

Nail-holding Capacity of Guiding Bore Hole Diameter in *P. massoniana* and *C. lanceolata* Dimension Lumber

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The nail-holding performance of two major commercial wood species in southern China, *P. massoniana* (Masson pine) and *C. lanceolata* (Chinese fir), were investigated in this paper. Nail-holding strength tests on the two kinds of wood were conducted using self-tapping screws and round steel nails, respectively, with the focus on analyzing the impact law of guiding bore diameter on nail-holding performance. Without the guiding hole, the nail-holding force of both kinds of nails was poor. When the guiding hole diameter increased moderately, the nail-holding force showed an upward trend. Nevertheless, if the guiding hole diameter was too large, the nail-holding force would drop sharply. The nail-holding force of self-tapping screws peaked when the guiding hole diameter was 2.0 mm, and that of round steel nails reached the maximum when the guiding hole diameter was 2.5 mm. In addition, there were remarkable differences in the nail-holding force performance of *P. massoniana* and *C. lanceolata* wood under different guiding hole diameters, and their load-displacement curve characteristics also varied. Reasonable design of the diameter of the guiding hole can significantly enhance the nail-holding performance of wood, ensuring the stability and reliability of wood structure connections.

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INTRODUCTION

Timber construction—celebrated for its seismic resilience and naturally healthful indoor climate—has become the hallmark of sustainable design. Yet the very joints that once embodied its craftsmanship, the venerable mortise-and tenon, now act as a bottleneck in contemporary practice. Each joint demands painstaking handwork and minute tolerances, a process that is contrary to the needs for speed, repeatability, and economies of scale demanded by modern mechanized production. Moreover, such joints require extremely precise workmanship, which not only leads to material waste but may also fall short of the high strength and stiffness demands of contemporary structural connections (Li *et al.* 2019; Berwart *et al.* 2022; Wu *et al.* 2022; Yu 2022; Ren *et al.* 2024; Wang *et al.* 2024). In contrast, mechanical fasteners, such as common round steel nails and self-tapping screws, have become integral to modern timber joints, because of their tight fit, ductility, and ease of installation (Celebi and Kilic 2007; Aytekin 2008; Gehloff 2011; Akyildiz 2014; Brandner 2019; Gutknecht and MacDougall 2019; Khai and Young 2024). Nevertheless, in service, nailed timber assemblies are repeatedly undone by the quiet but catastrophic

drama of nail withdrawal. One by one, fasteners inch outward under cycles of moisture, temperature, and load until joints slacken, bracing loosens, and entire load paths unravel. At the heart of this premature failure lies the tenuous dialogue between wood and steel: the slender annulus of contact between nail shank and cell wall must carry shear, tension, and the swelling-shrinkage strains of a bio-based material. Where this interface is weak—whether from low-density fibre, juvenile wood, or the brittle lignin-rich zones created by overdriving—withdrawal resistance collapses, eroding both the long-term durability and the structural safety that engineers and occupants rightfully expect (Ren *et al.* 2024; Wang *et al.* 2024; Tao *et al.* 2024).

The nail-holding capacity of wood is influenced by multiple factors, including the type and diameter of the fastener, the wood's density and moisture content, and the presence and dimensions of guiding bore holes (Teng *et al.* 2020; Rammer *et al.* 2001; Li *et al.* 2023, 2024). Proper design of guiding bore holes plays a crucial role in enhancing nail-holding performance. The standard GB/T 14018 (2009) confines itself to a narrow band of relatively dense timbers and prescribes a single, immutable nail diameter of 2.5 mm together with a rudimentary table of pilot-hole sizes and depths. In practice, this rigid edict collides with the exuberant variability of real wood. This variety includes density gradients within a single board, the brittle heartwood of fast-grown plantation species, or the low-strength juvenile cores that dominate modern engineered lumber. Locked into one fastener size and a handful of penetration depths, practitioners frequently observe that nails have passed through loose fibres or, conversely, that they have burst walls of brittle latewood, leaving withdrawal capacities that fall well below design targets. The resulting scatter in connection performance undermines the very stability and reliability that the code purports to safeguard, forcing engineers into costly redundancy—extra nails, steel side-plates, or adhesives—while still leaving unobserved reserves of risk embedded in the frame.

