Withdrawal resistance of the self-tapping screws in engineered bamboo scrimber

Citation for published version:
Li, H, Qiu, H, Wang, Z & Lu, Y 2021, 'Withdrawal resistance of the self-tapping screws in engineered bamboo scrimber', *Construction and Building Materials*, vol. 311, 125315. https://doi.org/10.1016/j.conbuildmat.2021.125315

Digital Object Identifier (DOI):
10.1016/j.conbuildmat.2021.125315

Published In:
Construction and Building Materials

Withdrawal Resistance of the Self-tapping Screws in Engineered Bamboo Scrimber

Hongmin Li [a,b*], Hongxing Qiu [c], Zhiqiang Wang [a], Yong Lu [d]

[a] Department of Timber Structures, College of Materials Science and Engineering, Nanjing Forestry University, No. 159 Longpan Road, Nanjing, 210037, China

[b] Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, Nanjing Forestry University, Nanjing 210037, China

[c] Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing 210096, China

[d] Institute for Infrastructure and Environment, School of Engineering, University of Edinburgh, Edinburgh EH9 3JL, UK

Abstract: The mechanical behaviour of the engineered bamboo scrimber connected by self-tapping screws (STSs) is strongly affected by the withdrawal resistance of the STSs in the bamboo scrimber. However, existing knowledge on the withdrawal resistance of STSs in such applications is quite limited. The main objective of this study is to investigate experimentally the withdrawal resistance of STSs inserted in engineered bamboo scrimber and propose an approach to its calculation in structural applications. In the experimental study, pull-out tests were conducted to obtain the load-displacement curves of STS-withdrawal specimens. The key parameters being investigated included the embedment length, the screw diameter, and the screw angle relative to the grain direction. The test results showed that the withdrawal resistance of the STSs connection increased with the increase of the embedment length, the diameter of the self-tapping screw, as well as the increase of the angle between the fiber and

[*] Corresponding author. Tel.:+86 15251857592

-*E-mail address*: lihongmin@njfu.edu.cn (Hongmin Li)

the axis of the STS. It has also been found that a critical anchoring slenderness ratio is around 7.5, and a longer embedment length would lead to the rupture of the STSs. For the calculation of the withdrawal resistance of the STSs in bamboo scrimber, several relevant calculation formulas are examined, and a modified formula is proposed. Verification of the modified formula against the current test results as well as relevant data from the literature shows satisfactory accuracy.

Keywords: Bamboo scrimber; Self-tapping screw; Anchor performance; Withdrawal resistance

1 Introduction

As a renewable material that can be used in structural engineering [1-3], engineered bamboo has attracted a lot of attention in the research community in recent years, with much of the interest focused on the mechanic behaviour and the processing technology [4-11]. While timber is more widely used in building structures, in many parts of the world such as China the timber resources are limited and the industrial use of timber relies heavily on imports. On the other hand, there exist numerous bamboo species and vast bamboo forest areas in many of those regions. From the structural application point of view, the tensile strength and compressive strength of bamboo are actually higher than wood, at about 2 times and 1.1 times that of wood, respectively [12]. The more recent advances in the processing technologies and industrialization level have promoted the production of engineered bamboo with excellent mechanical properties, such as glued bamboo [13], bamboo scrimber [14], laminated bamboo lumber [15] and bamboo-wood composite materials [16].

As one of the main engineering products in the market recently [17], bamboo scrimber is made by gluing the bamboo filament bundles together. The bamboo culm is disassembled into long bamboo strands firstly. After being dried and charred, the strands can be put into the molds and pressed into parallel bamboo strand lumber under hot pressing (or cold pressing) [18]. Both the tensile and compressive strengths along the grain of bamboo scrimber are higher than those of the wood material made from larch and spruce, with relatively low variability in material properties [19]. The tensile strength and modulus of elasticity along the bamboo grain can reach 100MPa and 10GPa, respectively. Thus, the bamboo scrimber has been used not only widely in furniture [20, 21], but also in building and bridge structures [18, 22]. The current research of bamboo scrimber generally focuses on the beam and column components [23-26]. However, the investigation on the connections in a bamboo scrimber structure is limited [27, 28]. In fact, the connection is often a weak link in a bamboo scrimber structure and so a sound connection design plays a key role in ensuring the integrity, strength and stiffness of the whole structure [28, 29]. Therefore, it is necessary to investigate the bamboo scrimber connection in detail.

