus massoniana*; B1. Cross section of *Cunninghamia lanceolata*; B2. Radial section of *Cunninghamia lanceolata*; B3. Tangential section of *Cunninghamia lanceolata*

The yield of the load-displacement curve decreased because when the nail was pulled out, the nail-holding power was mainly produced by static friction before the friction produced by the nail shaft squeezing the surrounding wood reached the ultimate strength (the nail-holding power reached the limit when static friction was the largest). As the displacement continued to increase, static friction was transformed into dynamic friction, which was gradually reduced to a certain extent and then transformed into static friction. The oscillating results correspond to stick-slip conditions, representing repeated transitions from dynamic friction to static friction states. That was to say, during the whole process, static friction and dynamic friction were constantly transformed, and the load-displacement curve fluctuated up and down, forming more yield peaks. However, as the nail was gradually pulled out, the contact surface between the nail shaft and the wood decreased, and the load-displacement curve showed an overall downward trend. When the nail diameter was 3.5 and 4.0 mm in the radial section and tangential section, the larger nail diameter caused cracking in the wood, static friction could not be converted into dynamic friction, and the load-displacement curve declined slowly and smoothly.

The load-displacement curves of the *Cunninghamia lanceolata* specimen in each section first rose slowly to reach the peak, then fell rapidly to form a big peak, and then fell in the form of repeated yield. However, the yield decrease of the load-displacement curve of the *Cunninghamia lanceolata* specimen was obviously larger than that of *Pinus massoniana*, and the fluctuation amplitude decreased with the increase in the diameter of round steel nails. This is because *Pinus massoniana* has high density and rigidity, and the contact between the nail and the wood is more relaxed at larger nail diameters. In addition, the rosin contained in *Pinus massoniana* can play a lubricating role in the process of pulling out the round steel nail, so the yield decline of the load-displacement curve of the *Pinus massoniana* specimen is smaller than that of *Cunninghamia lanceolata*.

Phenomena of Nail-holding Test

During the test, as the diameter of the round steel nail increased, the radial and tangential sections were susceptible to wood cracking (Figs. 9 and 10). In the absence of guiding bores, the nail-holding power of *Pinus massoniana* dimension lumber in the radial section was 12.6 N/mm at the nail diameter of 2.0 mm, and it reached the maximum value, 16.9 N/mm, at the nail diameter of 3.5 mm. However, the nail-holding power of *Cunninghamia lanceolata* dimension lumber in the radial section was 11.8 N/mm at the nail diameter of 2.0 mm, and reached the maximum value of 21.0 N/mm at the nail diameter of 3.5 mm. With the presence of guiding bores, the nail-holding power of *Pinus massoniana* dimension lumber was 17.3 N/mm at the nail diameter of 3.5 mm, and it reached the maximum value of 18.2 N/mm at 4.0 mm. For *Cunninghamia lanceolata* dimension lumber, the nail-holding power was 24.3 N/mm at the nail diameter of 3.5 mm and it reached the maximum value of 27.7 N/mm at 4.0 mm. Generally, a higher density indicates a stronger nail-holding power. High-density wood is also featured with large rigidity, and wood cracking can be induced at large diameters of round steel nails. For *Cunninghamia lanceolata* with small density and rigidity, the contact between wood fibers and round steel nails was tighter at larger diameters of round steel nails. Therefore, prefabricated building bores facilitate the closer contact between wood fibers and round steel nails.

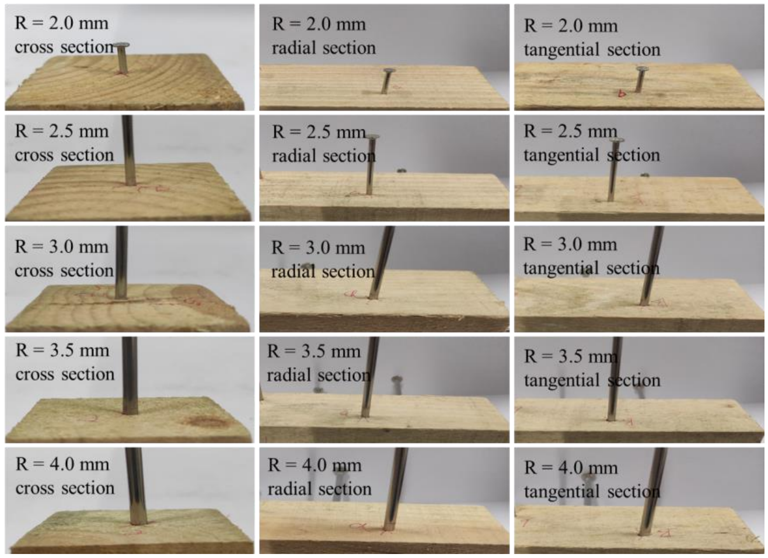

Fig. 9. Damage appearance of nail-holding test of *Pinus massoniana* dimension lumber

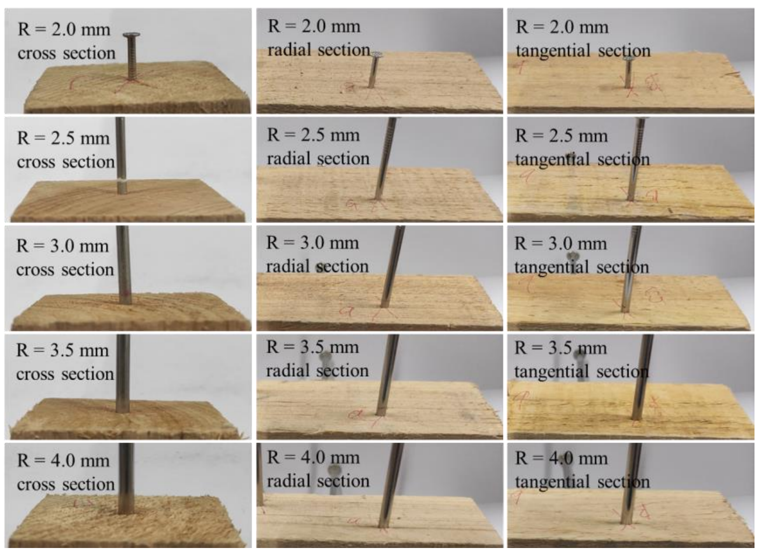

Fig. 10. Damage appearance of nail-holding test of *Cunninghamia lanceolata* dimension lumber

CONCLUSIONS

1. The nail-holding power of round steel nails mainly came from their friction with wood fibers, while the radial and tangential sections were also affected by the shearing action of wood fibers. The tangential section reached the largest nail-holding power, followed by the radial section and cross section.
2. Generally speaking, the greater the wood density, the higher the nail holding power. Under a large nail diameter, however, high-density wood was prone to plastic cracking, which influenced the nail holding power greatly.
3. Prefabricated guiding bores could avoid plastic cracking in wood to some extent, and they could further increase the nail holding power of *Pinus massoniana* and *Cunninghamia lanceolata* dimension lumber when diameter of round steel nails was

more than 3.0 mm. For *Cunninghamia lanceolata* characterized by low density and rigidity, the wood fiber was in close contact with the round steel nail and internal cracking could not be easily generated under a large diameter of round steel nails.

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