P. massoniana (Masson pine) and *C. lanceolata* (Chinese fir) are among the most important timber species in southern China. Due to their rapid growth, strong regeneration capacity, and high economic value, they are extensively cultivated and play a vital role in maintaining ecological security and timber supply (Wang *et al.* 2019; Wu *et al.* 2021; Lei *et al.* 2024; Tao *et al.* 2024; Xu *et al.* 2025). Despite this, systematic studies on the nail-holding performance of these two wood species remain limited. To ensure their safe and effective utilization in construction, furniture, and other industries, it is important to conduct in-depth investigations into their mechanical fastener interactions. This study focuses on *P. massoniana* and *C. lanceolata*, aiming to explore the effect of guiding bore diameter on nail-holding performance, thereby providing a scientific basis for the design of timber connections in structural applications.

EXPERIMENTAL

Materials

In this study, the timber specimens of *P. massoniana* (Masson pine) and *C. lanceolata* (Chinese fir) were sourced from Guiyang City (longitude 106 °E, latitude 26 °N, elevation approximately 1100 m). The trees were approximately 25 years old at the time of harvesting.

After felling, the logs were transported to the Huaxi Haiyuan Wood Processing Plant in Guiyang, where they were sawn into standardized specimens measuring 150 mm (length) $\times$ 50 mm (width) $\times$ 50 mm (height). The specimens were then air-dried under natural ventilation conditions. The self-tapping screws used in the tests were commercially available products, with a shank outer diameter of 3.5 mm, an inner diameter of 2.6 mm, a total length of 62 mm, a head diameter of 6.8 mm, and a thread pitch of 1.1 mm. The round steel nails were also commercially sourced, with a shank diameter of 3.5 mm, a length of 88.5 mm, and a head diameter of 7.5 mm.

Processing and Preparation of Materials

In accordance with the requirements specified in the GB/T 14018 (2009), the wood specimens were stored in a constant-temperature, constant-humidity, and well-ventilated environment for six months to stabilize their moisture content at approximately 12%. Specimens free of knots, cracks, decay, discoloration, and other defects were selected for density measurements.

After conditioning, the air-dry density of *P. massoniana* was measured at 0.49 g/cm³ with a moisture content of 11.7%, while that of *C. lanceolata* was 0.43 g/cm³ with a moisture content of 11.5%. Guiding bore holes were pre-drilled into the tangential surfaces of *P. massoniana* and *C. lanceolata* specimens. The locations of these guiding bore holes were carefully chosen to avoid regions with decay, knots, cracks, or inclined grain. Each guiding hole was drilled to a uniform depth of 20 mm (the length of screw tip was excluded), with diameters of 1.0, 1.5, 2.0, 2.5, and 3.0 mm. Additionally, commercially sourced self-tapping screws and round steel nails with a diameter of 3.5 mm were selected for the tests.

Fasteners were chosen to ensure straight shanks, free of rust, damage, or defects such as burrs or barbs at the tip (Li *et al.* 2023, 2024). For the experiments, all fasteners were driven to a consistent depth of 20 mm, with both the guiding bore hole and the fastener maintained perpendicular to the wood surface.

Nail-holding Strength Test

Nail-holding tests were carried out on a WDS-50 kN universal testing machine under controlled laboratory conditions: 22 to 25 °C, $\leq$ 60 % RH. To ensure accuracy and reliability of the test results, the loading process was carried out at a uniform rate of 2.5 mm/min, with each test duration controlled between 10 to 60 min. During the tests, the machine precisely applied the load while simultaneously monitoring and recording the deformation behavior of the wood specimens in real time. Upon completion of each test, the maximum load value for each specimen was meticulously recorded, and the corresponding load–displacement curve data were saved. The final nail-holding strength was calculated as the arithmetic mean of the maximum load values obtained from 20 specimens of the same specification, to minimize the influence of individual specimen variation on the test results.

Statistical Analysis

Experimental data were processed using Excel 2021 and Origin 2024 software. A one-way analysis of variance (ANOVA) was performed to assess the statistical significance of differences among groups, with significance set at $P < 0.05$.

RESULTS AND DISCUSSION

Effects of Guiding Bore Hole Diameter on the Nail-holding Strength of Self-tapping Screws in *P. massoniana* and *C. lanceolata*

According to the experimental methodology, guiding bore holes of varying diameters were drilled into standard specimens of *P. massoniana* and *C. lanceolata*. Self-tapping screws with a diameter of 3.5 mm were driven into the tangential surfaces of the wood samples, and the results are presented in Figs. 1 and 2.

