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Experiments and numerical simulation investigations on the mechanical performance of glulam enhanced with self-tapping screws along parallel glue seam

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Abstract
The reciprocal timber grid shell is a common structural form in timber spatial structures, widely used in engineering projects due to its aesthetic appeal and large spans. This study proposes the use of self-tapping screws to enhance the transverse grain at locally compressed areas on the side of glulam beams. Existing research has mainly focused on the mechanical properties of timber with grain reinforcement perpendicular to the direction of glue seam. However, there is limited research on the scenario where self-tapping screws are parallel to the glue seam of glulam, a condition commonly found in the connection of reciprocal timber grid shells. Therefore, this paper conducts experiments and finite element studies on the mechanical performance of glulam enhanced with self-tapping screws along parallel glue seam. The results show that all three reinforcement methods have improved the mechanical performance of glulam beams. Compared to the unreinforced specimens, those with screws penetrating through both sides, screws penetrating through one side, and screws intersecting on both sides increased by 25.9%, 34.5%, and 44.8%, respectively. Self-tapping screws can effectively improve the strain distribution of the timber below the compression surface. The finite element model can generally predict the mechanical performance of glulam reinforced with self-tapping screws.

Keywords: Reciprocal timber grid shell, Glulam enhanced with self-tapping screws, Mechanical performance.

1. Introduction
Wooden structures, characterized by their eco-friendly and low-carbon attributes, as well as their insulation properties, hold a significant market share within the construction industry. In contrast to steel, wood exhibits anisotropic characteristics, with superior strengths and elastic modulus along its grain direction as opposed to its transverse counterpart [1] . For timber spatial structures, glulam timber is conventionally employed as expansive-span beams, facilitating the creation of open and expansive architectural spaces. However, it is noteworthy that such beams inevitably undergo transverse compression, particularly at the terminal supports of wooden beams and lattice structures. Current scholarly investigations advocate for the adoption of various methodologies, including the utilization of self-tapping screws [2] [3] [4] , glued-in rods[5] [6] , fiber-reinforcing applications[7] [8] [9] , and the implementation of prestressing bolts[10] , all aimed at ameliorating transverse cracking phenomena in wood and enhancing its compressive performance perpendicular to the grain. Furthermore, studies also investigate the influence of different arrangements on improving the compressive performance of wood perpendicular to the grain.

However, the current scope of research predominantly concentrates on reinforcing measures perpendicular to the direction of glue seams. For timber grid shell, parallel to the glue seam direction, there exists a transverse compression scenario. This study advocates for the adoption of self-tapping screws along the parallel glue seam direction to enhance the transverse compression capabilities in this regard, as depicted in Fig 1. Notably, existing literature in this domain is sparse, necessitating further experimentation and finite element analyses. Consequently, this study endeavors to investigate various configurations of transverse reinforcement, encompassing specimens featuring screws penetrating through one side, screws penetrating through both sides, and screws intersecting on both sides.

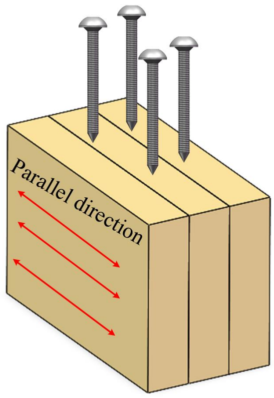


Fig.1 Glulam enhanced with self-tapping screws along parallel glue seam

2. Experimental tests

2.1. Material properties

The material properties of wood and steel in the tested connection are important for the mechanical properties of the component. Self-tapping screws are purchased from ROTHOBLAAS. The model numbers of the self-tapping screws are VGZ7×100, VGZ7×160, and VGZ7×180, respectively. For VGZ7×100, it implies a self-tapping screw with a diameter of 7 millimeters and a length of 100 millimeters. The tensile load-bearing capacity, yield strength, and elastic modulus of the self-tapping screws are 15.4 kN, 1,000 N/mm^2 , and 2.06×10^5 MPa, respectively. Glulam Douglas fir (TCt32) is selected as the tested specimen, and the material properties are listed in Table 1.

