



ORIGINAL ARTICLE

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Experimental and numerical study on the screw connection strength of bamboo-oriented strand board compared with wood-oriented strand board

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Abstract

The utilization of resourceful bamboo can alleviate the wood shortage problem. Bamboo-oriented strand board (BOSB) with the highest utilization of bamboo ratio and excellent mechanical properties was considered as a good engineering and furniture material. The strength of joints affects the safety of BOSB structure. This study aims to investigate the effect of screw spacing on the tensile and compressive stiffness and strength of corner joints from BOSB by experimental method combined with finite element method (FEM) compared with wood-oriented strand board (WOSB). The results showed that (1) the strength and stiffness of the corner joint was significantly affected by the screw spacing, and it affected the compressive strength and stiffness of WOSB more significantly; (2) the bending moment and stiffness coefficient of BOSB compressed joint decreased with the increase of spacing, while that of tensile joint increased first and then decreased, and it reached the maximum value, when the spacing was 48 mm; (3) compared with WOSB joint, BOSB joint had higher strength and stiffness, and the failure of the joint was due to the yielding of self-drilling screws. This was also verified by numerical analysis results; (4) the bending moment of BOSB joints was about 2.5 times that of WOSB joints, while the difference between stiffness coefficient was small; (5) the elastic deformations resulted from experimental tests and FEM are similar. It was shown that when the screw spacing is 48 mm, the Von Mises stresses on the BOSB joint were smaller, and the bending strength and stiffness were larger, which was the most suitable screw spacing.

Keywords: Screw spacing, Bamboo-oriented strand board, Corner joint, Finite element method, Strength and stiffness

Introduction

China is one of the countries with the richest bamboo resources and is known as the "Bamboo Kingdom" [1]. Moreover, bamboo utilization ranks first in the world in terms of product varieties, scale, and output [1–4]. In

recent years, the development of bamboo-oriented strand board (BOSB) made of bamboo shavings [5–7] improves the utilization of bamboo and makes it possible to use small diameter bamboo and poor-quality materials [8]. Moreover, BOSB has the advantages of more excellent mechanical properties [1] and better dimensional stability [9, 10] compared with wood-oriented strand board (WOSB), which is considered as a good engineering and furniture material [11, 12]. The strength of furniture is not only affected by the mechanical properties of materials, but also depends on the stiffness and stability of joints

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[13]. The joints in furniture are the weakest elements in terms of their strength and stiffness [14]. Therefore, many studies focus on the bending moment capacity and stiffness of joints [15]. So far, the mechanical properties of wood composite joints have been studied comprehensively, such as PB (particleboard), MDF (medium-density fiberboard), HDF (high-density fiberboard), WOSB as well as new adhesives and connectors. However, there are few researches on the strength of BOSB jointed.

BOSB with high hardness is more suitable for thread connections to obtain greater mechanical strength, compared with non-threaded connections [16–18]. Compared with the two-in-one, three-in-one (with embedded nut), wood screw, and other threaded connectors, the thread end of self-drilling screws is narrower, the thread spacing is smaller, and the thread has a greater effect on the shear and extrusion deformation of bamboo fiber, so its connection strength is greater than other threaded connectors [19]. Self-drilling screws are widely used in the design of contemporary furniture, especially wooden and non-disassemble furniture [20]. Screws can be used as an auxiliary for joining connectors and materials, and can also be directly used for fixing corner joints, such as the joint of back plates and side plates, feet and boxes, and laminate plates and side plates. In 2018, Guo et al. found that the screw withdrawal resistance of BOSB is much higher than conventional particleboard in all directions [21]. The durability of BOSB fixed with self-drilling screws is greater than that of WOSB and glued laminated bamboo [17]. However, the performance of BOSB corner joints fixed by screws has not been studied.

Moreover, the screw spacing affects the strength of joints in furniture [22–25]. Improper installation spacing of screws would affect both the efficiency and cost of production and the stability and safety of furniture. However, there is no research about the influence of installation spacing on the connection strength of BOSB. A review of the literature shows that the strength of most furniture corner joint is obtained by experimental method [13, 26], which is destructive and non-repeatable, and only the failure strength and pattern of joints can be obtained. Therefore, knowledge of the stress distribution of joint is limited, which is not conducive to the optimization of furniture structure [27]. With the development of finite element software functions, the finite element analysis method is applied to the structural design of furniture gradually [2, 28, 29]. In the process of furniture design, FEM (finite element analysis) can be used as a fast and effective simulation method. Mechanical analysis can be done by the simulations of complex materials and models under different loads [2]. And the simulations are repeatable.

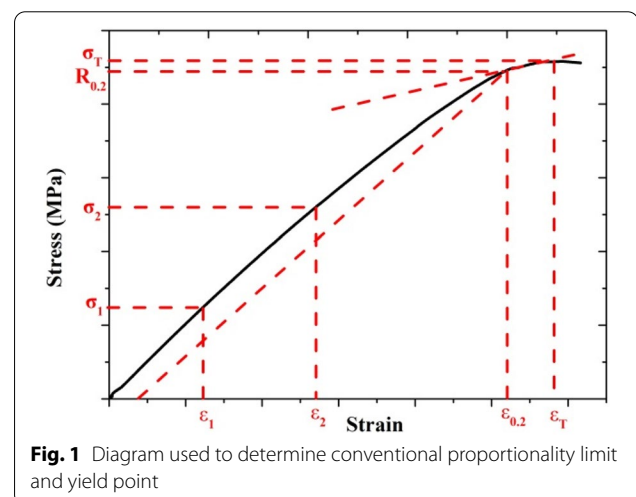
Therefore, the experimental and FEM analysis are used to investigate the effect of screw spacing on corner joint strength and stiffness of BOSB and WOSB to optimize screw connection. The specific objectives of this study are to (1) investigate the effect of screw spacing on the strength and stiffness of BOSB and WOSB joint by experimental and FEM method; (2) verify the accuracy of the FEM compared with the experimental results; (3) determine the optimal self-drilling screws installation spacing of BOSB and WOSB joint.