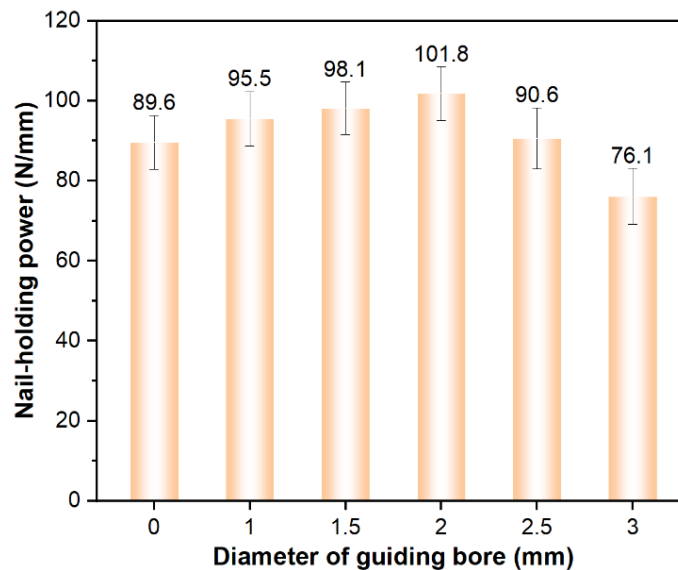


Fig. 1. Nail holding strength of self-tapping screw with different guiding bore hole diameter on *P. Massoniana* wood

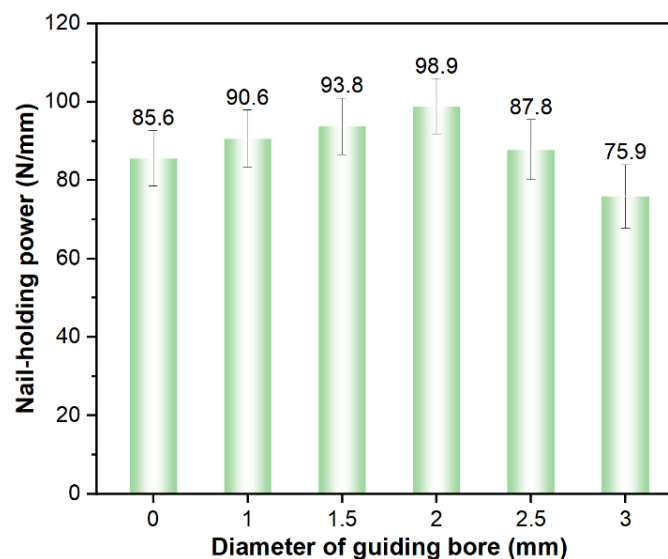


Fig. 2. Nail holding strength of self-tapping screw with different guiding bore hole diameter on *C. lanceolata* wood

Without guiding holes, the holding strength of self-tapping screws in *P. massoniana* and *C. lanceolata* was relatively low, at and 85.6 N/mm, respectively. As the

guiding bore hole diameter increased from 1.0 mm to 2.0 mm, the holding strength gradually increased in both species. The maximum values were reached at a guiding hole diameter of 2.0 mm, with holding strengths of 101.8 N/mm for *P. massoniana* and 98.9 N/mm for *C. lanceolata*. This improvement is mainly attributed to the guiding hole's ability to guide the screw into the wood more smoothly without greatly compromising the structural integrity of the surrounding material. At this optimal diameter, the contact between the screw and wood was tighter, thereby enhancing holding performance.

Guiding bore holes provided effective positioning and alignment, allowing the screw to distribute stress more evenly and increasing its resistance to withdrawal. The wood around the screw underwent moderate deformation, which increased anchorage and contributed to the rise in holding strength. However, as the guiding hole diameter further increased to 2.5 and 3.0 mm, the holding strength dropped sharply in both wood types. At a 3.0 mm pilot-hole diameter, withdrawal resistance fell below that observed without pre-drilling, underscoring the pronounced negative impact of an oversized bore hole. This decline is attributed to a marked loss of structural integrity in the surrounding wood and a concomitant drop in contact pressure between the screw threads and the substrate, which collectively diminish frictional anchorage and predispose the fastener to loosening within the wood matrix.

From specimens with no guiding bore holes to those with 1.0 mm guiding bore holes, the holding strength increased 6.6% for *P. massoniana* and 5.8% for *C. lanceolata*. As the guiding bore hole diameter continued to increase, the holding strength showed a gradual upward trend until it surpassed 2.0 mm, after which a sharp decline occurred. The largest decrease was observed at a diameter of 3.0 mm, with reductions of 16.0% and 13.6% for *P. massoniana* and *C. lanceolata*, respectively. The inner diameter of the self-tapping screw used in the experiment was 2.6 mm. When the guiding bore hole diameter was 2.0 mm, the surrounding wood was compacted to a critical point where the material was densely compressed but had not yet cracked. When the guiding bore hole diameter was smaller than 2.0 mm, excessive radial pressure led to cracking and strength loss; conversely, when the diameter exceeded 2.0 mm, insufficient compression of the surrounding fibers resulted in a significant decrease in holding strength.

