Flexural Properties of Wooden Nail Friction Welding of Laminated Timber

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The properties of single shear specimens connected by wooden nail frictional welding and twist nails were studied. The single shear properties of the specimens connected by wooden nail welding were lower than that of the twist nail specimens. The single shear capacity of the wooden nail welding specimen was determined by calculating the method of design value of the bearing capacity of the pin connection. Furthermore, the flexural properties of the wooden nail welding laminated timber were analyzed. Due to the larger diameter of the wooden nails compared with the twist nails, the wooden nail welding laminated timber in the elastic phase had higher stiffness. The elastic modulus of the wooden nail welding laminated timber exceeded the average elastic modulus of the constituent lumber pieces by 9.46%. The number of wood lumbers in wooden nail welding laminated timber had little effect on the elastic modulus of laminated timber, but the nail spacing had a certain effect. Therefore, in future research, it is recommended to use the construction method of twist nail connection to design the wooden nail welding laminated timber. In addition, the nail spacing should refer to the GB 50005 (2003) standard and the wood structure design manual.

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INTRODUCTION

Rotary friction welding is a connection method in which a round wooden dowel is inserted into the pre-drilled hole of a wood component by rotating it at a high speed. The species of the wood components, the welding speed, and the insertion speed all have a large impact on the performance of the welded joints (Amirou *et al*. 2016; Belleville *et al*. 2016; Korte *et al*. 2018). Belleville *et al*. (2013) found that wood round tenons of different species have different optimal rotational speeds, while other studies have found that the accelerated insertion and constant speed insertion of wood round tenons with different starting speeds have a greater effect on the joint strength of the joints (Auchet *et al*. 2010; Amirou *et al*. 2017a). Bocquet *et al*. (2007b) found that the maximum strength of the joint was obtained when the diameter of the wooden round tenon was 10 mm and the diameter of the pre-drilled hole of the wooden component was 8 mm. Kanazawa *et al*. (2005) also confirmed that the best joint performance was obtained when the diameter ratio of the wooden round tenon to the pre-drilled hole of the wooden component was 1.25. A lower moisture content of the wooden round tenon has been found to be beneficial to improving the performance of the rotary friction welding joint.

Researchers have studied the performance enhancement aspects of single dowel rotary friction welding joints. Four methods, such as setting cross slots at the end of round wooden tenons, pre-drilled holes of wooden components with large outer and small inner fits, impregnation of round wooden tenons with ethylene glycol solution, and friction welding under 100 °C thermal conditions failed to improve the performance of the joint joints (Horman *et al*. 2016). However, the use of smaller diameter wood components pre-drilled and rotary friction welded dry wood round tenons at room temperature can improve the performance of welded joints (Auchet *et al*. 2010). Peña *et al.* (2015, 2016) found that the addition of wood inclusion resin or lignin improves the water-resistance of friction welded joints. Amirou *et al*. (2017b) utilized citric acid as a water repellent to enhance the strength and water resistance of friction welded joints.

In the study of multi-bar rotary friction welding and structural performance of components based on Kreuzinger's stress-strain study, Girardon *et al*. (2014) established a structural stress model for multi-layered beams with rotary friction welding of wood circular tenons. This was applied to study the influence of factors such as the number of laminates, location and number of round wood tenons, loading method, material grade, and beam span on the structural performance of beams, among other factors. After the model analysis, the regression analysis model parameters related to yield stiffness and damage stiffness could be obtained, and the beam yield stiffness obtained from the model was found to be 14% lower than the test value through the method of test verification and simulation analysis comparison. Bocquet *et al*. (2007b) designed a 4 m × 4 m footprint wood floor slab with rotary friction welding at the joints. A smaller number of wood laminates were used, but the researchers were able to obtain a greater stiffness. However, wood joints and laminated wood beams assembled by mechanically-welded wood dowels showed lower stiffness properties (Bocquet *et al*. 2007a). Fukuta *et al*. (2017) used 10 mm diameter wood round tenons welded to fix framed shear walls, which had higher lateral strength and stiffness properties than 2.85 mm diameter nail connected framed shear walls under the same test conditions. However, the ductility and energy dissipation were not sufficient. So it could not be used in the cyclic load.