Materials and methods

Properties of selected materials

Samples were BOSB and WOSB, which were considered to be isotropic parallel to their wide surfaces. The density and moisture content were measured according to the ASTM D4442-92 [30] and ASTM D2395-93 [31], respectively. The Young's modulus and tensile strength (σ_T) were measured by uniaxial tension test [32–34]. Poisson's ratio was tested with strain gauge method according to ASTM D3039 [35]. Conventional yield point $R_{0.2}$ was determined using the uniaxial tensile tests method. Based on the stress–strain diagram, the yield strength $R_{0.2}$ (MPa) (Fig. 1) represents the stress value that produces 0.2% residual deformation [29]. The average test values of three square plate specimens can be obtained by repeated tests.

Self-drilling screw is stainless steel, with nominal diameter (D) of 3.97 mm, inner rod diameter (d) of 2.76 mm, length (L) of 39.73 mm, thread length (L_{Thread}) of 31.5 mm, screw pitch (P) of 1.40 mm (shown in Fig. 2) and the yield strength and modulus of elasticity were measured according to standard LY/T 3219–2020 [36].



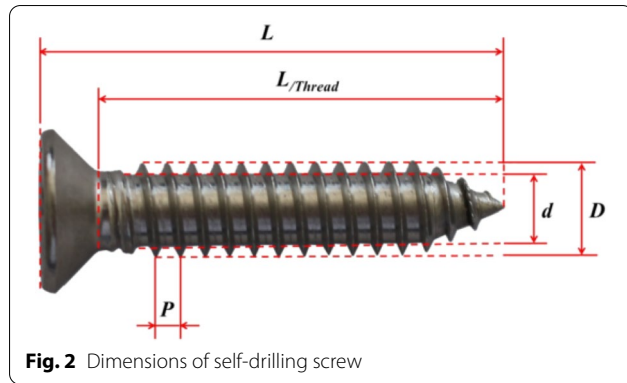


Fig. 2 Dimensions of self-drilling screw

Preparation of joints

The self-drilling screws were bought from a local commercial supplier (Hefei, China). The dimensions of BOSB were $150 \times 100 \times 15$ mm and $135 \times 100 \times 15$ mm, and the dimensions of WOSB were $150 \times 100 \times 18$ mm and $132 \times 100 \times 18$ mm. The screw spacing (S) was 16, 32, 48, 64, and 80 mm, respectively, symmetrically distributed, and fixed in the middle line of the thickness direction of the plates (shown in Fig. 3). Self-drilling screws were installed with a guide hole of 3.4 mm, penetrating one plate then inserting into the other one. 10 repetitions of each joint are prepared, and there were 100 specimens in total.

Strength testing

Joint mechanical properties were determined in compression and tension tests (Fig. 4). Tests were performed using a mechanical testing machine (model: WDW-100E, Jinan Chenda Testing Machine Manufacture Co., Ltd., Jinan, China). Crosshead speed was 10 mm/min. The experimental tests directly provided dependence between force P and

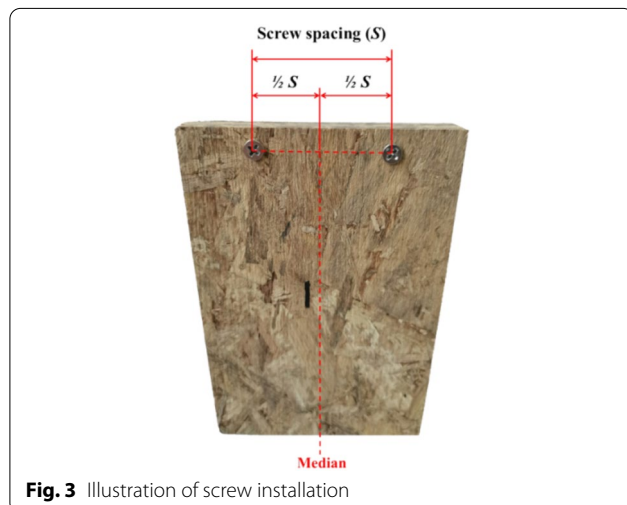


Fig. 3 Illustration of screw installation

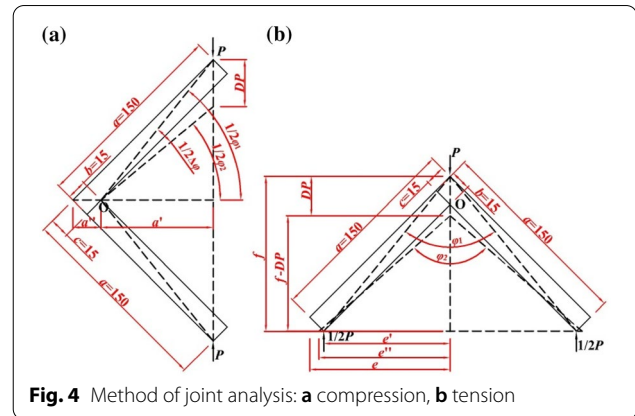


Fig. 4 Method of joint analysis: **a** compression, **b** tension

displacement DP . The strength of the joint was calculated as:

$$M_C = P_{\max} a', \quad (1)$$

$$M_T = 0.5 P_{\max} e', \quad (2)$$

where M_C was the bending moment resistance of the joint under compression loading (N m), M_T was the bending moment resistance of the joint under tension loading (N m), P_{\max} was the maximum load in each test sample (N), a' and e' were the moment arm in compression and tension, respectively (m).