The mechanical performance of the self-tapping screws (STSs) has improved with the progress of the metal processing technology. The STSs have shown potential in the beam-to-beam connection in timber structures [30-33]. Generally speaking, the STSs can reduce the possibility of splitting while used with small spacing and edge distance and increase operational efficiency. Besides, such a connection with STSs also possesses an aesthetical appearance and robust mechanical behavior [32]. Furthermore, STSs are effective in reinforcing timber joints [34], and they can also effectively transfer in-plane shear forces in connections of CLT shear walls and diaphragms [35]. Using fully threaded STS in the bamboo scrimber connections is a possible efficient choice.

In the above regards, the withdrawal resistance of the STSs in bamboo scrimber becomes a key factor. However, the research on the withdrawal resistance of the STSs in bamboo scrimber is still limited [21, 36, 37]. Test results of screw joints in bamboo scrimber furniture have shown that the screw-in depth and hole diameter have a significant influence on the pull-out resistance, whereas the type of screws has no apparent effect [21, 36]. It has been found that the face and edge withdrawal resistances of screws in bamboo scrimber tend to be higher as compared with those in medium-density fiberboard and particleboard [37]. It is also generally understood that the withdrawal resistance in bamboo scrimber used in furniture and structural applications has similar relations with the pilot hole diameter [21, 37]. More specifically, the withdrawal resistance of screws embedded in Phyllostachys edulis bamboo culm walls has been investigated and compared by a modified ASTM D1761 test [38]. Li et al [39] suggested that a suitable diameter of the guiding hole should be 80%–90% of the diameter of the screw in laminated bamboo lumber. Zhang [40] found that the relationship between the withdrawal resistance and the embedding depth of screw in Glued Laminated Bamboo followed a linear function. However, there is a lack of information regarding the influence of the screw angle on the withdrawal resistance of the STSs in bamboo scrimber, and moreover the calculation of the withdrawal resistance has not been investigated.

This paper presents an experimental investigation into the withdrawal resistance of self-tapping screws (STSs) inserted in bamboo scrimber for structural applications, with three common screw diameters. The influences of the STS embedment length, screw diameter and screw angle on the failure mode and the withdrawal resistance are investigated systematically.

Furthermore, several relevant calculation formulas are applied to estimate the withdrawal resistance of STS in bamboo scrimber. These include formulas in Eurocode 5 [41] and CCMC13677-R [42], which are originally suited for the screw bearing capacity in timber, and an empirical formula [43] for the withdrawal resistance in the raw bamboo. The results are compared and analysed. On this basis, modified formulas for the calculation of the withdrawal resistance of the STSs at an angle of 0° and 90° with the bamboo scrimber fiber are proposed.

2. Experimental program

2.1 Materials

The materials involved in this study include bamboo scrimber and STSs. The bamboo scrimber was supplied by a bamboo material producer in Jiangxi province, China. According to the "testing methods for physical and mechanical properties of bamboo used in building" [44], the average moisture content of the bamboo scrimber was determined to be 9.8%, and the average air-dry density was 1.05 g/cm^3. A total of 75 compressive tests and 6 bending tests of bamboo scrimber material were performed (Fig.1). The cross-sections of the samples were uniformly 20 mm × 20 mm. For compression tests, the sample specimens were 30 mm in length and the compressive loads were applied at the two ends of the samples via rigid steel plates [45, 46]. For the bending tests, specimens were 300mm in length and the tests were performed according to the ISO 3349 standard [47]. The compressive tests and bending tests of the samples were carried out using a 100kN mechanical testing machine and a 30 kN mechanical testing machine, respectively. Both types of tests were performed under a displacement control mode, and the loading rate was 5mm/min for the compression tests and 4mm/min for the bending tests.

The test results for the properties of the bamboo scrimber are shown in Table 1. It can be observed that the relative difference of the total compressive strength in the radial and tangential directions of the bamboo scrimber is only 2.9%. The relative difference of the local compressive strength in these two directions is also small, at 7.8%. This may be explained by the fact that in the process of restructuring bamboo, all four sides are compressed and the bamboo filaments are tightly combined, and as a result the mechanical properties of the two horizontal grain directions are close to each other. According to a separate experiment on the same bamboo scrimber [48], the compressive modulus of elasticity in the direction parallel to the grain is 11890 MPa, and that perpendicular to the grain is 1365 MPa.