Table 1 Material properties of Douglas fir

Density (g /cm^3)	Moisture content	Compressive modulus of elasticity parallel to grain (MPa)	Compressive strength parallel to grain (MPa)	Compressive strength perpendicular to grain (MPa)	Shear strength parallel to grain (MPa)
0.505	11. 2%	11 226	36. 0	42. 2	8. 4

2.2. Specimen configurations

Four types of groups are designed to investigate the improvement in the mechanical performance of glulam enhanced with self-tapping screws along parallel glue seams. Table 2 and Fig. 2 present the specimen configurations.

Table 2 Specimen details

ID	Width of glulam	Height of glulam	Length of glulam	Nominal diameter of self-tapping screws	Length of self-tapping screws	Number of self-tapping screws
S1	160	160	480	7	-	0
S2	160	160	480	7	160	4
S3	160	160	480	7	100	8
S4	160	160	480	7	180	16

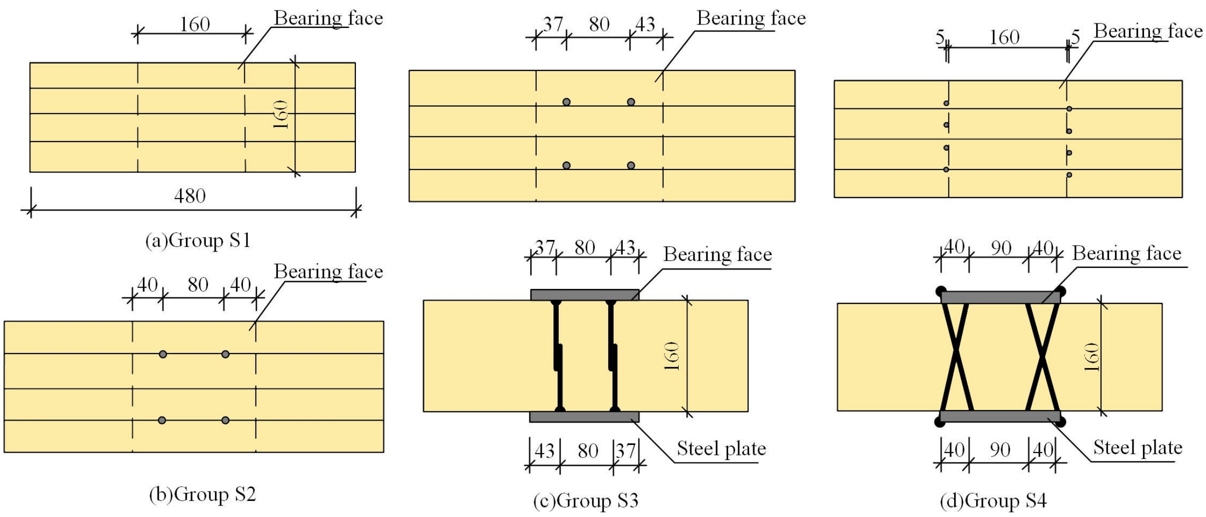
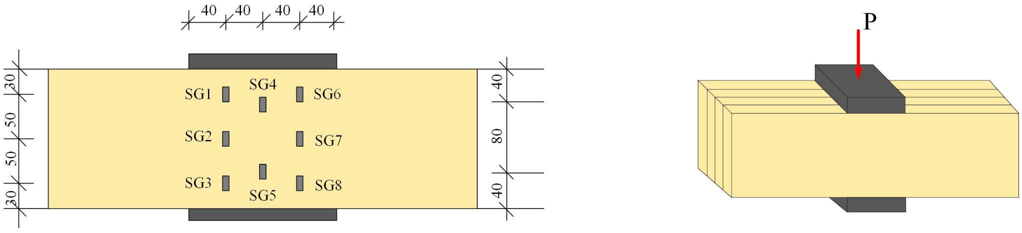


Fig. 2 Dimensions of the test specimens

Four groups were designed in this study to investigate the cross-grain compressive load of the specimens. In Group S1, specimens were untreated (control group), while Group S2 specimens featured single-sided through-length screws. Group S3 specimens had screws inserted from both sides, and Group S4 specimens utilized screws inserted from both sides at an angle. Each group comprised three duplicates. Prior to inserting the self-tapping screws into the specimens, pre-drilled pilot holes were made using a 4mm diameter drill bit.

