Effects of Selected Joint Parameters on Tensile Strength of Steel Bolt-nut Connections in *Cupressus funebris* Wood

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The influences of various factors on the tensile strength loading caused by steel bolt-nut connections on *Cupressus funebris* wood components in directions perpendicular and parallel to the grain were studied. The focus was the interference fit parameter between the nut and the pre-drilling hole, the nut embedded depth, and the embedded nut diameter using the single factor method. The optimum parameters for bolt-nut connections with *C. funebris* wood components both perpendicular and parallel to the grain component structures were obtained *via* a single factor experiment and verified by simulation using ANSYS finite element analysis software. The experimental and simulation-based results revealed that the optimum parameters with maximum tensile strength for the bolt-nut connections with *C. funebris* wood components were an interference fit of -0.80 mm, a nut embedded depth of 25 mm, and an embedded nut diameter of 15.5 mm. Considering the needs of practical applications, the optimum interference fit parameter between the nut and pre-drilling hole was -0.80 mm, increasing the length of the nut within the allowable range of part size was beneficial, and it was not suitable to increase the diameter of the embedded nut to improve the part's performance.

Keywords: Tensile strength; Cupressus funebris wood; Bolt-nut connection; Optimum parameter

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INTRODUCTION

Cupressus funebris is one of the four endemic species of the genus *Cupressus* to China, which is its country of origin (Fu *et al*. 1999). *Cupressus funebris* wood is a good material for construction of buildings, ships, and furniture, and it has been used since ancient times.

Most of the research literature focuses on forest resource management, biodiversity, and essential oils of *Cupressus funebris* (Zheng *et al*. 2011; Hou *et al*. 2013; Li *et al*. 2015; Lyu *et al*. 2018). Moreover, only a few studies have been conducted on the physical and mechanical properties of the joint performance of wood-based panel parts connected by hardware connectors; furthermore, studies on solid wood parts connected by hardware connectors or tenon and mortise joints are even rarer (Ozkaya *et al*. 2010; Zhang *et al*. 2015; Chen *et al*. 2016, 2018; Chen and Lyu 2018; Demirel *et al*. 2018). Therefore, there are almost no correlative studies on the joint performance of *C. funebris* wood parts connected by hardware connectors or tenon and mortise joints.

A metal insert nut is a part of a special structural connector that can be embedded in advance. It works with other parts, such as bolts, to produce a strong bonding force. Its connecting principle is to increase the contact area with the base material through wide, continuous, or discontinuous threads, and to increase bonding strength with the help of surface friction. It is widely used in the wood product industry because of its simple structure, mature technology, low cost, and strong bonding properties (Li 2013; Hao *et al*. 2015).

This study had three objectives. The first was to investigate the optimum parameters for steel bolt-nut connections with *C. funebris* wood components. The second was to determine the effects of the bolt-nut connections that were parallel and perpendicular to the grain of the *Cupressus funebris* wood parts on the joint performance of wood-based steel bolt-nut connections. The third objective was to fill the gap in the research field and to improve the level of standardization and the industrial utilization rate of *C. funebris* wood.

EXPERIMENTAL

Materials

The *Cupressus funebris* wood was selected as the experimental material and was purchased from a local timber enterprise (Yunsheng Wood Industry Co., Ltd., Chengdu, China). The tree was 45 to 50 years old. The values of hardness in the end, tangential, and radial faces of the wood were 5333 N, 4178 N, and 4066 N, respectively. Moreover, the modulus of elasticity, bending strength, compression strength parallel to grain, radial compression (entire) strength perpendicular to grain, and tangential compression strength of the wood were 8.2 GPa, 89.8 MPa, 45.8 MPa, 9.4 MPa, and 8.9 MPa, respectively.

The metric bolts and nuts were selected as the hardware connectors, since they are usually used in *Cupressus funebris* wood furniture. They were purchased from Guangdong Hui Cheng Feng Hardware Co., Ltd. (Shenzhen, China). The nut was a hexagonal socket nut with tooth threads both on the inside and outside surfaces of the nut and with zinc plating and coloring. The bolt was manufactured using grade 4.8 carbon steel, whose circular diameter matched the inside tooth of the nut, and it was 100 mm in length with zinc plating and coloring. The insert nut and the corresponding fitting bolt are illustrated in Fig. 1.

Fig. 1. The insert nut (left) and fitting bolt (right)

Methods

The tensile strength was determined in accordance with the Chinese nail-holding test method (GB/T 14018 2009). The tests were conducted using a Reger microcomputer-controlled electronic universal testing machine (Model RGM-2100; Shenzhen Reger Instrument Co., Ltd., Shenzhen, China). The rate of loading was 10 mm/min, and the loading continued until a non-recoverable drop-off in load occurred. The load and displacement values were expressed in newtons and millimeters, respectively. The load and displacement values were obtained from a load-displacement diagram. A linear regression analysis was applied between the displacement and the corresponding loading to calculate the relationship between deflection and loading. Subsequently, the wood material was machined to a size of 50 mm × 50 mm × 50 mm (length × height × thickness) using a flat plane and sliding table saw, consecutively. All of the components were sequentially numbered. The test setup is shown in Fig. 2.

The influencing factors, including the interference fit parameters, nut embedded depth, and insert nut diameter, were investigated through the single factor experiments. Both the variance analysis and regression analysis were applied using IBM SPSS Statistics software (Version 19, IBM, Armonk, NY, USA).

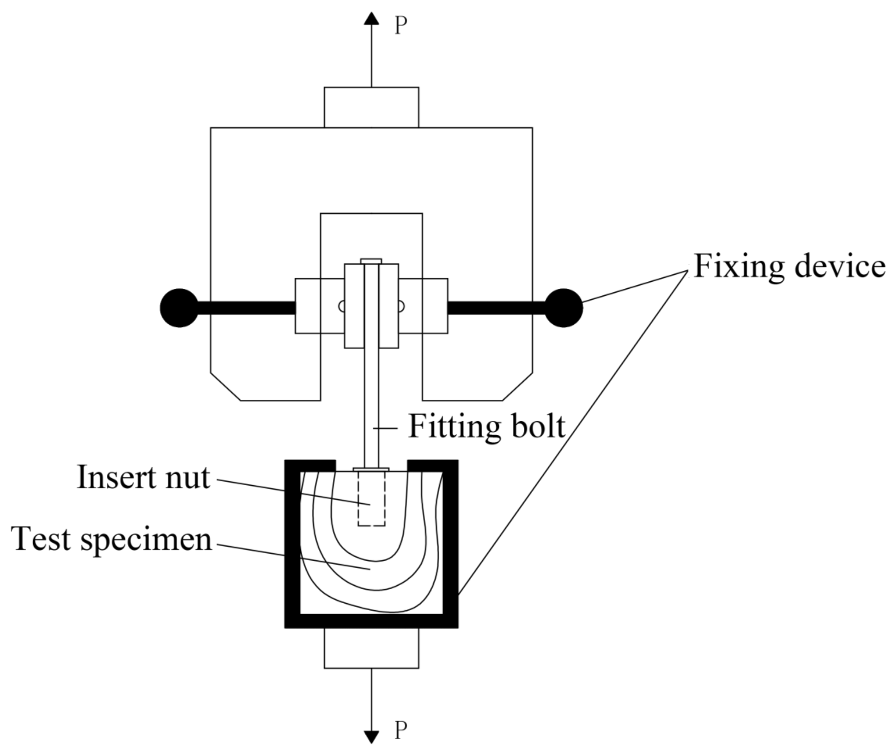


Fig. 2. Setup of tensile strength loading in steel bolt-nut connection tests

Interference fit parameters experiment

The steel insert nut used in this test satisfied the M6 specification, as shown in Fig. 3. An interference fit, also called a press fit or shrink fit, is a type of connection method used to join parts together in products or structures. In this type of joint, the two parts being connected are of slightly different sizes, and this discrepancy holds the pieces together. Making the insert nut maximum external diameter slightly larger than diameter of pre-drilling hole creates an interference fit joining the two parts. Changes in the amount of interference are accomplished by making the dimensions where the two parts are joined larger or smaller. In this part of the study, the influence of the pre-drilling interference fit parameters and maximum outer diameter of the nut on the tensile strength were studied using the single factor experiment for the samples that were perpendicular to the grain and parallel to the grain. These influences were studied using seven gradient tests and six repeated tests, as listed in Table 1.