Based on the study of rotary friction welding, researchers proposed the technique of wooden nail welding. Korte *et al*. (2018) used rosewood dowels frictionally driven at high speed into Norway spruce wood components without opening pre-drilled holes at a driving speed of up to 31 m/s. The tensile strength of the single dowel wooden nail welding joints was approximately twice that of single dowel twist nail joints under the same test conditions. The interfacial material was severely extruded and deformed, which also produced a black molten material similar to that in the rotary friction welding process.

(a) **(b)**

Fig. 1. Wooden nail (a) and twist nail (b)

In this paper, the different properties of wooded nail welding and twist nail (Fig. 1) were taken into consideration. Furthermore, wooden nail welding was used to connect the laminated timber, and the design calculation method of the wooden nail welding was complied with the GB 50005 (2017) standard for design of timber structures and the wood structure design manual.

EXPERIMENTAL

Materials

The diameter and length of the wooden nail were 4.6 mm and 76 mm, respectively. The diameter and length of the twist nails were 2.8 mm and 63 mm, respectively. The cross-section size of the spruce-pine-fir (SPF) was 38 mm × 89 mm. The wooden nails made from compressed birch wood were provided by BECK (Mauerkirchen, Austria). The twist nails and SPF were provided by Suzhou Crown Homes (Jiangsu, China).

Specimen Preparation

As shown in Fig. 2, two pieces of SPF specification material that were 400 mm long were connected by four twist nails or welded by four wooden nails within 200 mm of the end area. The nails were 50 mm from the end of the SPF specification material and 25 mm from the side. The nail spacing was 100 mm longitudinally and 49 mm transversely. There was a total of six specimens.

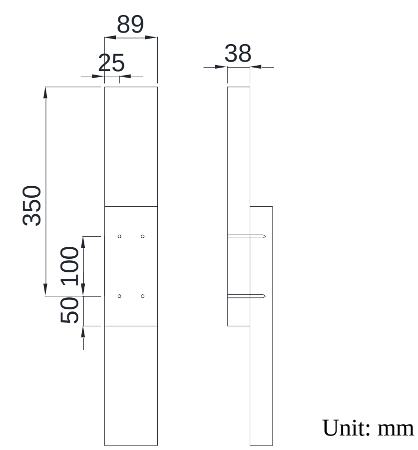

Fig. 2. The nailed connection single shear specimen

Figure 3 shows four pieces of 1,800 mm long SPF specification lumber. Each piece of lumber consisted of four pieced wooden nail welding laminated timbers, with the wooden nail welding staggered and punched in the layer by layer. For the specimen with 150 mm nail spacing, the nails were spaced 75 mm from the end, the nails of the same layer were spaced 150 mm apart, the nails between adjacent layers were spaced 75 mm apart, and twist nails were used to prepare the laminated timber in the same way as the control group. For the specimens with nail spacing of 300 mm, the nails were 150 mm from the end, the nails of the same layer were spaced 300 mm apart, and the nails of the adjacent layers were spaced 150 mm apart. Eight-piece wooden nail welding laminated timber was stacked layer by layer to eight pieces of SPF by wooden nail welding based on four-piece.