2.3. Test setup and loading protocol

The strain gauges are positioned on the compressed surface, as illustrated in Fig.3. DH3817 is employed to measure strain of the specimens, with a horizontal spacing of 40mm between strain gauges. 16mm-thickness steel plates are placed on both upper and lower surfaces, aligning with the actual thickness of the connection components in engineering projects. Additionally, it is ensured that the loading direction remains parallel to the bonded surface of the wooden specimen. displacement control is adopted in this experiment with a loading rate of 0.5mm/min.



(a) Arrangement of strain gauges (b) Test setup

Fig. 3 Test setup and arrangement of strain gauges

3. Test results and discussions

3.1. Monotonic load-displacement response

Fig. 4 presents the load-displacement curves for all specimens subjected to cross-grain compressive load. As illustrated in Fig. 4, most specimens exhibit distinct characteristics of yielding failure, characterized by elastic deformation followed by a plateau in the stress-strain curve. Notably, in the early stages of loading, specimens in the reinforced groups (S2, S3, and S4) show a brief period of slip in the load-displacement curve compared to the unreinforced group (S1). This phenomenon is attributed to the presence of gaps between the wood and steel plate, as well as slight surface irregularities caused by the insertion of self-tapping screw heads or tips. Overall, specimens in the reinforced groups demonstrate relatively higher cross-grain compressive yield capacities.

Fig. 5 shows the strain distribution at the center of the compressed surface of the specimen. The strain exhibits a progression of increasing values from group S1 to S3, then to S2, and ultimately to S4. This suggests that all three reinforcement methods effectively suppress strain development. Notably, group S4, characterized by screws applied on both sides, demonstrates the most notable enhancement in local compressive deformation of wood transverse fibers.

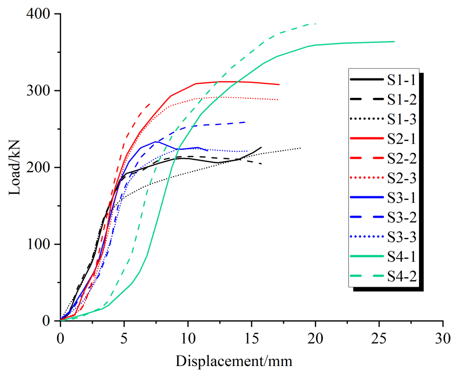


Fig. 4 Load-displacement curves

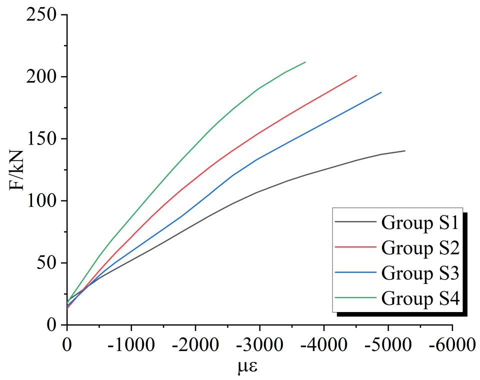


Fig. 5 Strain distribution at the center of the compressed surface of the specimen

According to the European standard EN 408, the method for determining the cross-grain compressive load of the specimen involves shifting the initial straight line segment by 1% of the specimen's height until it meets or intersects with the curve. The strength is calculated as follows:

$$f_{c,90} = \frac{F_{c,90}}{b \times l_1 \times k_{c,90}} \tag{1}$$

$$E_{c,90} = \frac{h \times (0.4F_{c,90} - 0.1F_{c,90})}{b \times l_1 \times (w_{0.4} - w_{0.1})} \tag{2}$$

$$k_{c,90} = k_c \times \sqrt{\frac{l_{eff}}{l}} \tag{3}$$

where h represents the height of specimen; $\omega_{0.4}$ and $\omega_{0.1}$ represent the displacement corresponding to 40% and 10% of the ultimate load respectively; k_c is the experimental correction coefficient, typically taken as 1.1; l_{eff} denotes the stress diffusion zone length at the bottom of the specimen under compression.