For selected load diagrams, the stiffness coefficient of joint K (N·m/rad) was presented as the quotient of the bending moment for joint posts or rails $0.4M_C$ or $0.4M_T$ and rotation angle $\Delta\phi$ between the joint arms. This angle was determined based on the changes in joint geometry [15, 29, 34]. The coefficient of stiffness coefficient K subjected to compression (Fig. 4a) for the range of linear elasticity of joint was described by the equation [15]:

$$K_C = \frac{0.4M_C}{\Delta\phi}, \quad (3)$$

where:

$$\Delta\phi = \frac{\pi}{90} (\phi_1 - \phi_2), \quad (4)$$

$$a' = \frac{\sqrt{2}}{2} a - a'', \quad (5)$$

$$a'' = \sqrt{b^2 - c^2}, \quad (6)$$

$$\varphi_1 = \operatorname{atg}\left(\frac{\frac{\sqrt{2}}{2}a}{a'}\right), \quad (7)$$

$$\varphi_2 = \operatorname{asin}\left(\frac{\frac{\sqrt{2}}{2}a - DP_{0.4P_{max}}}{\sqrt{c^2 + (a-b)^2}}\right), \quad (8)$$

$$DP_{0.4P_{max}} = 0.4 \times DP_{max}. \quad (9)$$

The stiffness of joints subjected to tension (Fig. 3b) for the range of linear elasticity was calculated from the following equations:

$$K_T = \frac{0.4M_T}{\Delta\varphi}, \quad (10)$$

$$\Delta\varphi = \frac{\pi}{90}(\varphi_2 - \varphi_1), \quad (11)$$

$$e' = \frac{\sqrt{2}}{2}(a-b), \quad (12)$$

$$a'' = \sqrt{b^2 - c^2}, \quad (13)$$

$$0.5\varphi_1 = \operatorname{atg}\left(\frac{e'}{f}\right), \quad (14)$$

$$0.5\varphi_2 = \operatorname{atg}\left(\frac{e''}{f - DP_{0.4P_{max}}}\right), \quad (15)$$

$$f = e + \frac{\sqrt{2}}{2}b, \quad (16)$$

$$e'' = \sqrt{e'^2 + f^2 - (f - DP_{0.4P_{max}})^2}, \quad (17)$$

$$DP_{0.4P_{max}} = 0.4 \times DP_{max}. \quad (18)$$

The numerical model of joints

Modeling and numerical simulations were performed using the Siemens NX 12.0 program and Ansys workbench 17.0 software, respectively. Geometry, loading and boundary conditions of the model were based on Fig. 3. The thread features of screw were ignored in Numerical simulation. Between the hole in the board and screw, the bonded interaction was applied. The contact property between boards was specified with a friction coefficient of 0.1. The elements sizes of board and screw were approximately 3 mm and 5 mm, while for contact parts, the sizes of elements were approximate 3 mm to make the model more accurate. In general, 10-node modified quadratic tetrahedron element C3D10M was used (about 48,240 elements and 74,640 nodes per model). In addition, geometric nonlinearity is considered to represent the large deformation of the structure.

Results and analysis

Properties of materials

As seen in Table 1, the mean density of BOSB was 806.61 kg/m³, which was about 1.4 times that of WOSB. The Young's modulus and tensile strength of BOSB were both about three times that of WOSB. The data in Table 1 would be used for the finite element analysis.