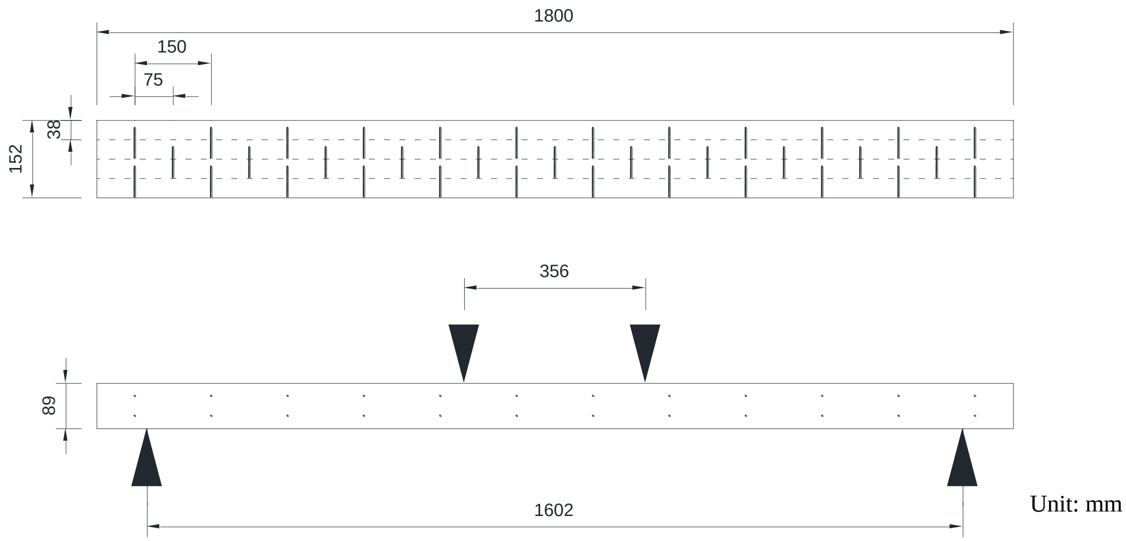

Fig. 3. The test method of wooden nail welding laminated timber and its bending resistance

Test Methods

The tensile test method for a single shear specimen welded with a wooden nail is shown in Fig. 4. Both ends of the specimens were connected by bolts and steel plates. And then the load from the opposite direction was imposed on the specimens. The modulus of elasticity in bending in the full bearing capability of both the SPF and laminated timber was carried out in the manner of Fig. 3. The elastic modulus of the SPF lumber and laminated material was calculated according to Eq. 1,

$$E = \frac{\Delta P(l-s)(2l^2+2ls-s^2)}{8\Delta ybh^3} \tag{1}$$

where E is the elastic modulus of laminated timber (MPa), ΔP is the difference between the 10% and 40 % of the ultimate load in the elastic load range (N), l is the span distance (1,602 mm), s is the distance between two loading points (356 mm), Δy is the deflection in the corresponding span (mm), b is the width of laminated timber (mm), and h is the height of laminated timber (mm).

Fig. 4. Tensile testing setup for the single shear specimens of wooden nail welding

The three-point loading setup for the local modulus of elasticity in bending test is shown in Fig. 5. A 25-mm diameter steel disc was used as the loading head. And then the elastic modulus could be calculated by the ratio of stress and strain.

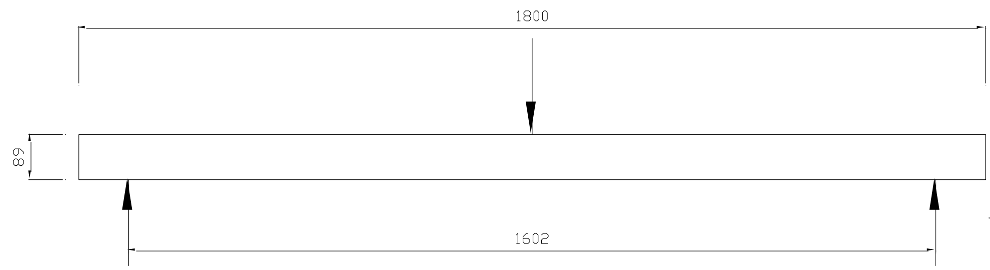

Fig. 5. Setup for the local modulus of elasticity in bending test of the laminated timber

RESULTS AND DISCUSSION

Single Shear Performance of Wooden Nail Welding joints

From Table 1, the maximum bearing capacity values of the wooden nail welding single shear joint and the twist nail joint were 3.51 and 5.75 kN, respectively. The initial stiffness values of the wooden nail welding single shear joint and the twist nail joint were 1.235 and 0.958 kN/mm, respectively. The final deformation values of the wooden nail welding single shear joint and the twist nail joint were 7.074 and 25.32 mm, respectively. The average energy dissipation values of the wooden nail welding single shear joint and the twist nail joint were 7.24 kN·mm and 99.7 kN·mm, respectively. The performance of the wooden nail welding single shear joint was inferior to that of the twist nail joints. A typical wooden nail welding single shear joint load-bearing curve is shown in Fig. 6. There was a "linear region" of stress *vs*. displacement from about 4 to 6.5 mm displacement, then there was brittle failure of the bonded line. The twist nail joint load-bearing curve is shown in Fig. 7. It showed a better toughness with higher energy consumption than the joint connected by wooden nails. The failure mode of the wooden nail welding single shear joint conforms to the IV mode of pin yielding, *i.e.*, the plastic hinge of the dowel until rupture, the test extrapolated design value of 2.169 kN.