(a) (b) (c) (d)

Fig. 1. Test of material properties of bamboo scrimber: (a) Compressive strength parallel to the grain, (b) compressive strength perpendicular to the grain, (c) Local compressive strength perpendicular to the grain, and (d) Bending strength

Table 1 Parameters of the bamboo scrimber

Material	Bending strength (Mpa)	Compressive strength parallel to grain (Mpa)	Compressive strength perpendicular to the grain (MPa)			
			Radial total strength	Radial local strength	Tangential total strength	Tangential local strength
Bamboo scrimber	260	75.5	24.9	13.6	24.2	14.9

Fully threaded STSs with double countersunk head were used in this test. Three screw diameters of 6mm, 8mm and 10mm with the same length of 140mm were considered. Table 2 lists the technical specifications of the screws as provided by the manufacturer.

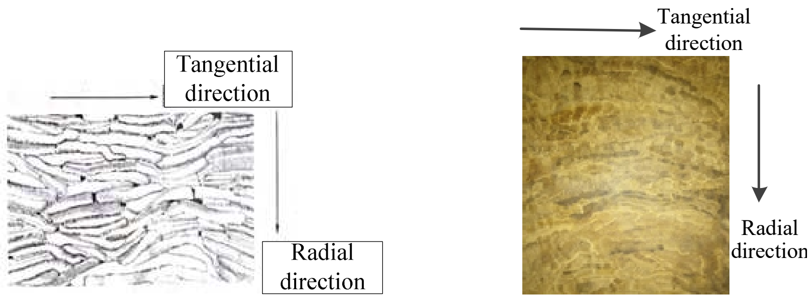
Table 2 Specification and strengths of STSs

Specification	Outside diameter (mm)	Root diameter (mm)	Total length (mm)	Thread length (mm)	Head diameter (mm)	Bending yield strength (MPa)	Tension strength (MPa)
FTCD-6	6	4	140	130	11.8	1000.0	1100.0
FTCD-8	8	5.3	140	130	15.5	1000.0	1100.0

FTCD-10	10	6.3	140	130	17.8	1000.0	1100.0

2.2 Test specimens and parameters

The texture of the bamboo scrimber is similar to that of the engineered wood, so the texture directions can be defined according to the definitions for parallel strand lumber (PSL) [49]. Since the bamboo slices that form the bamboo scrimber usually have a larger width than the thickness, the direction along the width of the bamboo slices is defined as the tangential direction and that along the thickness is defined as radial direction (Fig. 2).



(a) (b)

Fig. 2. Bamboo scrimber sectional definition: (a) PSL Sectional features [30], (b) Bamboo scrimber Sectional features

The specimens were designed in conformation with ASTM D1761 [50] and the Chinese Standard LY-T2377-2014 [51] for testing fasteners in wood. Three main factors affecting the withdrawal resistance were investigated, namely, a) effective embedment length l_{ef}, b) screw angle relative to grain direction α, and c) insert texture directions (Group T). Totally 210 specimens were tested with the same type of bamboo scrimber, and these were divided into three main groups, as follows:

Group RD: this group was designed to investigate the effect of the embedment length on the withdrawal resistance, with the embedment length varying between 20mm, 30mm and 40mm, while the screw angle α was kept at 90 degrees. Three different screw diameters of