After the experiment, the damage forms were examined, and the experimental data were analyzed *via* variance analysis and range analysis. Meanwhile, the results of equivalent stress and equivalent strain were compared with the results of the ANSYS workbench software (Version 15.0, ANSYS, Canonsburg, PA, USA).

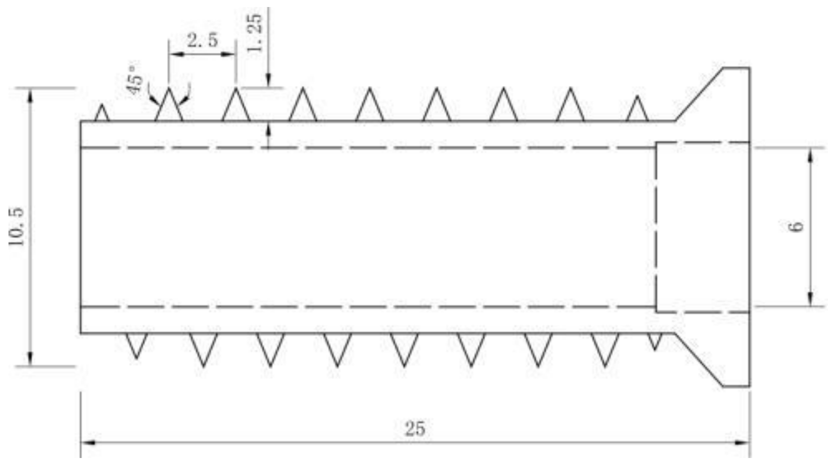


Fig. 3. Cross-section of steel insert nut in interference fit parameters experiment (unit: mm)

Table 1. Interference Fit Parameter of Pre-drilling Diameter in Interference Fit Parameters Experiment

Test Number	1	2	3	4	5	6	7
Interference Fit Parameter (mm)	-0.2	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4
Pre-drilling Diameter (mm)	10.3	10.1	9.9	9.7	9.5	9.3	9.1

Nut embedded depth experiment

The same type of steel insert nut that satisfied the M6 specification was used in this experiment, as shown in Fig. 4.

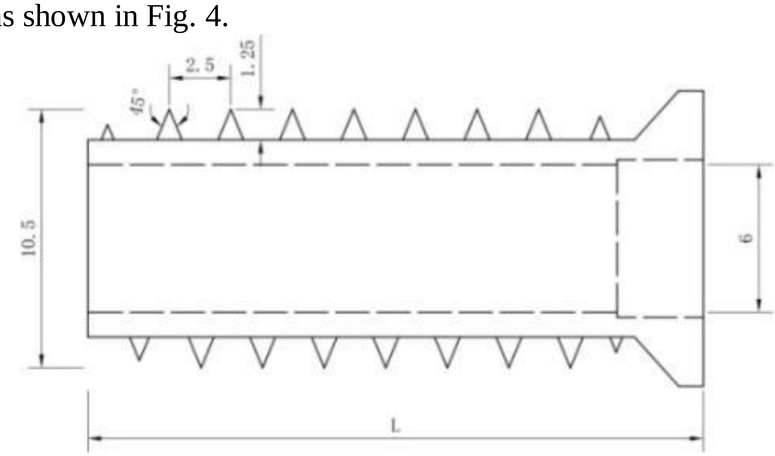


Fig. 4. Cross-section of steel insert nut in nut embedded depth experiment (unit: mm)

The influence of the nut length on the tensile strength was studied by the single factor experiment for the samples that were perpendicular and parallel to the grain. The samples were studied for six different gradients at 10 mm, 13 mm, 15 mm, 17 mm, 20 mm, and 25 mm nut lengths and with six repeated tests. After the experiment, the failure forms were examined, and the experimental data were analyzed *via* variance analysis and range analysis. Meanwhile, the results of equivalent stress and equivalent strain were compared with the results of the ANSYS workbench software.

Diameter of insert nut experiment

Three different kinds of steel insert nuts (M6, M8, and M10) were used in this experiment, which were classified into three categories based on the diameter of the inner teeth of the nuts, *i.e.*, 6 mm, 8 mm, and 10 mm. The influence of the insert nut diameter, *i.e.*, the maximum external diameters of the threads (10.5 mm, 12.5 mm, and 15.5 mm), on the tensile strength were studied by the single factor experiment for test pieces that were perpendicular to the grain and parallel to the grain. The test pieces were studied with six repeated tests, as shown in Fig. 5. An optimum interference fit parameter value of -0.8 mm and nut embedded depth of 25 mm were chosen from the results of previous experiments.

After the experiment, the failure forms were examined, and the experimental data were analyzed using variance analysis and range analysis. Meanwhile, the results of equivalent stress and equivalent strain were compared with the results of the ANSYS workbench software.

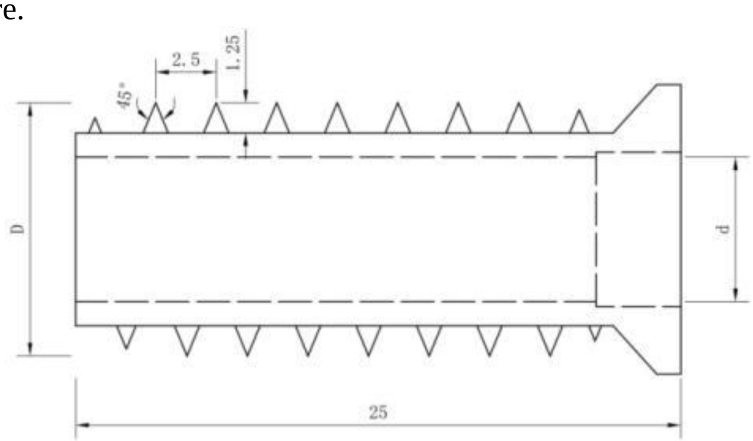


Fig. 5. Cross-section of steel insert nut in diameter of insert nut experiment (unit: mm)