In summary, guiding bore hole diameter was found to have a pronounced effect on the holding performance of self-tapping screws in both *P. massoniana* and *C. lanceolata*. An appropriate range of 1.0 to 2.0 mm significantly improved holding strength, primarily by increasing the shear resistance of wood fibers engaged with the screw threads and the contact pressure between the screw shank and the wood substrate.

Effects of Guiding Bore Hole Diameter on the Nail-holding Strength of Round Steel Nails in *P. massoniana* and *C. lanceolata*

The effects of guiding bore hole diameter on the nail-holding strength of round steel nails in *P. massoniana* and *C. lanceolata* are illustrated in Figs. 3 and 4. In the absence of guiding bore holes, the holding strength of round steel nails in both wood species was relatively low, with *P. massoniana* exhibiting a strength of 22.0 N/mm and *C. lanceolata* 23.1 N/mm. When the guiding bore hole diameter increased gradually from 1.0 mm to 2.5 mm, the holding strength for both species improved steadily. At a guiding bore hole diameter of 2.5 mm, peak values were observed: 36.5 N/mm for *P. massoniana* and 35.5 N/mm for *C. lanceolata*. However, when the diameter was further increased to 3.0 mm, a sharp decline in holding strength occurred, with values dropping to 23.2 N/mm for *P. massoniana* and 20.6 N/mm for *C. lanceolata*. Under such conditions, slippage and

loosening of the nail within the wood were likely to occur, significantly reducing both compressive and frictional forces. This, in turn, compromised the anchorage effect, severely affecting the stability and reliability of the nail connection.

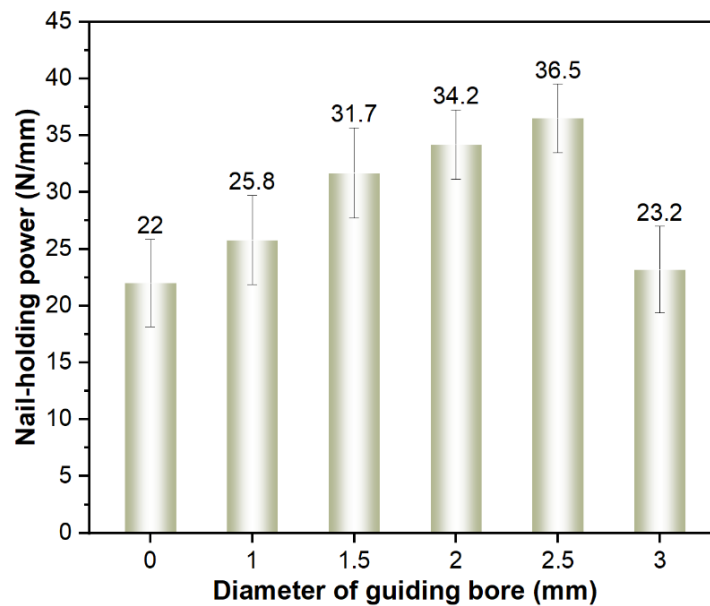


Fig. 3. Nail-holding strength of round steel nail with different guiding bore hole diameters on *P. Massoniana* wood

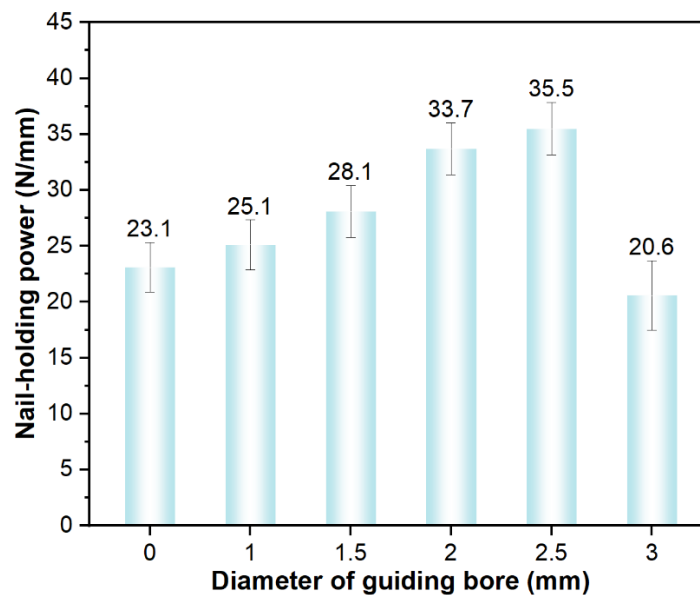


Fig. 4. Nail-holding strength of round steel nail with different guiding bore hole diameters on *C. lanceolata* wood