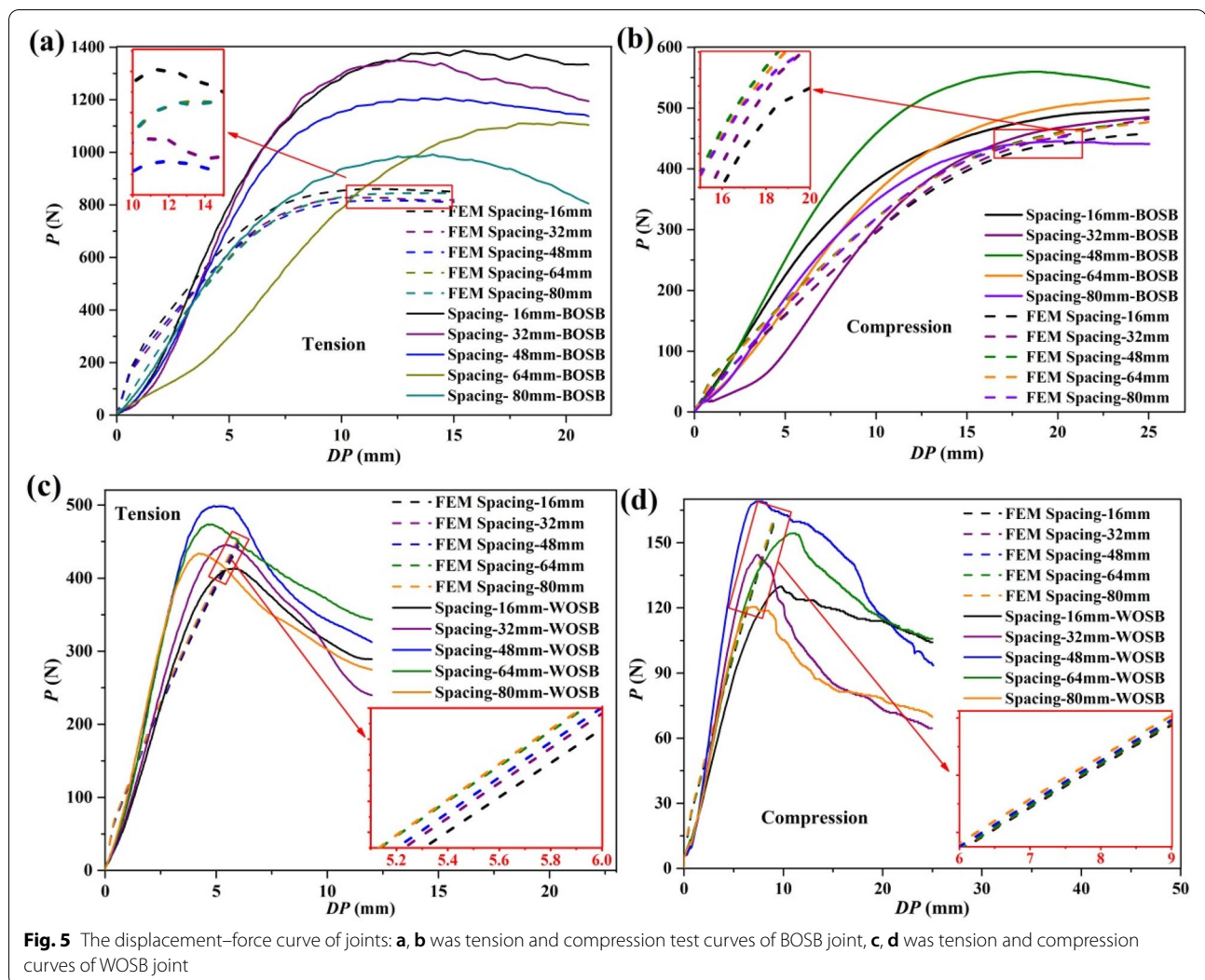
Strength of joints

It could be observed in Fig. 5a, b that curves for BOSB joint were smooth with no rapid changes after the maximum forces, but the curve of WOSB joint dropped rapidly after reaching the maximum force. This mean that the BOSB joints fixed by self-drilling screw had good durability and the strength of the joints did not decrease rapidly after reaching ultimate load, which could ensure the safety of the joint. Numerical calculations for the examined joints are also presented in Fig. 5, and the regularity of the loading curves obtained from the FEM was similar to test curves.

Seen from Fig. 5, the displacement–force curve could be approximately categorized into two stages. In the first stage, the correlation between force and displacement was almost linear, which confirmed the Hook's law [25]. The angle of curves with the horizontal axis represented the stiffness of joint [33]. In the case of compression, the

Table 1 Physical and mechanical properties of board and screw

Material	Thickness/ diameter (mm)	Density (kg/m ³)	Young's modulus (MPa)	Tensile strength (MPa)	Poisson's ratio	Yield point (MPa)
BOSB	15	806.61	6770.86	32.09	0.33	27.85
WOSB	18	569.20	2096.15	9.10	0.32	7.98
Screw	4		36,521.08		0.30	646.44



angle of BOSB joints with screws spacing of 48 mm was the largest, which represented the maximum strength and stiffness of this joint. Also, the angle was the largest for the WOSB joint with screw spacing of 48 mm. Moreover, the angles of BOSB joints with the spacing of 32, 64 and 80 mm were almost the same, but the maximum force was obviously different, which indicated that the three joints had similar stiffness, but the strength was different. Among BOSB joints, the compression ultimate force with screw spacing of 64 mm was largest, 505 N, and that of 80 mm was smallest (456 N). In the tensile test results, the BOSB joint with screw spacing of 16 mm had the maximum ultimate force (1460 N), which was 36% higher than that of the BOSB joint with the spacing of 80 mm (1071 N). For the WOSB joints with screw spacing of 48 mm, 64 mm and 80 mm had the same angle between the curve and the horizontal coordinate, which indicated that the stiffness was similar, while, the WOSB

joint with screw spacing of 48 mm had the highest ultimate force (501 N), followed by that of 64 mm (477 N).

Overall, the strength of joints subjected to tension was almost twofold greater than compressed joints, and the deflection of joints in the tension test was approximately twofold smaller than compressed samples. At the same time, the maximum force of BOSB was about 3 times of WOSB.

Typical damages of arms are illustrated in Fig. 6 caused by joint compression or tension. It should be noted that in the case of BOSB joint, the self-drilling screws were bent (due to the yield of the screws) and the shavings near them were pulled out, resulting in the failure of the joint. But in the case of WOSB joint, the board cracked and large pieces were pulled out (the board is damaged). This was also the reason that obvious peak appeared in the displacement–force curve of Fig. 5b, c.