Table 1. Single Shear Performance of the Wooden Nail and Twist Nail Joint

Connection Mode	Maximum Bearing Capacity (MPa)	Initial Stiffness (MPa)	Final Deformation (mm)	Average Energy Dissipation (kN·mm)
Wooden nail	3.51 (0.21)	1.235 (0.24)	7.074 (1.58)	7.235 (2.11)
Twist Nail	5.75 (1.04)	0.958 (0.28)	25.319 (4.23)	99.678 (10.64)

Note: The standard deviation is shown in parentheses.

The calculation of the design value of the pressure-bearing capacity was done with reference to the pin connection. The ratio of the pressure-bearing strength of the pin groove of the middle component to that of the side component (R_e) was equal to one, the elastic-plastic strengthening factor (K_{ep}) was equal to one, the force-resistance subfactor (γ_{IV}) was equal to 1.62, the diameter of the dowel (d) was equal to 4.7, the thickness of the connecting wood lumber (t_s) was equal to 38, and the yield strength of the dowel (f_{yk}) was equal to 250.

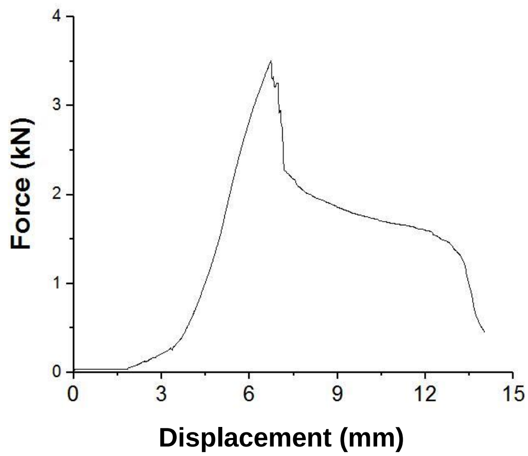

Fig. 6. Wooden nail welding single shear joint bearing curve

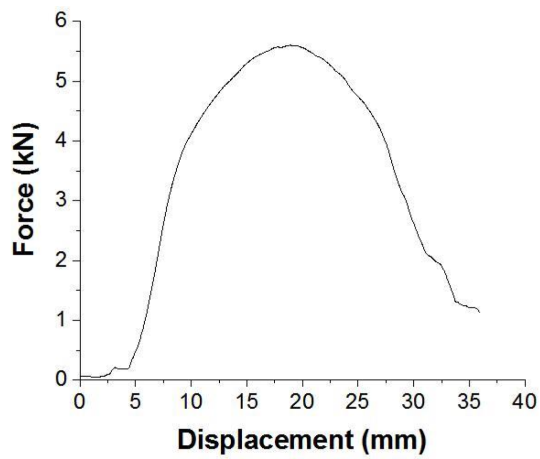

Fig. 7. Load bearing curve of the single shear joint with twist nail connection

The pin groove pressure-bearing strength (f_e) was calculated using Eq. 2, where *G* was the density of the wood substrate, which was SPF here.

$$f_e = 115G^{1.84} = 115 \times 0.42^{1.84} = 21.31kN \qquad (2)$$

The effective length factor of pin groove pressure-bearing capability for side components of dowels in yield IV mode (k_{IV}) was calculated according to Eqs. 3 and 4,

$$k_{sIV} = \frac{d}{t_s}\sqrt{\frac{1.647R_e k_{ep} f_{yk}}{3(1+R_e)f_{es}}} = 0.212 \qquad (3)$$

$$k_{IV} = \frac{k_{sIV}}{\gamma_{IV}} = 0.131 \qquad (4)$$

The reference design value of bearing capacity per shear surface for a single dowel (*Z*) was calculated according to Eq. 5,

$$Z = k_{IV} t_s d f_{es} = 0.545kN \qquad (5)$$

The adjustment of parameters considers the influence of various factors during actual use. The design value of bearing capacity per shear surface for a single dowel (Z_d)

can be defined by Eq. 6,

$$Z_d = C_m C_n C_t k_g Z = 0.496kN \quad (6)$$

where C_m is the water content is less than 15% during use (1.0), C_n is considering a design life of 50 years (1.0), C_t is the temperature adjustment factor (1.0), and k_g is the combination factor of group bolus (0.91).