A comparative analysis of the round steel nail holding strength between *P. massoniana* and *C. lanceolata* revealed that, without a guiding bore hole, *C. lanceolata* demonstrated superior performance. This can be attributed to its better resistance to cracking and deformation compared to *P. massoniana*. However, once guiding bore holes were introduced, *P. massoniana* surpassed *C. lanceolata* in nail-holding strength. This

suggests that the presence of guiding bore holes effectively mitigated the tendency for cracking during nail insertion into *P. massoniana*. Furthermore, there are significant anatomical differences between the two wood species in terms of material properties, grain structure, and cellular organization. These distinctions allow *P. massoniana* to exhibit superior nail-holding capacity when combined with round steel nails. Specifically, *P. massoniana* possesses thicker secondary cell walls and a fiber alignment that is more conducive to generating friction and mechanical interlocking with the nail, compared to the structural characteristics of *C. lanceolata* (Horbelt *et al.* 2021).

The nail-holding strength of specimens using self-tapping screws was significantly higher than that of specimens using common round steel nails. For both types of fasteners, the holding strength exhibited a characteristic trend: increasing initially with guiding bore hole diameter and subsequently declining after reaching a peak. Notably, the maximum holding strength for self-tapping screws occurred at a guiding bore hole diameter of 2.0 mm, whereas round steel nails reached their peak at 2.5 mm. This difference is primarily attributed to the distinct local stress distributions induced by the two fastener types and the guiding bore holes' capacity to mitigate wood damage.

When 3.5 mm diameter self-tapping screws or round steel nails are driven directly into the wood, the compressive force between the shank and surrounding fibers may induce localized cracking, thereby reducing holding strength. Pre-drilled guiding bore holes can effectively reduce the direct compressive stress on wood fibers, lowering the risk of splitting and improving nail-holding performance. Self-tapping screws, featuring a threaded inner diameter of 2.6 mm, possess a smaller overall volume than round steel nails of the same outer diameter. As a result, at smaller guiding bore hole diameters, the effective contact area between the self-tapping screw and wood is relatively large, enabling it to reach peak holding strength more rapidly. In contrast, the unthreaded round steel nails have smaller contact areas and require larger guiding bore hole diameters to adequately alleviate insertion-induced wood damage, thereby achieving optimal holding capacity.

In summary, pre-drilling guiding bore holes markedly elevates the withdrawal resistance of both *P. massoniana* and *C. lanceolata*. This advantage is indispensable when driving large-diameter self-tapping screws or round steel nails, because direct insertion frequently triggers radial splitting or longitudinal cracking. An adequately dimensioned guiding bore hole redistributes the stress concentrations generated around the shank, preventing premature brittle failure of the wood matrix. Consequently, nail-holding capacity is improved for both species, and the resulting joints exhibit higher stiffness, reliability, and long-term load-bearing performance. Furthermore, the mechanical response of self-tapping screws is appreciably less sensitive to variations in guiding bore hole diameter than that of round steel nails. In *P. massoniana* and *C. lanceolata*, self-tapping screws were found to retain adequate withdrawal resistance over a comparatively broad range of bore hole diameters. By contrast, round steel nails display pronounced sensitivity: even modest oversizing of the bore hole was found to precipitate a steep decline in holding strength, thereby eroding the joint's safety margin. Construction specifications must therefore enforce stringent dimensional control—particularly for round steel nails—to prevent disproportionate losses in capacity and to safeguard structural integrity and connection reliability.