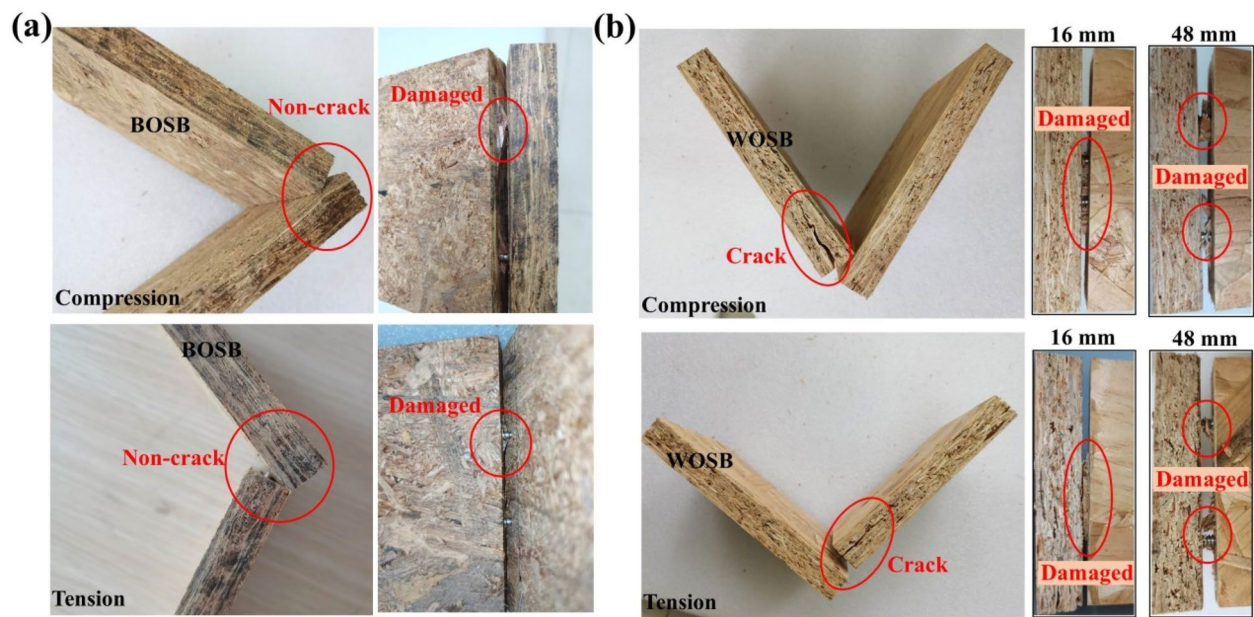


Fig. 6 Typical damage of joints: **a** BOSB, **b** WOSB

An important and reliable indicator of joint strength was provided by the maximum bending moment. Figure 7 shows the effect of screw spacing on the bending moment. It could be seen from Fig. 7a that in the tensile test, it was clear from this figure that in the tensile test, the bending moment of BOSB joint with screw spacing of 16 mm ($M_T = 69.97$ N m) was 38% higher than that of BOSB joint with screw spacing of 16 mm ($M_T = 50.80$ N m). It indicated that screw spacing significantly affected the strength of BOSB joint [28]. In contrast, screw spacing has little effect on WOSB joint.

The bending moment of joints subjected to tensile was greater than that of compression joints. For BOSB joint, the M_T was about 1.5 times M_C , and the M_T was about 2 times M_C for WOSB joint. The M_C of the BOSB joint was almost 3.5- to 4-fold higher than that of the WOSB joint. It can be seen from Fig. 7b that the bending moment of the BOSB joint in the compressive test increased and then decreased with the increase of screw spacing, and the maximum bending moment at the screw spacing of 48 mm ($M_C = 47.4$ N m) was 23% higher than the smallest bending moment at the screw spacing of

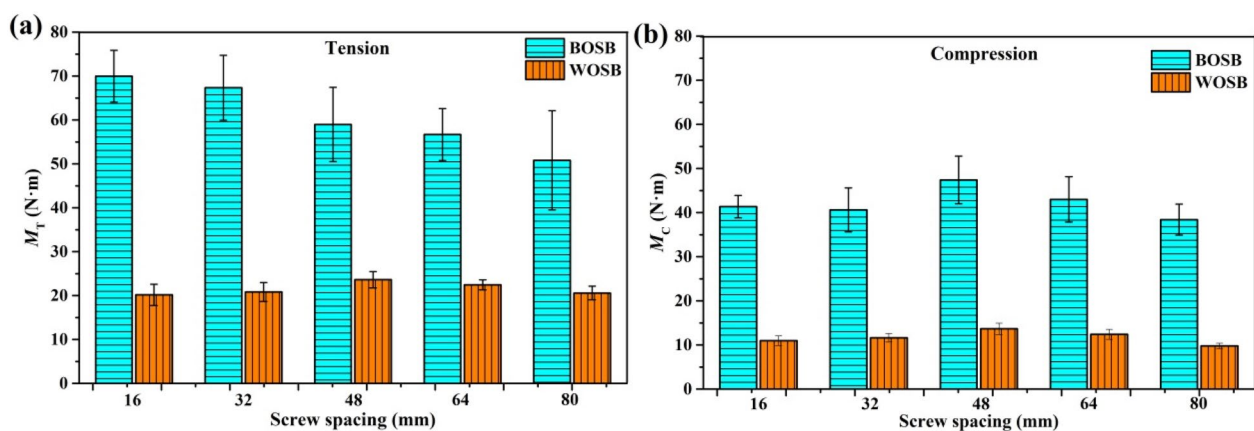


Fig. 7 Bending moment of joints at: **a** tension, **b** compression

80 mm ($M_C = 38.39$ N m). However, for WOSB joints, the highest bending moment at the screw spacing of 48 mm ($M_C = 13.65$ N m) was 40% higher than the smallest bending moment at the screw spacing of 80 mm ($M_C = 9.78$ N m), which indicated that the screw spacing had much more obvious effect on the bending moment of WOSB joints during compression test.

Analysis of variance (Tables 2 and 3) revealed a significant difference between the bending moments for joints connected with different screws spacing. For the tension test, F (BOSB) = 7.652 > F (WOSB) = 4.785, thus screw spacing affected the bending moment of BOSB joint more than that of WOSB. While, for the compression test, F (BOSB) = 4.573 < F (WOSB) = 15.780, which indicated screw spacing affected the bending moment of WOSB joint more than that of BOSB.

Summing up it may be generalized that the screw spacing was 48 mm, the BOSB joints had the largest bending moment for compressive and the smallest difference with the tensile bending moment, so this screw spacing was beneficial to improve the safety of furniture structure [37]. In this case, the WOSB joint also has better strength. Moreover, when the strength of joint with screw-fixed joint was greater compared to two-in-one and three-in-one [19].

Joint stiffness

Stiffness of joints was evaluated based on the change of stiffness coefficient K (N m/rad) in the function of rotation angle $\Delta\phi$ (rad). Analyses of results given in Fig. 8

indicated that the $\Delta\phi$ – K curves were smooth, and stiffness coefficient K increased with the increase of rotation angle $\Delta\phi$ nonlinearly before reaching the maximum value. In the tension test curve, the peak width of BOSB joints was greater than that of WOSB joints, which indicated that BOSB joints had better durability. The curves also showed that the stiffness coefficient of the BOSB joints was greater than that of the WOSB joints. Additionally, the stiffness coefficient curves showed that in the compression test joints obtain maximum stiffness coefficient at an almost twofold greater than that of subjected to tension. Besides, when the stiffness coefficient reaches the maximum, the DP of the BOSB joint in the case of the compression and tensile tests were around 7.7 mm and 5.5 mm, respectively, and it greater than that of WOSB. It confirms that the BOSB joint has better durability.