RESULTS AND DISCUSSION

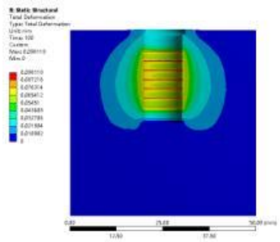
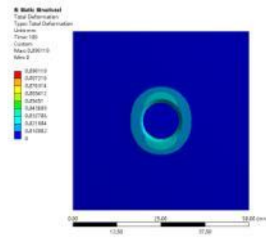
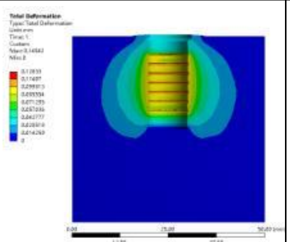
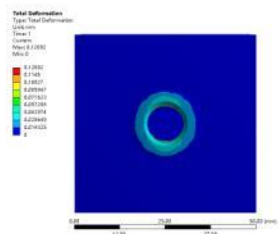
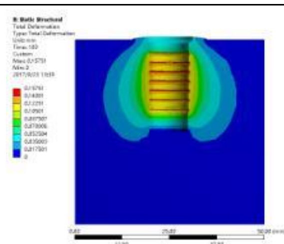
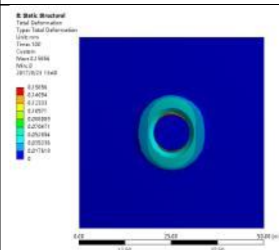
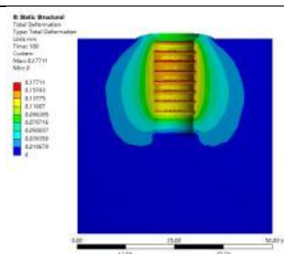
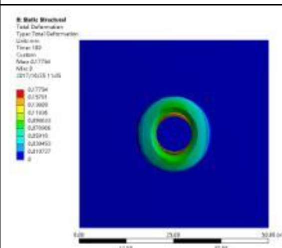
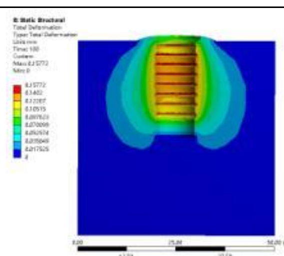
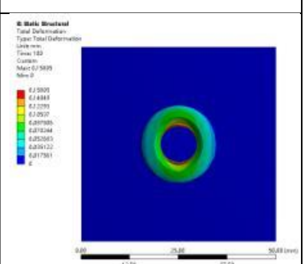
Interference Fit Parameters Experiment

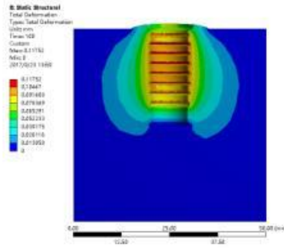
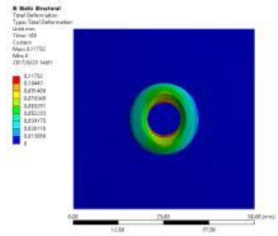
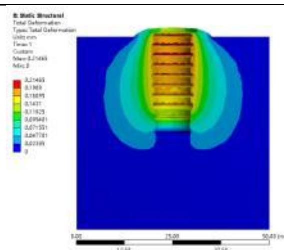
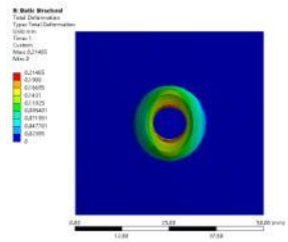
Failure mode analysis

The failure characteristics and simulation verification in tensile strength tests of perpendicular-to-grain test pieces are shown in Table 2.

When the interference fit parameter was -0.2 mm, the depth of thread embedded in the specimen was very shallow, and there were minor scratches on the inner wall of the aperture, which indicated that the force on the inner wall of the aperture was minor. Moreover, there was no obvious peeling off of the wood fiber at the end face of the specimen.

Table 2. Failure Characteristics and Simulation Verification of Tensile Strength Tests on Perpendicular-to-Grain Test Pieces in Interference Fit Parameters Experiment

Interference Fit Parameter (mm)	Internal Failure Mode	Internal Equivalent Strain	End Face Failure Mode	End Face Equivalent Strain
-0.2				
-0.4				
-0.6				
-0.8				
-1.0				

Interference Fit Parameter (mm)	Internal Failure Mode	Internal Equivalent Strain	End Face Failure Mode	End Face Equivalent Strain
-1.2				
-1.4				

While the interference fit parameter is -0.4 mm, the scratches on the inner wall of the hole diameter and the damage to the wood fiber were obvious. The warping height of the wood fiber at the aperture was 1 mm to 2 mm. The damage demonstrated that the stress on the wood fiber at the inner wall of the hole diameter had increased. There was a visible uplift on the end surface of the specimen.

With the increase of the interference fit parameter from -0.4 mm to -0.6 mm, the thread embedded in the specimen was obvious, the middle and bottom of the hole displayed minor wood fiber tear, the scratches were obvious, and the height of the wood fiber warping was 2 mm to 3 mm. These results indicate that the stress on the wood fiber at the inner wall of the pore diameter was large; further, the end face of the specimen was noticeably protruded, accompanied by fracture.

With further increasing interference fit parameter to -1.0 mm, the thread embedding trace became shallow, the tear damage on the wood fiber in the horizontal direction at the thread occlusion was lesser, and the wood fiber in the bottom thread occlusion of the bore diameter inner wall was slightly broken. The damage demonstrated that the force on the wood fiber in the bore diameter inner wall had decreased. Moreover, the height of wood fiber warping was 6 mm. The uplift area of the surface wood fiber was larger, and the tear along the grain direction was more obvious. The damage extent was around the aperture diameter.

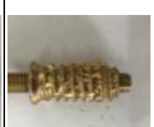
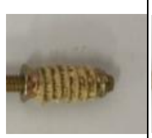
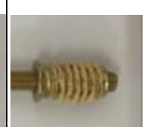
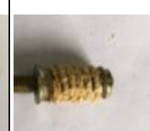
When the interference fit parameter was -1.2 mm, the thread embedding trace was shallow, there was less tear damage on the wood fiber in the horizontal direction, and a major part of the wood fiber broke at the thread occlusion. The damage demonstrated that the force on the inner wall of the hole had decreased, and the warping height of the entire hole was 6 mm to 7 mm. The area was larger, the wood fiber was more stripped, and the damage level was beyond the diameter of the aperture.

When the interference fit parameter reached the maximum value -1.4 mm, the thread embedded in the specimen was very deep, and the wood fibers were basically broken at the thread occlusion. The wood fibers were severely torn at the thread insertion position, and the height of the entire orifice of the wood fibers was 6 mm to 7 mm.

However, during the pull-out process, the load dropped abruptly, and the hardware parts were damaged. Then, the test was concluded.

The failure characteristics in the tensile strength tests of test pieces perpendicular to the wood grain are as shown in Table 3.

Table 3. Failure Characteristics of Tensile Strength Tests on Parallel-to-Grain Test Pieces in Interference Fit Parameters Experiment

Interference Fit Parameter (mm)	-0.2	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4
Internal Failure Mode							
End Face Failure Mode							
Nut							

When the interference fit parameter was -0.2 mm, there were scratches on the inner wall of the pore diameter, and the wood fibers were torn and had curled toward the load direction. A small amount of wood fiber had peeled off and was attached to the nuts that were removed, indicating that the force on the inner wall of the pore diameter was minimal, and the end face of the specimen was not uplifted or damaged.

When the interference fit parameter was -0.4 mm, the scratch on the inner wall of the hole diameter was obvious, the wood fiber curled in the direction of the load, and part of the wood fiber was stripped and had attached to the nut that was removed, indicating that the force on the inner wall of the hole diameter was small. Furthermore, the end face of the specimen was not damaged, indicating that the force on the inner wall of the hole diameter was small.

With the increase of the interference fit parameter from -0.4 mm to -0.6 mm, the thread embedding trace in the hole diameter was shallow, and more wood chips were removed by the nut, which indicated that the stress on the wood fiber at the inner wall of the hole diameter had increased. However, the end face of the specimen was not destroyed.