Load-displacement Curves of Nail-holding Test Based on Self-tapping Screws

Figure 5 presents the load–displacement curves obtained from withdrawal tests of 3.5 mm diameter self-tapping screws inserted into the tangential surfaces of *P. massoniana* and *C. lanceolata*, with guiding bore holes pre-drilled at diameters of 1.0, 1.5, 2.0, 2.5, and 3.0 mm, respectively. The load–displacement curve can be divided into three distinct phases: the elastic ascending phase, the peak load phase (ultimate strength), and the descending phase. As the self-tapping screw is withdrawn, the holding strength reaches a maximum, corresponding to the shearing of the surrounding wood fibers. At this point, the resistance is primarily governed by the shear strength of the wood fiber matrix. Among all tested conditions, the load–displacement curve associated with a 3.0 mm guiding bore hole exhibited the lowest slope in the initial elastic phase, indicating a relatively lower stiffness. Throughout the elastic ascending phase, the ultimate strength phase, and the descending phase, the curve corresponding to the 3.0 mm guiding bore hole showed a more delayed displacement response compared to other guiding bore hole diameters. This behavior is attributed to the reduced compressive interaction between the screw shank and the surrounding wood during insertion, due to the relatively large diameter of the 3.0 mm guiding bore hole. As a result, a greater gap remained between the screw threads and the wood fibers, forming a looser fit. During withdrawal, this increased clearance led to delayed compaction and engagement of the wood material, thereby shifting the curve toward greater displacements and indicating lower structural stiffness and resistance. The apparent reduction in initial stiffness for the 1.5 and 2.0 mm guide holes is, at first sight, counter-intuitive because larger holes might be expected to lower only the ultimate withdrawal capacity. However, closer inspection of the individual curves reveals that this “softer” response is driven by two outliers in the 1.5 mm group and one very low-stiffness specimen in the 2.0 mm group—both associated with undetected micro-cracks that originated during the pre-drilling operation.

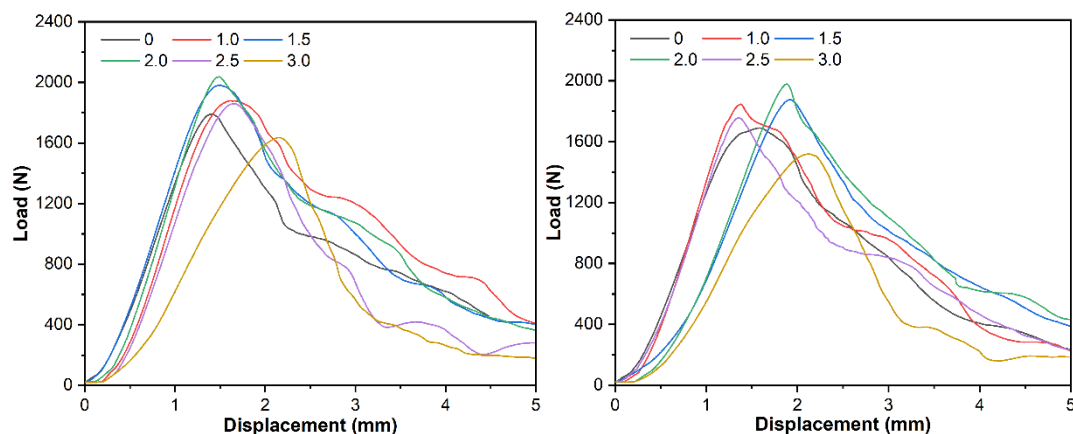


Fig. 5. Effects of the diameters of the guiding bore holes on the self-tapping screw load-displacement of *P. massoniana* and *C. lanceolata* wood

Load-displacement Curves of Nail-holding Test Based on Round Steel Nails

Figure 6 illustrates the load–displacement curves obtained from withdrawal tests using 3.5 mm diameter round steel nails inserted into the tangential surfaces of *P. massoniana* and *C. lanceolata*, with guiding bore holes pre-drilled at various diameters (1.0, 1.5, 2.0, 2.5, and 3.0 mm). Similar to the self-tapping screws, the load–displacement

curves for round steel nails could also be divided into three phases: elastic ascending, peak load, and post-peak descending stages. However, the overall curve profiles differed significantly from those of the self-tapping screws. Specifically, the round steel nail curves showed a rapid rise to a sharp peak, followed by an abrupt drop, and then a transition into a gentler descending trend. The precipitous drop in holding force was attributed to a transition of the moment static friction yields to kinetic: once the compressive grip between the nail shank and the enveloping wood fibres reached its frictional ceiling, the bond slipped into a lower-energy sliding regime, and resistance collapsed. As displacement continued to increase, kinetic friction gradually decreased, and then it intermittently reverted to static friction, resulting in fluctuations along the load–displacement curve characterized by multiple fluctuating peaks. With the progressive withdrawal of the nail, the contact area between the shank and wood decreased, leading to a general downward trend in the curve.