Figure 9 shows the effect of the screw spacing on the stiffness coefficient. It could be seen from Fig. 9a that the stiffness coefficient of BOSB joint decreased with the increase of screw spacing, while it increased for WOSB joint in tension test. In the compression test, the stiffness coefficient of the BOSB and WOSB joint tended to increase and then decrease with increasing spacing, their stiffness coefficient reaches the maximum when the screw spacing was 48 mm. Compared with the difference in bending moment, the difference in stiffness coefficient between WOSB and BOSB joint was slightly smaller. For BOSB joints with screw spacing of 48 mm the stiffness coefficient takes values of $K_T = 324.54$ Nm/rad in the case of tension and

Table 2 ANOVA results of tension moment of joints

Material	Source of variation	Sum of squares	df	Mean square	F	Level of significance
BOSB	Between groups	1976.597	4	494.149	7.652	0.000
	Within groups	2260.235	35	64.578		
	Total	4236.832	39			
WOSB	Between groups	67.405	4	16.851	4.785	0.003
	Within groups	123.268	35	3.522		
	Total	190.672	39			

Table 3 ANOVA results of compression moment of joints

Material	Source of variation	Sum of squares	df	Mean square	F	Level of significance
BOSB	Between groups	362.825	4	90.706	4.573	0.004
	Within groups	694.189	35	19.834		
	Total	1057.014	39			
WOSB	Between groups	68.437	4	17.109	15.780	0.000
	Within groups	37.947	35	1.084		
	Total	106.384	39			

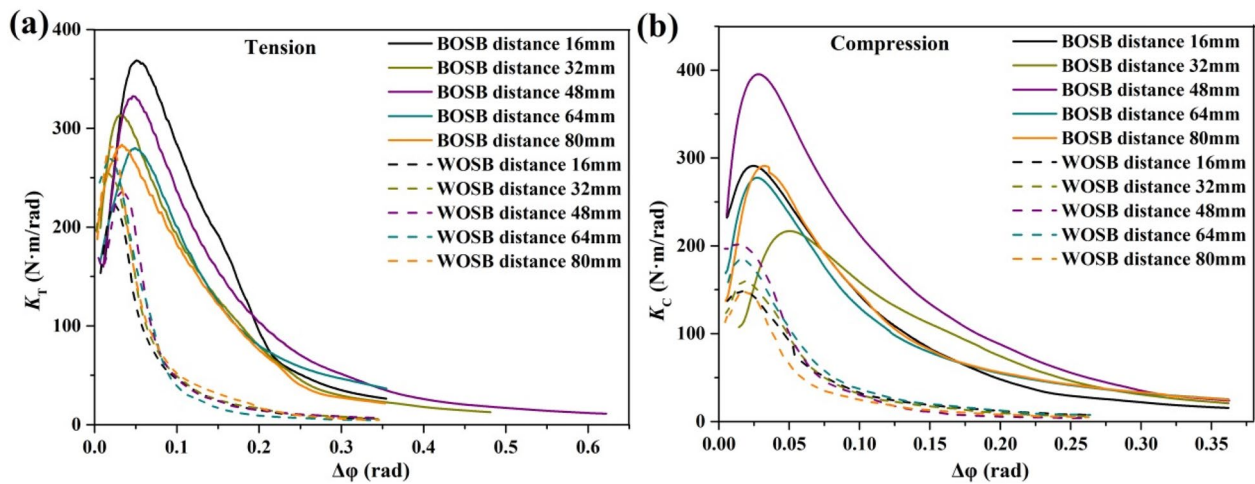


Fig. 8 Variation of stiffness coefficient K (N·m/rad) in the function of the rotation angle $\Delta\phi$ (rad) of joint: **a** compression, **b** tension