The total bearing capacity of the connection of the four wooden nail welding single shear specimens was 1.984 kN, which was less than the design value of 2.169 kN derived from the test. This can be seen in Eq. 7,

$$n_b n_v Z_d = 1.984kN < 2.169kN \quad (7)$$

Therefore, the bearing capacity calculation of the wooden nail welding joints can be referred to in the pin connection section of the wood structure design manual.

Comparative Analysis of the Flexural Elastic Modulus of the Twist Nail and Wooden Nail Welding Laminated Timber

Table 2 shows the full modulus of elasticity in bending of the laminated timber with 150 mm nail spacing and the four-piece twist nail connections. Different nail spacing (150 mm and 300 mm), four-piece and eight-piece, full pressure-bearing and partial pressure-bearing wooden nail welding laminates were tested, and the results are listed in Table 3.

Table 2. Full Pressure-Bearing Flexural Elastic Modulus of Twist Nailed Joint Laminated Timber

Number	Wood Lumber Elastic Modulus (MPa)						Laminated Timber Elastic Modulus (MPa)
	1	2	3	4	Average value	Standard deviation	Test value
1	5,880	7,050	9,960	7,910	7,700	1,721.1	6,717
2	13,290	9,210	11,260	10,320	11020	1,729.8	9,603
3	9,160	10,830	9,460	6,060	8,877.5	2,014.1	7,960
4	9,700	8,780	12,950	7,430	9,715	2,349.5	8,296
5	9,540	12,710	8870	14,040	11,290	2,483.1	9,841
6	13,250	13,290	7370	12,890	11,700	2,892.3	10,489
7	9,830	10,520	10,860	10,360	10,392.5	429.1	10,246
8	8,280	11,160	8,800	10,750	9,747.5	1,420.3	8,516
9	7,680	8,240	10,490	8,860	8,817.5	1,214.7	7,802
10	5,514	8,947	9,099	7,486	7,761.5	1,665.5	7,019
11	6,712	9,864	10,184	8,795	8,888.75	1,568.0	7,618
12	7,979	10,317	11,000	8,439	9,433.75	1,453.6	8,362
Average value							8,539
Standard deviation							1,243

Table 3. Full Pressure-Bearing Flexural Elastic Modulus and Local Pressure-Bearing Stiffness of Wooden Nail Welded Laminated Timber

Number	Four-piece Laminated Timber			Eight-piece Laminated Timber			
	150 mm	300 mm		150 mm		300 mm	
	Full pressure-bearing (MPa)	Full pressure-bearing (MPa)	Mean value and standard deviation of wood lumber (MPa)	Full pressure-bearing (MPa)	Local pressure-bearing (MPa)	Full pressure-bearing (MPa)	Local pressure-bearing (MPa)
1	10,825	10,806	10,020 (1,625)	9,468	1,720	9,595	1,588
2	11,353	9,593	9,415 (2,455)	9,360	1,842	10,084	1,700
3	10,920	9,723	8,943 (790)	10,510	1,905	9,621	1,800
4	10,151	8,540	7,990 (2,605)	10,892	1,976	10,657	1,528
5	10,535	10,109	9,528 (2,545)	10,850	2,067	10,185	1,472
6	10,250	11,096	9,913 (525)	9,800	/	10,017	1,793
7	10,778	11,244	10,100 (573)	10,584	1,859	10,102	2,028
8	11,066	10,323	9,933 (917)	10,061	1,810	9,507	1,203
9	9,501	10,322	9,840 (1,821)	10,657	1,740	10,790	1,329
10	11,121	9,634	9,015 (1,023)	11,750	1,983	10,972	1,426
11	10,619	11,078	10,533 (1,404)	10,369	1,872	9,404	1,427
12	10,672	10,407	10,348 (1,386)	11,283	1,999	9,886	1,447
13	10,205	10,008	8,903 (804)	10,307	1,869	10,973	1,497
14	11,106	10,956	10,263 (559)	10,202	1,800	9,326	1,722
15	11,962	10,557	9,830 (1,620)	10,131	1,759	11,020	1,537
Average value	10,738	10,293	9,638	10,415	1,872	10,143	1,566
Standard deviation	583	727	1,504	638	104	604	210