With further increasing interference fit parameters to -0.8 mm and -1.0 mm, the thread embedding marks on the inner wall of the hole were clear, and most of the wood fibers were peeled off. A considerable quantity of wood fibers was pulled out from the screw tooth clearance, which indicated that the wood fibers at the inner wall of the hole were under great stress. However, the end face of the specimen was still not uplifted.

When the interference fit parameters reached the maximum value -1.2 mm and -1.4 mm, the hole diameter was relatively flat, the thread embedding trace became shallow, and the wood fiber was more destroyed. The curled wood chips were removed by the nut, and there were more unpeeled wood chips attached to the edge of the hole aperture. These results indicated that the stress on the wood fiber at the inner wall of the hole diameter had decreased, and the end face of the specimen remained undamaged.

Test data analysis

Both variance analysis and regression analysis were applied to the interference fit parameters and tensile strengths using IBM SPSS Statistics.

Table 4 lists the statistical analysis of the tensile strength tests of test pieces perpendicular to the grain. For perpendicular-to-grain specimens, the average tensile strength was 6.221 kN, and the greatest tensile strength was 8.661 kN, which occurred with the -1.4 mm interference fit. The second greatest value of tensile strength, 7.581 kN, was measured with the -0.8 mm interference fit. When the interference fit parameter was -1.4 mm, the tensile strength abruptly increased and then suddenly dropped. Thus, the hardware broke, and the test was terminated. Therefore, the test data values with -1.4 mm interference fit were not considered in the variance and regression analyses.

Table 4. Basic Statistical Analysis of Tensile Strength Tests on Perpendicular-to-Grain Test Pieces in the Interference Fit Parameters Experiment

Interference Fit Parameter (mm)	-0.2	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4
Sample 1 (kN)	2.750	5.245	6.169	6.905	8.117	5.345	9.717
Sample 2 (kN)	3.481	5.366	6.093	8.439	7.493	4.935	7.079
Sample 3 (kN)	3.096	5.234	6.404	7.530	6.469	5.776	9.565
Sample 4 (kN)	3.023	4.709	7.002	7.221	6.817	5.414	7.471
Sample 5 (kN)	2.970	4.534	6.049	7.838	6.784	5.183	8.757
Sample 6 (kN)	3.190	5.122	6.976	7.496	8.055	5.207	9.376
Mean (kN)	3.085	5.035	6.584	7.581	7.294	5.310	8.661
Coefficient of Variation (%)	7.13	6.05	5.95	6.58	8.71	4.84	11.90
Standard Deviation (kN)	0.22	0.30	0.39	0.50	0.63	0.26	1.03

Table 5 lists the results of the analysis of variance of tensile strength tests of test pieces perpendicular to the grain. The results demonstrated that the interference fit parameter exhibited a significant effect on the tensile strength of test pieces perpendicular to the grain ($p < 0.01$).

Table 5. Variance Analysis of Tensile Strength Tests on Test Pieces Perpendicular-to-Grain in the Interference Fit Parameters Experiment

Source	Sum of Squares	df	Mean Square	F	p-value
Between Groups	1.2674	5	0.2535	1.315	0.2897
Within Groups	85.2682	5	17.0536	88.478	0.0001
Error	4.8186	25			
Total Variation	91.3542	35			

Figure 6 illustrates the correlation between the tensile strength and interference fit parameters. The tensile strength initially increased and subsequently decreased with respect to the interference fit parameter, which implies that the transition from clearance fit to interference fit results in an increase in tensile strength (Chen and Lyu 2018).

The optimum regression equation for tensile strength, $y = -12.06x^2 - 19.584x - 0.5774$, could be obtained from Fig. 6, and the coefficient of determination was 0.970. When the interference fit parameter ranged from -0.2 mm to -0.8 mm, along with a deeper depth of thread, a greater tensile strength was demonstrated. However, when the interference fit parameters were -1.0 mm and -1.2 mm, the thread embedded in the wood was too deep, and the wood fibers broke, resulting in a decrease in tensile strength. When the interference fit parameter was -0.8 mm, the maximum tensile strength occurred. Based on the test data and failure mode analyses, it was inferred that the optimum interference fit parameter for tensile strength tests of test pieces perpendicular to the grain was -0.8 mm.

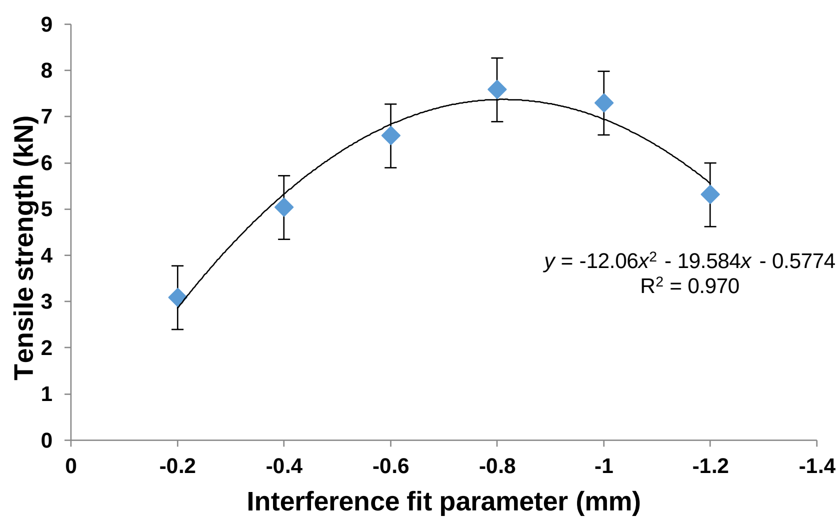


Fig. 6. Relationship between interference fit and tensile strength in perpendicular-to-grain interference fit parameters experiment

Table 6 shows the statistical analysis of the tensile strength tests of test pieces parallel to the wood grain. For parallel-to-grain specimens, the average tensile strength was 4.273 kN, and the greatest tensile strength was 5.470 kN, which occurred with the -1.2 mm interference fit. Both of these values were less than the tensile strength data for specimens perpendicular to the wood grain.

Table 6. Basic Statistical Analysis of Tensile Strength Tests on Test Pieces Parallel-to-Grain in Interference Fit Parameters Experiment

Interference Fit Parameter (mm)	-0.2	-0.4	-0.6	-0.8	-1.0	-1.2	-1.4
Sample 1 (kN)	1.974	3.502	3.849	5.230	5.813	5.876	4.685
Sample 2 (kN)	2.286	2.768	3.983	5.717	5.423	5.516	5.385
Sample 3 (kN)	1.641	2.838	4.633	4.750	5.891	5.234	4.539
Sample 4 (kN)	1.875	3.549	3.791	4.720	5.065	5.920	5.249
Sample 5 (kN)	1.670	3.233	3.655	5.766	5.377	5.429	3.965
Sample 6 (kN)	1.894	3.212	4.674	5.324	5.203	4.848	3.522
Mean (kN)	1.890	3.184	4.098	5.251	5.462	5.470	4.557
Coefficient of Variation (%)	12.169	10.364	10.737	8.570	5.859	7.313	16.020
Standard Deviation (kN)	0.23	0.33	0.44	0.45	0.32	0.40	0.73

Table 7 lists the results of the analysis of variance of tensile strength tests of specimens parallel to the grain. The results demonstrated that the interference fit parameter had a significant effect on the tensile strength of parallel to grain specimens ($p < 0.01$).