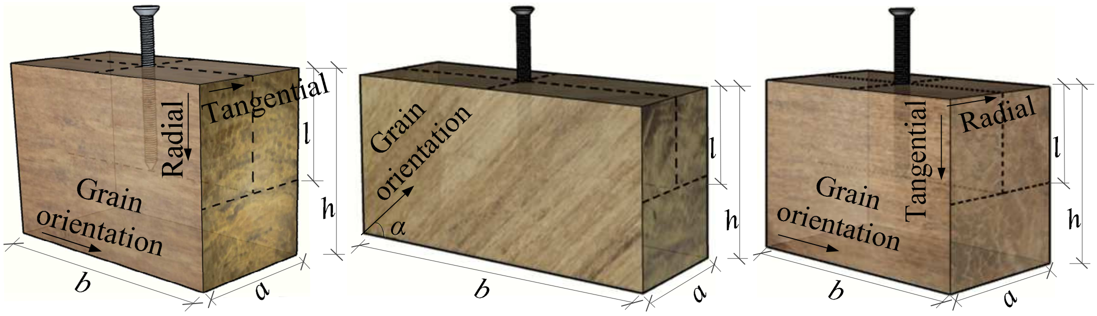
6mm, 8mm and 10mm, respectively, were considered. Thus, Group RD actually consisted of 9 series of specimens, as listed in detail in Table 3.

Group RA: this group focused on the effect of the insertion angle on the withdrawal resistance. In addition to the 90° angle already tested in Group RD, two further angles, namely 0° and 45°, were included. For each angle, three different screw diameters of 6mm, 8mm and 10mm, respectively, were considered. The embedment length was kept constant at 30mm. Thus, 6 new series of specimens were tested in this group.

Group T: this group was added to test the screw insertion in the tangential direction of the bamboo scrimber from the section point of view (Fig. 2(b)), in addition to the radial direction as in Group RD and RA. Two screw angles relative to the grain direction (α= 45°, 90°) and three screw diameters (6mm, 8mm and 10mm) were considered for Group T, making further 6 series of test specimens as listed also in Table 3.

Fig. 3 shows a representative diagram of specimens in three groups. The length, width, height of the specimens and the screw embedment length are denoted by a, b, h, and l respectively. The effective embedment length, l_{ef}, is defined by l minus the length of the screw tip which is assumed equal to the diameter of the screws, d; thus $l_{ef} = l$ - d. The size parameters of the specimens are listed in Table 3.

The specimens are labelled according to their parameter settings, for example R-6d-90-20. The first character, R or T, represents that the thrust direction of the self-tapping screw, i.e., in the radial direction (R) or tangential direction (T) of the bamboo scrimber. The second part represents the outer diameter of the STS, with 6d, 8d and 10d denoting 6 mm, 8 mm, and 10 mm of the STS diameter, respectively. The 3rd part represents the angle between the axis of the STSs and the bamboo scrimber fiber. For example, 90 means that the STS is driven to the bamboo scrimber fiber bundle perpendicularly, and 0 indicates that the axis of STS is the same as the direction along the grain of the bamboo (Fig. 4). The 4th part denotes the effective embedment length of the STS. λ represents the anchoring slenderness ratio, i.e., the ratio of the effective embedment length to the diameter of the STS. Prior to the selection of the effective embedment lengths for the specimens, a preliminary experiment was carried out to determine the baseline value of λ which corresponded to the yield failure of the STSs. Details of the preliminary experiment are given in Section 2.1.



(a) (b) (c)

Fig. 3. Test specimens: (a) Group RD, (b) Group RA, (c) Group T

Fig. 4. R-8d-0-30

It is common practice with wood materials that when the wood density exceeds 0.5 g/cm^3, the wood needs to be pre-drilled for STSs installation [52]. In the present test, the average density of the bamboo scrimber was 1.05 g/cm^3, so pre-drilling was considered for the installation of STSs. For confirmation purpose, a comparative test was firstly carried out between trial specimens with and without pre-drilling in the installation of the STSs. Test results showed that the STSs without pre-drilled holes were pulled out earlier with damage in the thread of the STSs, and the withdrawal resistance was much smaller than that of the STSs with pre-drilled holes. This indicates that the bamboo scrimber under investigation cannot provide sufficient holding strength without pre-drilling. Therefore, pre-drilling was adopted in all the formal test specimens. The diameter of the pre-drilled hole was made no greater than 0.6 times the outer diameter of the STSs [52].