When comparing the two wood species, the load–displacement curves of *C. lanceolata* exhibited more pronounced fluctuations than those of *P. massoniana*. This is mainly attributed to differences in their physical properties. *P. massoniana* has higher density and rigidity, leading to relatively looser contact under large nail diameters. Additionally, the presence of resin in *P. massoniana* serves as a natural lubricant during nail withdrawal, reducing frictional resistance. Consequently, the load–displacement trace for *P. massoniana* descended far more gradually after yielding, revealing a pronounced capacity to sustain load and a reassuringly stable grip long past the point of first distress.

In summary, self-tapping screws and round steel nails exhibited markedly different load–displacement behaviors under withdrawal loads. Joints formed with round steel nails in *P. massoniana* and *C. lanceolata* displayed greater brittleness, whereas self-tapping screw joints demonstrated enhanced ductility. Selecting an appropriate guiding bore hole diameter can further improve the ductile response of self-tapping screw connections, thereby enhancing their reliability and durability in practical applications.

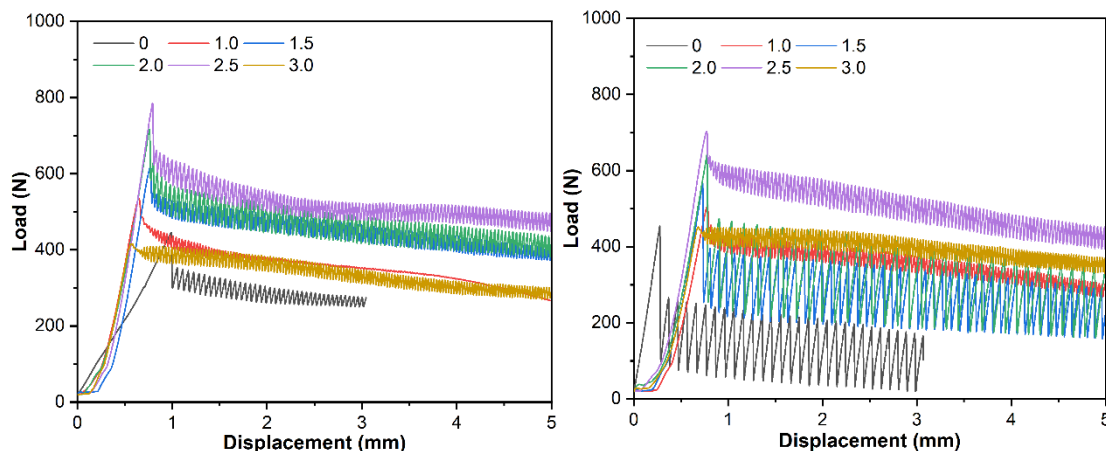


Fig. 6. Effects of the diameters of the guiding bore hole on the round steel nail load-displacement of *P. massoniana* and *C. lanceolata* wood

Failure Phenomena

Figure 7 illustrates the wood failure modes observed during nail-holding tests involving self-tapping screws and round steel nails in *P. massoniana* and *C. lanceolata*. In specimens with 1.0 mm diameter guiding bore holes, minor surface cracks appeared in the wood after insertion of round steel nails, with the cracks being particularly pronounced in

P. massoniana specimens. When the guiding bore hole diameter was increased to 1.5 mm, this condition improved, and no visible surface cracks were observed. During the withdrawal of round steel nails, no fiber pull-out was detected, which is likely due to the smooth shank surface, which lacks mechanical interlocking with the wood fibers.

In contrast, withdrawal of self-tapping screws resulted in substantial fiber extraction due to the threaded design. This phenomenon was especially pronounced in *P. massoniana* specimens with guiding bore hole diameters of 1.0, 1.5, and 2.0 mm, where visible “bulging” or raised fiber deformation zones formed around the screw shank. In *C. lanceolata*, similar fiber pull-out and surface bulging occurred in the 1.0 and 1.5 mm guiding bore hole specimens, although the extent of deformation was less pronounced than in *P. massoniana*, further indicating that *C. lanceolata* is a relatively softer wood species.

Furthermore, when the guiding bore hole diameter was increased to 3.0 mm, neither *P. massoniana* nor *C. lanceolata* specimens exhibited visible fiber extraction during the withdrawal of self-tapping screws. This indicates that, at larger guiding bore hole diameters, the compressive interaction between the screw threads and the surrounding wood was significantly reduced. As a result, frictional resistance during screw withdrawal decreased, making it less likely for wood fibers to be carried out along with the screw.