Table 7. Variance Analysis of Tensile Strength Tests on Parallel-to-Grain Specimens in Interference Fit Parameters Experiment

Source	Sum of Squares	df	Mean Square	F	p-value
Between Groups	0.6859	5	0.1372	0.677	0.6443
Within Groups	64.6897	6	10.7816	53.19	0.0001
Error	6.0809	30	0.2027		
Total Variation	71.4566	41			

Figure 7 shows the correlation between the tensile strength and interference fit parameter. The tensile strength first increased and subsequently decreased with respect to the interference fit parameter, which implies that the transition from clearance fit to interference fit results in an increase in tensile strength (Chen and Lyu 2018).

The optimum regression equation for the tensile strength, $y = -5.1927x^2 - 10.798x - 0.2107$, could be obtained from Fig. 7, and the coefficient of determination was 0.979. When the interference fit parameter ranged from -0.2 mm to -1.2 mm, along with a deeper depth of thread, a greater tensile strength was demonstrated. When the interference fit parameter was -1.4 mm, the thread was embedded too deeply into the wood, and the wood fibers peeled and broke during the removal process, which reduced the pull-out resistance. However, when the interference fit parameters were -0.8 mm, -1.0 mm, and -1.2 mm, the ultimate pull-out strengths of the specimens were nearly identical. For smaller interference fit parameters it was more difficult to screw the steel pre-embedded nuts into the wood specimens, and it was easy to cause cracking and other damage. Based on the test data and failure mode analyses, the interference fit parameter of -0.8 mm was the most suitable for tensile strength tests of the parallel-to-grain specimens.

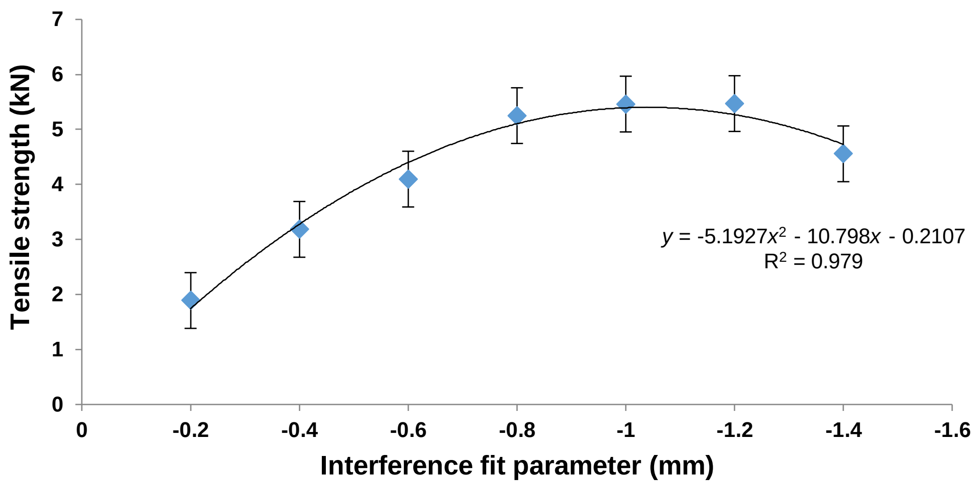


Fig. 7. Relationship between interference fit and tensile strength in parallel-to-grain interference fit parameters experiment

The results of the perpendicular- and parallel-to-grain tests demonstrated that the tensile strengths of parallel-to-grain specimens were much lower than those of perpendicular-to-grain specimens under the same interference fit. In perpendicular-to-grain tests, excessive interference fit will lead to slight cracks along the grain in some specimens, resulting in greater internal stress in the joints, and leading to specimens have been damaged to a certain extent.

In parallel-to-grain tests, excessive interference fit will lead to deep wood fiber biting into the hole wall. While it breaks the wood fiber joined with the nut tooth and drives the wood fiber to rotate to the bottom of the hole together, which results in the failure of the connecting force of the nut tooth to the base material, thus reducing the tensile strength. The main reason for this phenomenon is that the perpendicular-to-grain shear strength of *Cupressus funebris* wood fiber is greater than the parallel-to-grain tensile strength of the fiber. Secondly, when the specimen is joined parallel to the grain, the screw teeth cause extrusion damage to the wood fiber during the screw-in process, which reduces the bonding strength.

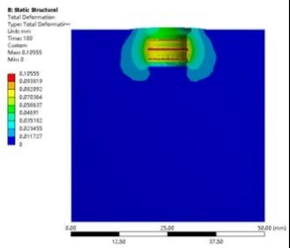
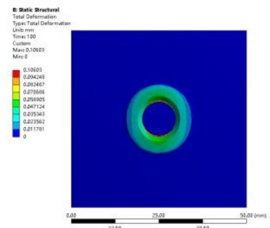
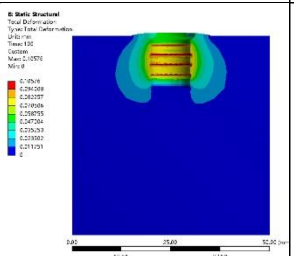
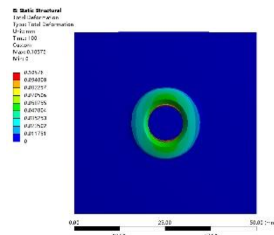
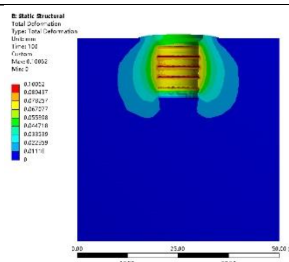
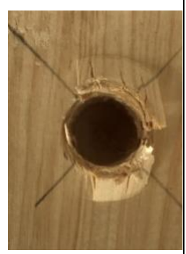
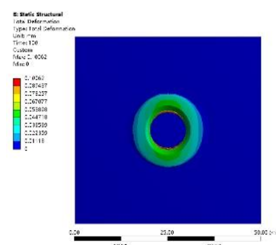
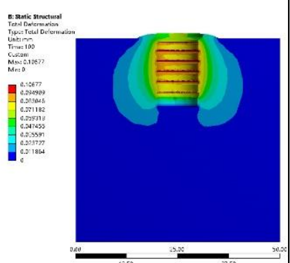
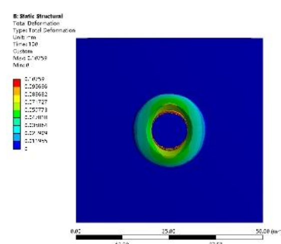
When the specimen is joined perpendicular to the grain, the screw teeth were better embedded and closely bonded along the direction of the wood fiber. If higher structural strength is preferred in practical production, then the steel insert nut should be embedded perpendicular to the grain. The optimum pre-embedded interference fit parameter of the steel insert nut was -0.8 mm when the joining was both perpendicular and parallel to the grain.

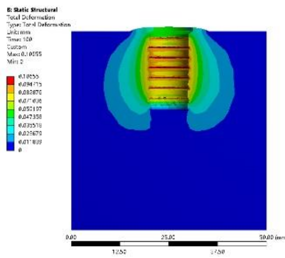
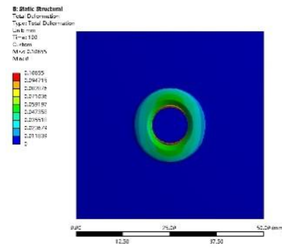
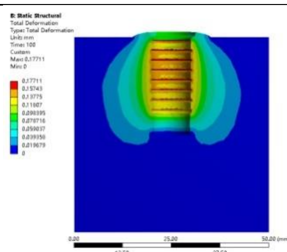
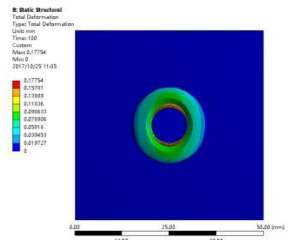
Nut Embedded Depth Experiment

Failure mode analysis

The failure characteristics and simulation verification in the tensile strength tests of perpendicular to grain specimens are shown in Table 8.