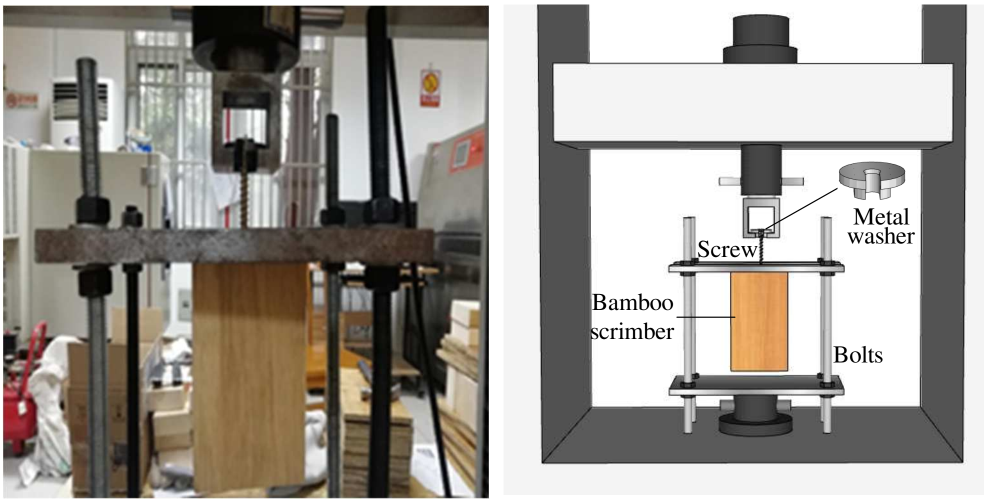
Table 3 Dimensional parameters of the specimens

Specimens group	Specimens Series	d (mm)	α (°)	l_{ef} (mm)	a (mm)	b (mm)	h (mm)	ρ (g/cm^3)	λ	n
RD	R-6d-90-20	6	90°	20	60	120	90	1.17	3.3	10
	R-6d-90-30	6	90°	30	60	120	110	1.05	5	10
	R-6d-90-40	6	90°	40	60	120	130	1.05	6.6	10
	R-8d-90-20	8	90°	20	80	160	100	1.07	2.5	10
	R-8d-90-30	8	90°	30	80	160	120	1.01	3.75	10
	R-8d-90-40	8	90°	40	80	160	140	1.04	5	10
	R-10d-90-20	10	90°	20	100	200	110	1.05	2	10
	R-10d-90-30	10	90°	30	100	200	130	1.02	3	10
	R-10d-90-40	10	90°	40	100	200	150	1.04	4	10
RA	R-6d-0-30	6	0°	30	60	60	110	1.05	5	10
	R-6d-45-30	6	45°	30	130	60	130	1.09	5	10
	R-8d-0-30	8	0°	30	80	80	120	0.97	3.75	10
	R-8d-45-30	8	45°	30	160	80	130	1.01	3.75	10
	R-10d-0-30	10	0°	30	100	100	130	1.04	3	10
	R-10d-45-30	10	45°	30	200	100	130	1.01	3	10
T	T-6d-90-30	6	90°	30	60	120	110	1.05	5	10
	T-8d-90-30	8	90°	30	80	160	120	1.05	3.75	10
	T-10d-90-30	10	90°	30	100	200	130	1.04	3	10
	T-6d-45-30	6	45°	30	130	60	130	1.24	5	10
	T-8d-45-30	8	45°	30	160	80	130	1.22	3.75	10
	T-10d-45-30	10	45°	30	200	100	130	1.19	3	10

Note: d, l_{ef} denotes the outside diameter, the effective embedment length into the member of the STSs; α denotes the angle between the axial of STSs and the grain; ρ and n denote the density and number of the specimens.

2.3 Test method

The test was conducted using a 100kN mechanical testing machine. The bamboo scrimber specimen was fixed on the testing machine with a dowel-connected special fixture, and the head of the STSs was fixed to the loading head of the testing machine with metal washers and bolts. The loading configuration is shown in Fig. 5. According to ASTM D5652 [53], the displacement control method at the rate of loading of 3 mm/min was adopted. The actual loading time for each test piece was 3~5 min and the loading was terminated when the test piece broke or the load-displacement curve developed a significant drop. In the test, the load and displacement were measured and recorded by the MTS force sensor and displacement sensor.



(a) (b)

Fig. 5. Test setup: (a) specimen under testing, (b) schematic of setup

3 Test results and analysis

3.1 Preliminary test

To determine an appropriate range of embedding length, a preliminary test was designed and carried out ahead of the formal test. In the preliminary test group, tests were performed on the specimens with anchoring slenderness ratios λ of 6, 7, and 8.