By comparing the elastic modulus of the four wood lumber types and the elastic modulus of their constituent twist-nailed laminated timber in Table 2, it was found that the elastic modulus of the twist-nailed laminated timber was higher than the smallest elastic modulus of the corresponding four wood lumber types, but lower than the average value of the elastic modulus of the four wood lumber types. As can be seen in Fig. 8, the influence of the knots on the twist-nailed laminated timber was greater, and cracks and damage occurred at the knots. The elastic modulus of the twist-nailed laminated timber was influenced by the elastic modulus of the four wood lumber types, especially by the wood lumber with the lowest elastic modulus. At the same time, the smaller the difference between the elastic modulus of the four laminates, *i.e.*, the smaller the standard deviation, the closer the elastic modulus of the twist-nailed laminated timber was to the average elastic modulus of the four wood lumber types, as can be seen in the specimen No.7 in Table 2.

Fig. 8. Damage pattern of the laminated timber connected by twist nails

By comparing the elastic modulus of the wooden nail welding laminated timber and the twist-nailed laminated timber with a spacing of 150 mm, it was found that the average elastic modulus of the twist-nailed laminated timber was 8,540 MPa. The average elastic modulus of the corresponding wood lumbers was 9,610 MPa, with a standard deviation of 2,051 MPa. However, the average elastic modulus value of the 4th and 5th wooden nail welding laminated timber samples was 10,300 MPa. The average elastic modulus of the corresponding wood lumbers was 9,450 MPa with a standard deviation of 583 MPa. This indicated that the wooden nails compared with the twist nails. Because the wooden nails had a larger diameter than the twist nails, the wooden nail welding laminated timber in the elastic phase had better stiffness properties. The elastic modulus of the wooden nail welding laminated timber was able to exceed the average elastic modulus of the constituent laminates by 9.46%. The same pattern was found in the four-piece laminated timber with nail spacing of 300 mm and the eight-piece nail spacing of 150 mm and 300 mm, which were 6.80%, 6.05%, and 6.30% above the average elastic modulus of the constituent wood lumbers, respectively.

As can be seen in Table 3, the number of wood lumbers in wooden nail welding laminated timber had little effect on the elastic modulus of the laminated timber, but the nail spacing had a certain effect. For the full pressure-bearing four-piece wooden nail welding laminate, the elastic modulus of the nail spacing at 150 mm was 4.23% higher than that of the nail spacing at 300 mm. Additionally, in the full pressure-bearing eight-piece laminated timber, the nail spacing at 150 mm was 2.68% higher than that of 300 mm, and the nail spacing showed little effect on the elastic modulus.

Further analysis of the stiffness of the local pressure-bearing eight-piece laminated timber found that the influence of nail spacing at 150 mm had a 19.54% greater impact than the laminated timber with nail spacing at 300 mm. The 25 mm diameter pressure-bearing plate was used in the local pressure loading test. The plate was set on the center of the laminated timber, and the deformation occurred obviously among the middle local 2 to 4 pieces of lumber of the laminated timber. At this time, the local wooden nail welding joints could withstand a greater loading, so the more the number of nails per unit length, the stronger its ability to withstand the load. For the full compression mode, the entire laminated timber section was under load. During this time, the nails played a role in stabilizing and fastening the laminated timber, so that all the plies that make up the laminated timber were under load at the same time, which had a negligible impact. Therefore, in a future project, it is recommended to use the construction method of a twist nail connection to design the wooden nail welding laminated timber, and nail spacing should also refer to the GB 50005 (2017) wood structure design standards and wood structure design manual.

CONCLUSIONS

1. The single shear capacity of wooden nail welding specimen could be calculated by calculating method of design value of the bearing capacity of the pin connection.
2. Due to the larger diameter of the wooden nails compared to the twist nails, the wooden nail welding laminated timber in the elastic phase exhibited higher stiffness. The elastic modulus of the wooden nail welding laminated timber was able to exceed the average elastic modulus of the constituent laminates by 9.46%.

3. The number of wood lumber pieces in the wooden nail welding laminated timber had little effect on the elastic modulus of laminated timber, but the nail spacing had a certain effect.
4. It is recommended to use the construction method of twist nail connection to design the wooden nail welding laminated timber, and nail spacing should also refer to the GB 50005 (2017) wood structure design standards and wood structure design manual.

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