Table 8. Failure Characteristics and Simulation Verification of Tensile Strength Tests on Perpendicular-to-Grain Specimens in Nut Embedded Depth Experiment

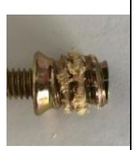
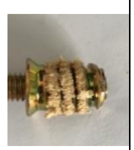
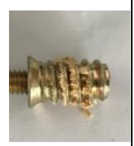
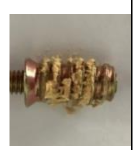
Embedded Depth (mm)	Internal Failure Mode	Internal Equivalent Strain	End Face Failure Mode	End Face Equivalent Strain
10				
13				
15				
17				

Embedded Depth (mm)	Internal Failure Mode	Internal Equivalent Strain	End Face Failure Mode	End Face Equivalent Strain
20				
25				

In the perpendicular-to-grain tests, the metal pre-embedded hollow sleeve nuts with different pre-embedded depths were pulled out from the specimens, and the range of failure depth of the specimens in the aperture gradually increased. When the embedding depth was 10 mm, the stress was too small, and the damage to wood fibers in the aperture was not obvious, so it was not considered as a good joint. When the embedding depth was 13 mm to 17 mm, the stress increased, the damage to wood fibers in the aperture was obvious, and the tearing in the direction of the load was visible at the contact point between the thread and the specimen, accompanied by wood fiber tearing. When the embedding depth was 20 mm to 25 mm, the stress continually increased, the damage to wood fibers in the aperture was serious, and the tearing at the contact point between the thread and the specimen was more severe. The end faces of the specimens were raised, accompanied by wood fiber tearing and a small amount of peeling. In the simulation results, the yellow and orange color ranges were very wide. As the embedding depth increased, the range of dyeing depth increased, and the internal equivalent strain increased, while the range of dyeing and the dyeing on the end surface were proportional. Furthermore, the equivalent strain on the end surface did not greatly change. The simulated results were similar to the failure phenomena of the experiment.

The failure characteristics in the tensile strength tests of parallel-to-grain specimens are shown in Table 9. As shown, when the embedding depth was 10 mm, the hole diameter was flat, and there was no tearing of wood fibers, which indicated that the wood fibers in the hole diameter experienced small stresses at the time. When the embedding depth ranged from 13 mm to 20 mm, the tearing curl of wood fibers in the hole diameter was obvious. As embedding depth increased, the amount and degree of the tearing curl of wood fibers continuously deepened. Further, peeling appeared at 20 mm, which showed that the stress of the wood fibers in the pore diameter gradually increased. When the embedded depth was 25 mm, the screw thread occlusion marks were clear, and the aperture was flat, which indicated that many wood fibers in the aperture were stressed so greatly that they were torn and peeled out with the nuts. A small amount of sawdust was attached to the end of the specimen, and there was no damage such as uplift or tearing.

Table 9. Failure Characteristics of Tensile Strength Tests on Parallel-to-Grain Specimens in Nut Embedded Depth Experiment

Embedded Depth (mm)	10	13	15	17	20	25
Internal Failure Mode						
End Face Failure Mode						
Nut						

Test data analysis

Variance analysis and regression analysis were applied to the nut embedded depth and tensile strength by using IBM SPSS Statistics software.

Table 10 lists the statistical analysis of the tensile strength tests of specimens perpendicular to the grain. For perpendicular-to-grain specimens, the average tensile strength was 3.783 kN, and the greatest tensile strength was 7.581 kN, which occurred at 25 mm of nut embedded depth. The second greatest value of tensile strength was 4.499 kN, which occurred at 20 mm of nut embedded depth.

As shown in Tables 10 and 12 and in Fig. 8, the tensile strength of the specimens increased with increasing pre-embedded depth of nuts, and the tensile strengths of perpendicular-to-grain specimens were much greater than those of parallel-to-grain specimens. There was a linear correlation between pre-embedded depth and tensile strength. In the perpendicular-to-grain tests, it could be expressed by the linear equation $y = 0.386x - 2.6499$, and the coefficient of determination was 0.955. In the parallel-to-grain tests, it could be expressed by the linear equation $y = 0.3106x - 2.6603$, and the correlation coefficient was 0.984.

Table 10. Basic Statistical Analysis of Tensile Strength Tests on Perpendicular-to-Grain Specimens in Nut Embedded Depth Experiment

Embedded Depth (mm)	10	13	15	17	20	25
Sample 1 (kN)	1.725	2.927	2.712	3.330	5.322	6.905
Sample 2 (kN)	1.818	2.528	3.012	3.940	4.220	8.493
Sample 3 (kN)	1.599	2.195	3.049	3.585	4.281	7.530
Sample 4 (kN)	1.379	1.950	3.871	3.553	4.858	7.221
Sample 5 (kN)	1.772	2.148	2.561	3.490	4.034	7.838
Sample 6 (kN)	1.666	2.469	2.974	3.452	4.281	7.496
Mean (kN)	1.660	2.370	3.030	3.558	4.499	7.581
Coefficient of Variation (%)	9.639	14.768	14.851	5.902	10.891	7.2550
Standard Deviation (kN)	0.16	0.35	0.45	0.21	0.49	0.55

Table 11. Variance Analysis of Tensile Strength Tests on Perpendicular-to-Grain Specimens in Nut Embedded Depth Experiment

Source	Sum of Squares	df	Mean Square	F	p-value
Between Groups	0.5874	5	0.1175	0.721	0.6141
Within Groups	132.3462	5	26.4692	162.402	0.0001
Error	4.0746	25	0.163		
Total Variation	137.0082	35			

Table 12. Basic Statistical Analysis of Tensile Strength Tests on Parallel-to-Grain Specimens in Nut Embedded Depth Experiment

Embedded Depth (mm)	10	13	15	17	20	25
Sample 1 (kN)	0.563	1.322	1.949	1.925	3.802	5.230
Sample 2 (kN)	0.475	1.513	1.986	2.889	3.971	5.717
Sample 3 (kN)	0.504	1.507	1.576	2.514	3.197	4.750
Sample 4 (kN)	0.563	2.030	1.674	1.996	3.330	4.720
Sample 5 (kN)	0.443	1.868	1.806	2.400	3.353	5.766
Sample 6 (kN)	0.437	1.821	1.612	2.549	3.503	5.324
Mean (kN)	0.497	1.677	1.767	2.379	3.526	5.251
Coefficient of Variation (%)	10.060	16.100	9.6208	15.132	8.508	8.570
Standard Deviation (kN)	0.05	0.27	0.17	0.36	0.30	0.45

Table 13. Variance Analysis of Tensile Strength Tests on Parallel-to-Grain Specimens in Nut Embedded Depth Experiment

Source	Sum of Squares	df	Mean Square	F	p-value
Between Groups	0.7059	5	0.1412	1.803	0.1489
Within Groups	83.1561	5	16.6312	212.334	0.0001
Error	1.9581	25	0.0783		
Total Variation	85.8201	35			