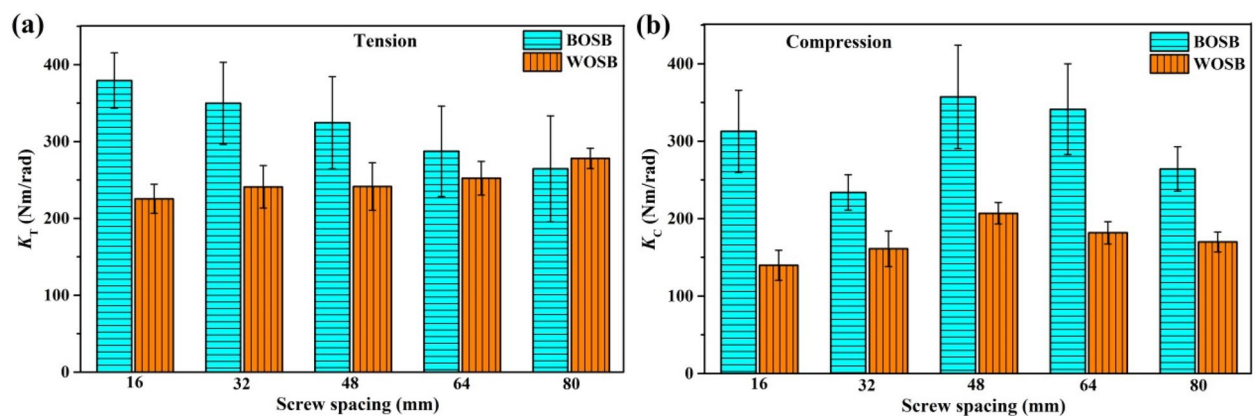


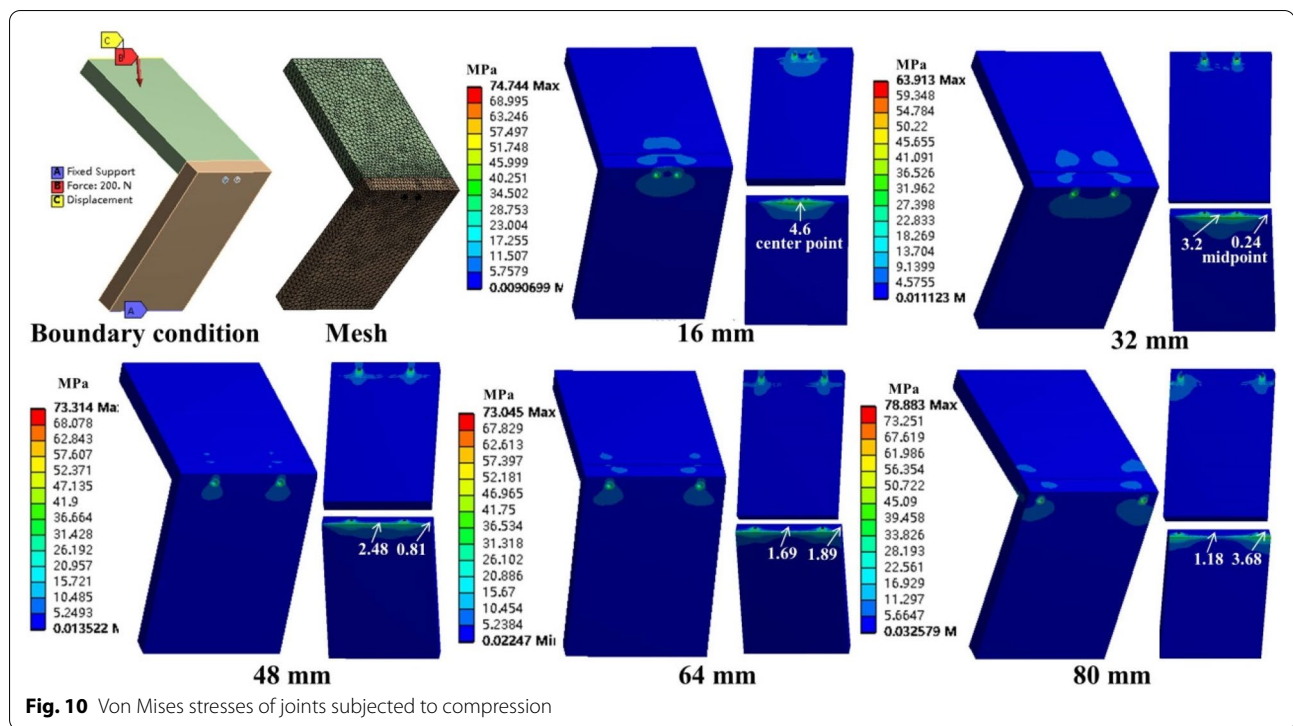
Fig. 9 Stiffness coefficient for joints subjected to: **a** tension, **b** compression

$K_C = 357.06$ Nm/rad for compression, which differs by as little as 9%. This showed that the loading mode has less influence on the stiffness coefficient of BOSB joints with screw spacing of 48 mm. In the tension test the stiffness coefficient of BOSB joints with screw spacing of 32 mm, $K_T = 349.68$ Nm/rad, was slightly greater than that of the joint in compression test was minimum at $K_C = 233.78$ Nm/rad. Thus the difference of 33% was significant. The difference of stiffness coefficient of BOSB joint with screw spacing of 16 mm between in tension and compression test was 18%. To the structural design of frame furniture, such a trend was highly disadvantageous. This was connected with the commonly observed type of deformation, e.g., in the side plating of bedsteads. In this case, joints were subjected alternately to tension and compression [15]. Thus, the BOSB joint with screw spacing of 48 mm has a comparable or

identical stiffness to ensure high structural reliability. The results of ANOVA results show the screw spacing had significant influence on the stiffness coefficient of both BOSB and WOSB joint, and it affected the tensile stiffness more than compression stiffness.

Results of numerical calculations for modeled joints

Figure 10 presents the Von Mises stresses of joints subjected to compression. From Fig. 10, we can observe that the highest stresses were concentrated in bottom of holes. It meant that with the load increases, the first damage occurred in this part of the plate [29]. The developing stresses were caused by the pressure of the self-drilling screws on the side surface of the hole. The boards on the inside of the joint also had large stresses due to compression. The results showed that the place with higher stress was the most vulnerable to failure, which was confirmed by the failure mode in the experimental test. And it also



showed the validity of the numerical analysis results. Moreover, it was found from Fig. 10 that under the same force, the stress distribution on the BOSB joints with screw spacing of 48 and 64 mm was significantly smaller than that with screw spacing of 16, 32 and 80 mm. This indicated that the safety of BOSB joints with screw spacing of 48 and 64 mm were higher than that of BOSB joints with other screw spacing, which was also verified by the experimental data.