Table 3 presents the compression strength and equivalent elastic modulus of the specimens obtained based on the calculation method described above. From Table 3, it can be observed that the specimens in group S2 exhibit the highest equivalent transverse compression elastic modulus, while the values of equivalent transverse elastic modulus for groups S3 and S4 are slightly lower than that of group S1 (control group), indicating that the reinforcement method in group S2 is most effective in improving the compressive stiffness of wood. Compared to group S1, the compression capacities of groups S3, S2, and

S4 have increased by 25.9%, 34.5%, and 44.8% respectively, suggesting that the reinforcement effect of drilling 16 self-tapping screws diagonally from both sides is optimal.

Table 3 Compressive strength of specimens in the direction perpendicular to grain

No.	$f_{c,90}$ (MPa)	$E_{c,90}$ (MPa)
S1-1	5.05	322.1
S1-2	5.30	220.0
S1-3	4.39	258.2
S2-1	7.36	322.1
S2-2	7.44	463.9
S2-3	7.20	301.4
S3-1	5.86	214.7
S3-2	6.36	207.3
S3-3	5.71	189.9
S4-1	8.18	218.0
S4-2	7.33	294.5

4. Numerical models

Ansys was adopted to develop a finite element model of the specimens. The glulam was modeled using a bilinear constitutive relationship, with a longitudinal elastic modulus of 11226 MPa and a transverse elastic modulus of 374 MPa, employing the Hill yield criterion. Simplifying the screw as a smooth rod in the model, it was characterized using an effective diameter. In the model, the screw was in rigid contact with the wood hole wall, with tangential Coulomb friction defined with a coefficient of 0.6. The model's simulation results are depicted in Fig. 6. Fig. 6 illustrates the comparison between the simulation and experimental results of specimens in group S1. The simulation curve effectively predicts the transverse compressive stiffness and strength of the specimen. However, the simulation results lack the "zero stiffness" segment present in the experimental curve, primarily due to the unevenness of the wood surface caused by the absence of preloading during the experiment and the screw's penetration into the wood.

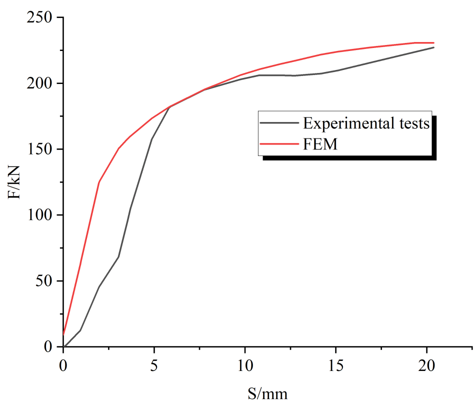


Fig. 6 Comparison between FEM and experimental results

4. Conclusion: submission of contributions

In this study, experiments and numerical simulation are conducted to investigate the mechanical performance of glulam enhanced with self-tapping screws along parallel glue seam. The test findings demonstrate that the glulam enhanced vertically, or diagonally with self-tapping screws along parallel glue seam, effectively improves the compressive strength of the specimens. When self-tapping screws penetrate fully on one side, they better transfer pressure to the opposing pressure-bearing steel plate, yielding slightly superior results compared to the reinforcement achieved by screws penetrating vertically on both sides. Among the three types of reinforced screw groups, the compressive load is highest in the double-sided diagonal screw group.

Acknowledgements

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