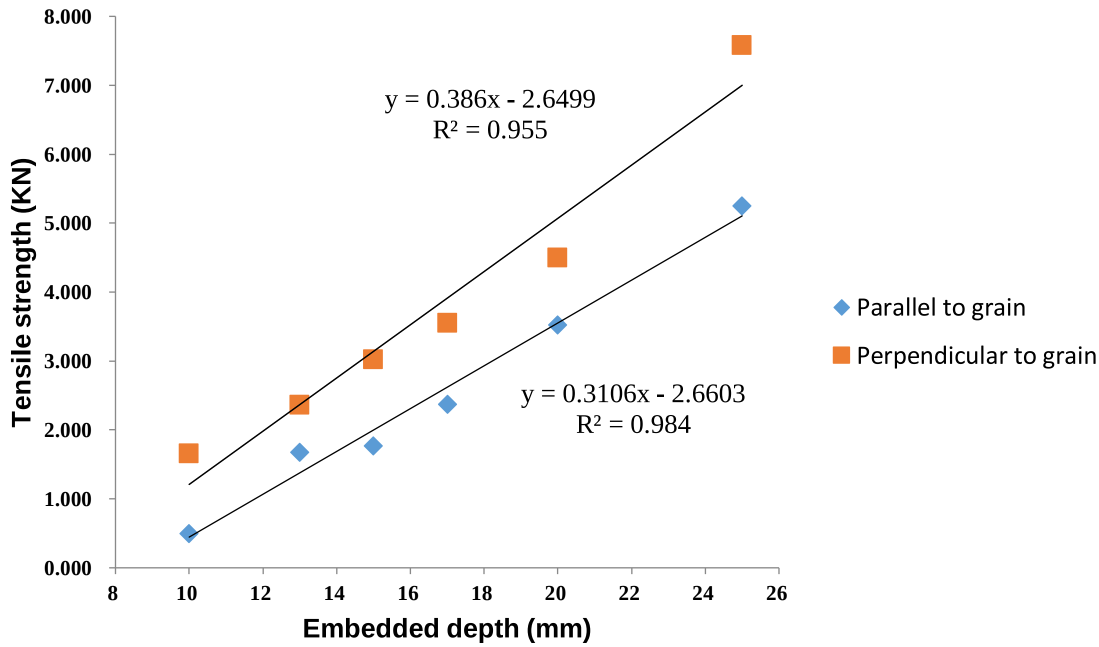


Fig. 8. Relationship between interference fit and tensile strength in nut embedded depth experiment

As shown in Tables 11 and 13, the influence of embedded depth on the tensile strength was significant in both the perpendicular- and parallel-to-grain specimens, which was consistent with the conclusions of other researchers (Li 2013; Hao *et al*. 2015). According to the damage of specimens under different embedded depths, one can significantly improve the tensile strength and enhance the joint performance of furniture components by choosing an embedded nut if it is possible, depending on the part size.

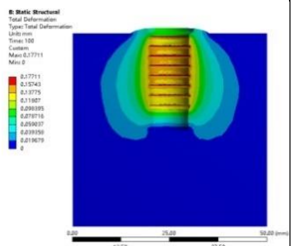
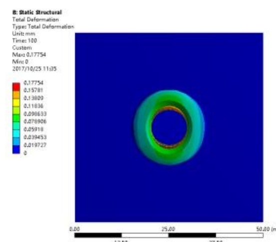
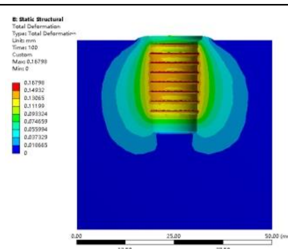
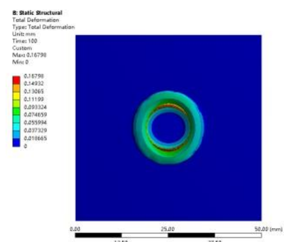
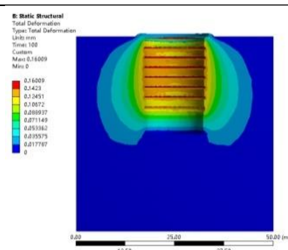
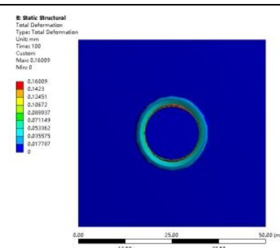
Diameter of Embedded Nut Experiment

Failure mode analysis

The failure characteristics and simulation verification in tensile strength tests of perpendicular-to-grain specimens are shown in Table 14.

When the maximum external diameter of the thread was 10.5 mm, the specimen with the thread embedded in the wood was deeper, the trace of the thread embedded was clear, the tearing failure of wood fibers at the thread occlusion at the bottom of the hole diameter developed horizontally, and the warping height of wood fibers at the hole diameter was 5 mm to 6 mm. The damage demonstrated that the wood fibers in the inner wall of the hole diameter endured a high force, but the wood fibers at the thread occlusion location did not break. The wood fiber bulge at the end of the specimen was obvious, accompanied by tearing along the grain direction.

Table 14. Failure Characteristics and Simulation Verification of Tensile Strength Tests on Perpendicular-to-Grain Specimens in Diameter of Embedded Nut Experiment

Embedded Nut Diameter (mm)	Internal Failure Mode	Internal Equivalent Strain	End Face Failure Mode	End Face Equivalent Strain
10.5				
12.5				
15.5				

With the increase of the maximum external diameter of the thread to 12.5 mm, the insertion of the thread into the wood specimen was deeper, the insertion trace of the thread was slightly shallow, the tearing damage of wood fibers at the thread occlusion at the bottom of the hole diameter developed horizontally, and the warping height of wood fibers at the aperture was 5 mm. The damage indicated that the wood fibers in the inner wall of the aperture were also under great stress, and the wood fibers marginally broke at the thread occlusion. The wood fibers on the end face of the specimens bulged obviously, which was more serious than the case of the 10.5 mm diameter.

When the maximum external diameter of the thread reached the maximum value 15.5 mm, the insertion of the thread into the wood specimen was deeper, the insertion trace of the thread was marginally shallow, and the tearing damage of wood fibers at the middle and upper thread occlusions of the hole diameter developed horizontally. The damage indicated that the stress of wood fibers in the inner wall of the hole diameter increased, and a small amount of wood fibers broke at the thread occlusion. As the interface size of nuts of M10 specification was 17 mm, and the diameter of the hole opening of the steel frame used for the nailing force test was 20 mm, the surface of the specimen was compressed by the steel frame, and the wood fiber uplift, tearing, and warping on the end face of the specimen were reduced.

For the simulated equivalent strain, as the embedded nut diameter increased, the variations of the color, coloring range, and corresponding deformation value in the aperture were small. The change of equivalent strain of the end surface verified the failure of the end surface in the test, and the range of equivalent strain clearly decreased at 15.5 mm.

The failure characteristics in the tensile strength tests of parallel-to-grain specimens are shown in Table 15.

When the maximum external diameter of the thread ranged from 10.5 mm to 15.5 mm, the thread on the inner wall of the hole was clear. However, the scratch on the inner wall of the hole became increasingly obvious, which indicated that the stress of the wood fiber on the inner wall of the hole had increased, and the end face of the specimen had no uplift failure.

Table 15. Failure Characteristics of Tensile Strength Tests on Parallel-to-Grain Specimens in Diameter of Embedded Nut Experiment

Embedded Nut Diameter (mm)	10.5	12.5	15.5
Internal Failure mode			
End Face Failure Mode			
Nut			

Test data analysis

The variance and regression analyses were applied to the diameter of the embedded nut and the tensile strength using IBM SPSS Statistics.