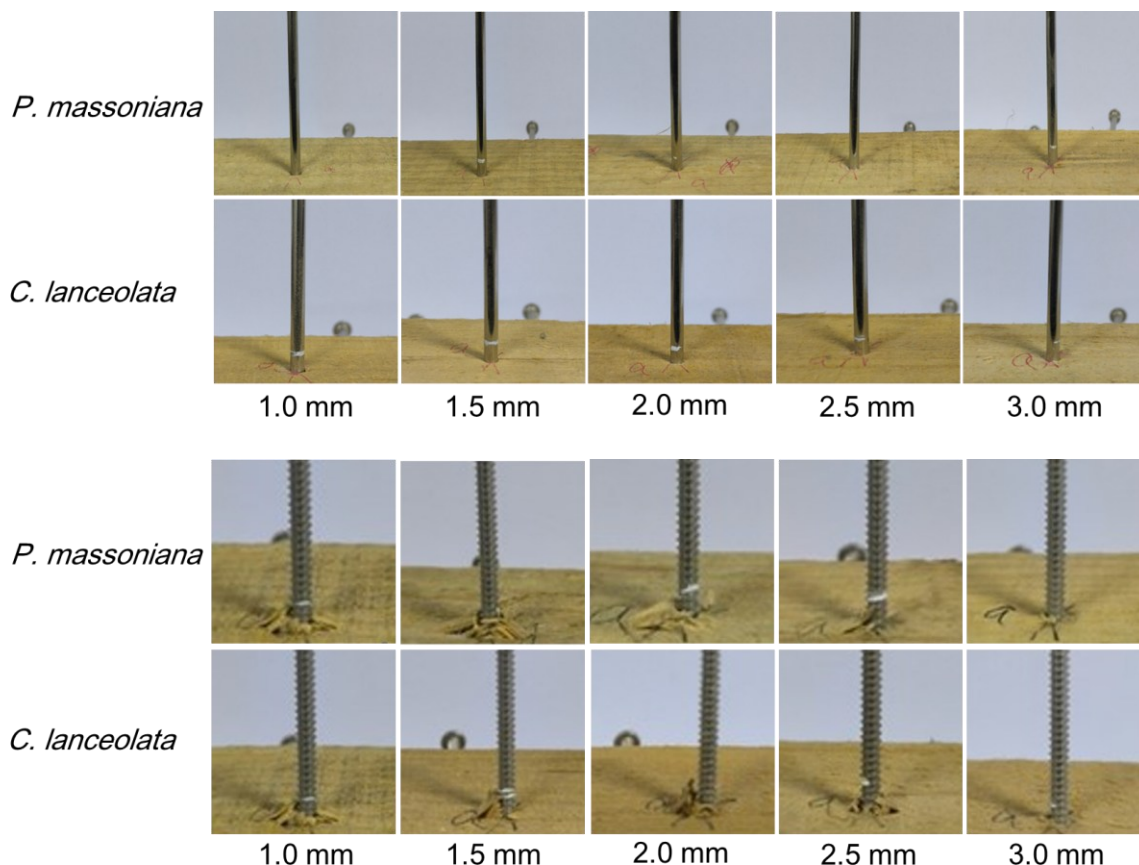


Fig. 7. Damage appearance of nail-holding test of *P. massoniana* and *C. lanceolata* wood based on the self-tapping screw and the round steel nail

CONCLUSIONS

1. The diameter of the guiding bore hole was found to exert a decisive influence on the withdrawal resistance of both *P. massoniana* and *C. lanceolata*. For self-tapping screws, withdrawal capacity rose steadily as the pilot hole was widened from 1.0 to 2.0 mm, peaking at 2.0 mm, beyond which it plummeted. In contrast, common round-wire nails reached their maximum holding power at a 2.5 mm pilot hole—after increasing from 1.0 mm—yet an expansion to 3.0 mm triggered a sharp decline.
2. Pre-drilled guiding bore holes was found to play a crucial role in enhancing the withdrawal resistance of self-tapping screws and round steel nails in both wood species. When large-diameter fasteners are driven directly into the wood, there is a high risk of splitting or cracking. Properly designed guiding bore holes effectively reduce the stress concentration around the fastener shank, thereby mitigating the risk of wood failure due to excessive localized pressure.
3. In the absence of guiding bore holes, *C. lanceolata* exhibited superior holding strength with round steel nails compared to *P. massoniana*. However, when guiding bore holes were introduced, *P. massoniana* surpassed *C. lanceolata* in round steel nail holding strength. This discrepancy is closely related to differences in wood density, grain structure, and internal cellular arrangement.

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