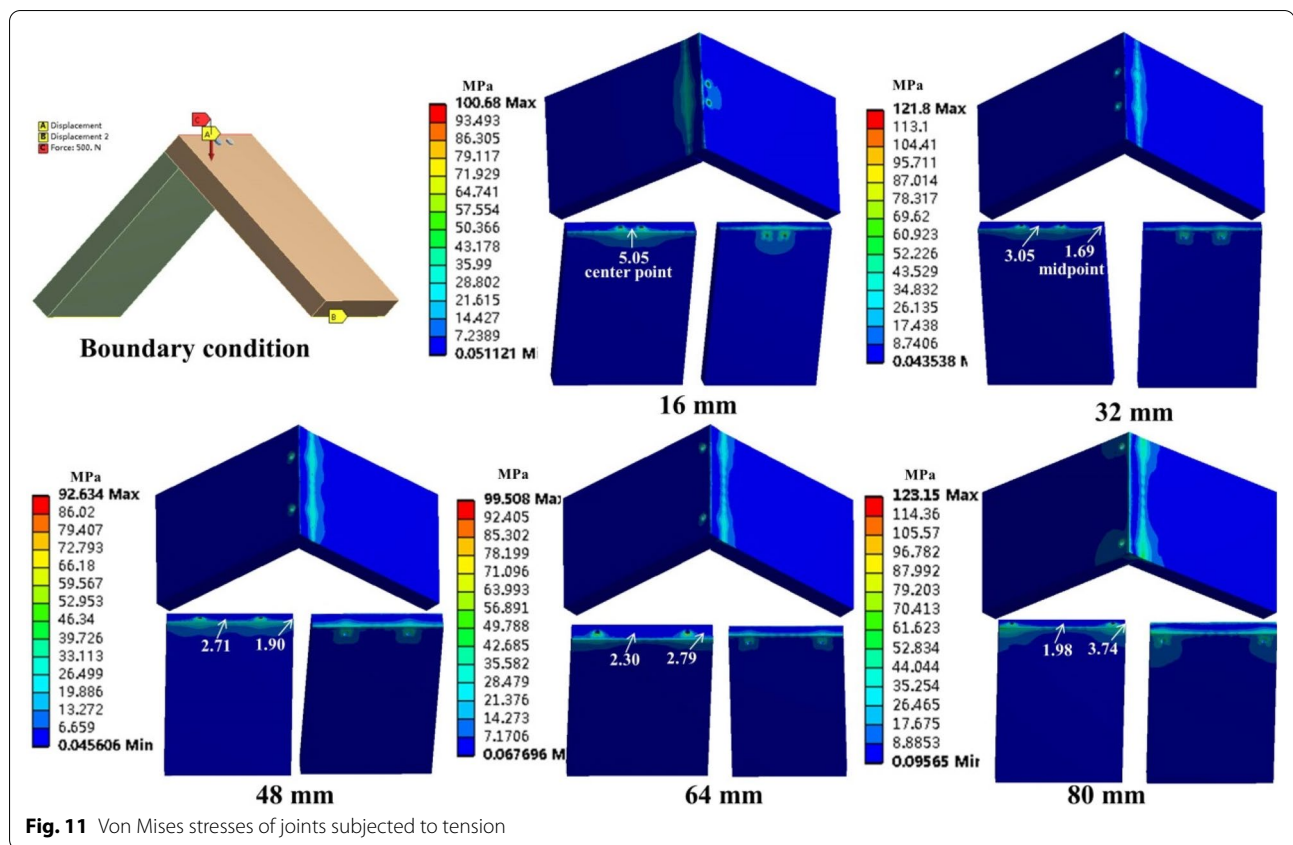
Figure 11 presents the Von Mises stresses of joints subjected to tension. The maximum stress was also concentrated near the hole on the inside of the screw bend. For boards parallel to the screw installation direction, the leverage on the screw causes the boards to delaminate and crack. Typical damages of arms illustrated in Fig. 6 caused by joint compression or tension corresponded with the results of numerical calculations indicating the same places of failure. Comparing the Von Mises stresses of different joints in Fig. 11, it was found that the maximum stress of joints with screw spacing of 48 and 64 mm was smaller, which indicates that the joints were safer. This result corresponds to the experimental result.

Conclusions

In this study, the effect of screw spacing on corner joint stiffness and strength of BOSB was studied using FEM and experimental test to optimize self-drilling screw

spacing compared with WOSB. The following conclusions were drawn:

- (1) The bending moment and stiffness coefficient were significantly affected by screw spacing. The screw spacing affected the mechanical property of BOSB joints more significantly than that of WOSB joints in tension test, while for compression test the screw spacing affected the bending moment and stiffness coefficient of WOSB joints more significantly than that of BOSB joints. The bending moment of BOSB joints subjected to compression and tension were almost 3.5- to 4-fold greater than that of WOSB joints, while the difference of stiffness coefficient was small. Moreover, the bending moment of BOSB joints subjected to tension was almost twofold greater than compressed samples.
- (2) For BOSB, the screw spacing of 48 mm could ensure the maximum strength and stiffness of corner joints and improve the safety of furniture.
- (3) The failure of BOSB joints was caused by the screw yielding and pulling out from the board (non-cracking). Due to the small mechanical strength of WOSB, the boards cracked during joint bending, resulting in the failure of the corner joints.



- (4) A comparison of displacement and failure mode of joints between experiment test and FEM showed that their results were the same and confirm the finite element analysis was effective.

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 17 May 2021 Accepted: 19 November 2021

Published online: 15 December 2021

Abbreviations

BOSB: Bamboo-oriented strand board; FEM: Finite element method; WOSB: Wood-oriented strand board; PB: Particleboard; MDF: Medium-density fiberboard; HDF: High-density fiberboard.

Acknowledgements

The authors would like to thank the anonymous reviewers and editor for their valuable comments and suggestions for improving the quality of this paper.

Authors' contributions

Conceptualization, SL, YC, and YG; data curation, KZ, XF, CL, and YB; formal analysis, KZ, and RX; funding acquisition, YC, SL, and YG; investigation, KZ and XF; methodology, KZ and FW; resources, YC and YG; supervision, YC and YG; validation, YC, SL, and YG; writing—original draft preparation, KZ; writing—review and editing, KZ and FW; funding acquisition, YC, SL, and YG. All authors read and approved the final manuscript.

Funding

The authors would like to express their heartfelt gratitude to the National Science and Technology Major Project of China (2016 YFD 0600905), China Natural Science Foundation (3180047) and the National Key Research and Development Program (2017YFD0600201).

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