The statistical analysis of tensile strength tests of perpendicular-to-grain specimens is listed in Table 16, and the variance analysis of the tensile strength tests of perpendicular-to-grain specimens is listed in Table 17. The statistical analysis of tensile strength tests of parallel-to-grain specimens is listed in Table 18, and the variance analysis of the tensile strength tests of parallel-to-grain specimens is listed in Table 19.

Table 16. Basic Statistical Analysis of Tensile Strength Tests on Perpendicular-to-Grain Specimens in Diameter of Embedded Nut Experiment

Diameter of Embedded Nut (mm)	10.5	12.5	15.5
Sample 1 (kN)	6.905	7.746	8.218
Sample 2 (kN)	8.439	8.110	7.568
Sample 3 (kN)	7.530	7.523	8.475
Sample 4 (kN)	7.221	8.081	8.476
Sample 5 (kN)	7.838	7.230	7.840
Sample 6 (kN)	7.496	7.876	8.369
Mean (kN)	7.581	7.761	8.158
Coefficient of Variation (%)	7.255	4.381	4.535
Standard Deviation (kN)	0.55	0.34	0.37

Table 17. Variance Analysis of Tensile Strength Tests on Perpendicular-to-Grain Specimens

Source	Sum of Squares	df	Mean Square	F	p-value
Between Groups	0.445	5	0.089	0.383	0.8495
Within Groups	1.0461	2	0.523	2.25	0.156
Error	2.3244	10	0.2324		
Total Variation	3.8155	17			

As shown in Tables 16 and 18 and in Fig. 9, the tensile strength of the specimens slightly increased as the embedded nut diameter increased, and the tensile strengths of perpendicular-to-grain specimens were significantly greater than those of parallel-to-grain specimens. There was a linear correlation between the embedded nut diameter and the tensile strength. In the perpendicular-to-grain tests, it could be expressed by the linear equation $y = 0.116x + 6.334$, and the correlation coefficient was 0.990. In the parallel-to-grain tests, it could be expressed by the linear equation $y = 0.092x + 4.311$, and the correlation coefficient was 0.968.

Table 18. Basic Statistical Analysis of Tensile Strength Tests on Parallel-to-Grain Specimens in Diameter of Embedded Nut Experiment

Diameter of Embedded Nut (mm)	10.5	12.5	15.5
Sample 1 (kN)	5.230	5.498	5.375
Sample 2 (kN)	5.717	5.413	6.124
Sample 3 (kN)	4.750	5.440	5.094
Sample 4 (kN)	4.720	4.855	5.791
Sample 5 (kN)	5.766	6.017	5.775
Sample 6 (kN)	5.324	5.854	6.174
Mean (kN)	5.251	5.513	5.722
Coefficient of Variation (%)	8.570	7.256	7.340
Standard Deviation (kN)	0.45	0.40	0.42

Table 19. Variance Analysis of Tensile Strength Tests on Parallel-to-Grain Specimens

Source	Sum of Squares	df	Mean Square	F	p-value
Between Groups	1.7783	5	0.3557	3.744	0.036
Within Groups	0.6683	2	0.3341	3.517	0.0697
Error	0.9499	10	0.095		
Total Variation	3.3965	17			

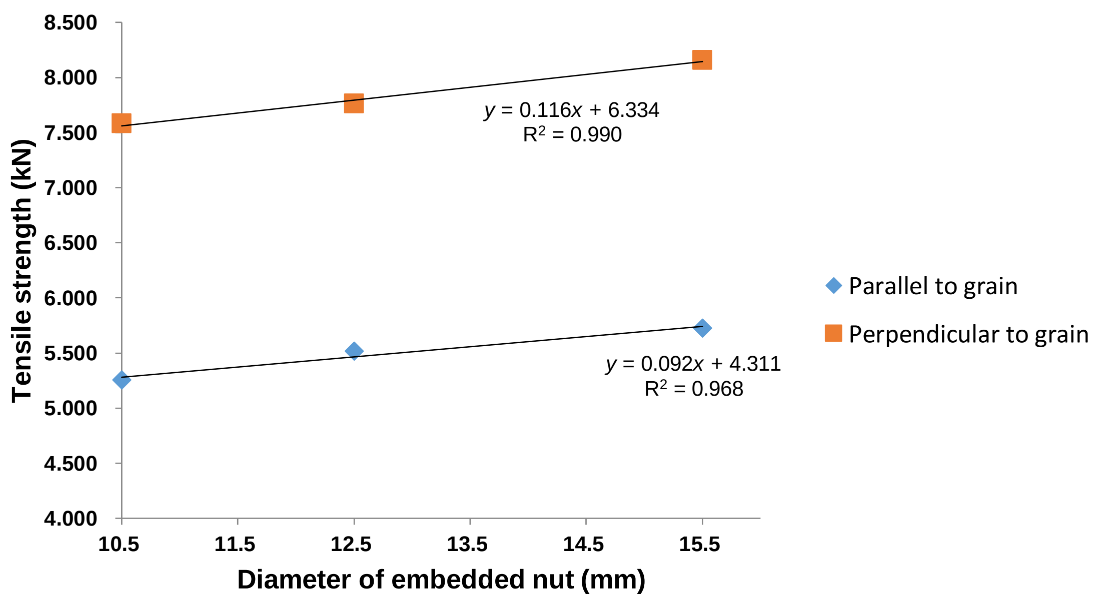


Fig. 9. Relationship between diameter of embedded nut and tensile strength in diameter of embedded nut experiment

As shown in Tables 17 and 19, the influence of the embedded nut diameter on the tensile strength was not significant in both the perpendicular- and parallel-to-grain specimens, which was not completely consistent with other studies (Li 2013; Hao *et al*. 2015). With the increase of the outer diameter of the nut, the diameter of the interface obviously increased, which indicated higher requirements for the area of the end surface of the specimen. The end area is too small to use a large nut, and cracks easily occur in the process of screwing. In practical production and application, according to the size of the specimen, it is not suitable to increase the diameter of the nut to improve the tensile strength of the specimen.

CONCLUSIONS

1. The interference fit parameter had a considerable effect on the tensile strength of steel bolt-nut connections on *Cupressus funebris* wood components in both the perpendicular- and parallel-to-grain specimens ($p < 0.01$). Combined with the failure mode and test data analyses, the optimal interference fit parameter for both perpendicular- and parallel-to-grain combined *C. funebris* wood components and steel insert nuts was -0.8 mm.
2. The nut embedded depth had a significant effect on the tensile strength of steel bolt-nut connections on *C. funebris* wood components in both the perpendicular- and parallel-to-grain specimens ($p < 0.01$). In the production of *C. funebris* wood furniture, the tensile strength of the *C. funebris* wood members joined with either perpendicular-to-grain or parallel-to-grain specimens was significantly improved through an increase in the length of nuts within the allowable range of specimen size.
3. The diameter of the embedded nut had no significant influence on the tensile strength of steel bolt-nut connections on *C. funebris* wood components in both perpendicular- and parallel-to-grain. In practical production and applications, it is not appropriate to increase the diameter of the embedded nut to improve the tensile strength of *C. funebris* wood furniture.
4. Simulation section in this study validates the tensile strength tests on perpendicular-to-grain specimens in interference fit, nut embedded depth, and embedded nut diameter experiments, which were similar to the failure phenomena of the experiment. A limitation of this study is that only failure mode and stress variation trend of the specimens are considered. Notwithstanding these limitations, the study suggests that simulation method has good application potential to assist experiment means of steel bolt-nut connections in wood parts.

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