When the values of λ were 6 and 7, the specimen behaved in an elastic manner at the initial stage, with no obvious damage. Beyond a certain elastic limit, the load increased at reduced rates with increase of the displacement, showing inelastic behaviours which were accompanied with slight bamboo fibre fracture sound. When the loading reached the maximum level, a rapid decrease of the load was followed with an apparent sound of wood breaking. During the whole process, the screw was in the elastic stage and there was no yielding failure. When the value of λ was 8, the specimens exhibited a similar general behaviour as described above. However, when the loading reached a certain level, the screw ruptured at the end region with a loud bang (Fig. 6), marking a total failure of the specimens. By further narrowing the range of λ, it was found that λ equal to 7.5 approximately marked a critical embedment length; a longer embedment length would lead to the rupture of the STSs, whereas a shorter embedment length would generally guarantee an STS pull-out failure.

For STS of a diameter of 6mm, the embedment length for λ=7.5 is 45mm. Finally, the test embedment lengths of the STSs were determined as 20mm, 30mm, and 40mm for STS specimens of all three diameters to ensure a pull-out mode of failure. As will be presented in the test results later, all of the specimens did exhibit an STS pull-out failure, enabling the determination of the STS withdrawal resistance of the specimens.

Fig. 6. Rupture failure of the STSs for λ=7.5

3.2 General response and failure mode

The performance of each specimen was similar before the attainment of the ultimate bearing capacity. During the initial loading stage, the anchoring surface of the restructured bamboo remained intact (Fig. 7a), and the load increased linearly with the displacement. After the displacement reached a certain level, the increasing rate of the load decreased, while a slight bamboo tearing sound was heard. When the loading approached the withdrawal resistance of the STSs, the relative slip became pronounced and this was accompanied by the bamboo fibre fracture sound (Fig. 7b).

After reaching the ultimate bearing capacity, all specimens exhibited a pull-out failure of the STSs. Due to a different angle α between the pull-out force of the STSs and the bamboo scrimber bundle, different groups of specimens showed different failure modes. In the RD group and the T group with α=90°, the bamboo fiber was torn horizontally. In the later stage of loading, the load reduction rate was stable, and a certain residual withdrawal capacity remained (Fig. 8a). In the RA group with α=45°, the affected part of the bamboo scrimber fiber underwent shear failure along the grain. In the later stage of loading, the load dropped faster than the specimens in the former two groups with α=90° and the residual withdrawal capacity was smaller (Fig. 8b). In the RA group with α=0°, the bamboo fiber bundle underwent shear along the grain and was pulled out together with the STSs. After the ultimate bearing capacity, the load dropped rapidly (Fig. 8c). It is worth noting that in the special case where the STS was nailed at the glue layer, the failure mode was that the reorganized bamboo split along the glue joint. Therefore, for α=0°, the nailing position should be kept sufficiently away from the glue joint.

(a) (b)

Fig. 7. Specimens under loading: (a) Initial stage of loading, (b) Approaching peak load

(a) (b) (c)

Fig. 8. Typical failure modes for different insertion angles: (a) 90°, (b) 45°, (c) 0°

3.3 Withdrawal resistance

With reference to the law of lognormal distribution of wood strength [54], the withdrawal resistance of STSs is analyzed using the lognormal distribution herein. The withdrawal resistance results of the test specimens are shown in Table 4, including the distribution parameters. A comparison between the probability distribution curves of predicted data and test data is shown in Figs. 9 - 11.

As shown in Table 4, the average value and the 5th percentile value of the withdrawal resistance in the RD group gradually increase with the increase of the embedment length. Especially, the 5th percentile value increases linearly with the embedment length (Fig. 9). The withdrawal resistance of the RD group also increases with the increase of the diameter of STSs. It is noted that the average withdrawal resistance of the STSs with a diameter of 6mm (R-6d-90-20) is greater than the diameter of 8mm (R-8d-90-20). In addition to the larger density of the R-6d-90-20 series, the main reason is that the anchor slenderness ratio λ of the latter two series (R-8d-90-20, R-10d-90-20) is markedly small. The small value of λ affects the development of the withdrawal resistance of STSs, and based on the present observation it is recommended that the minimum λ of the STSs in bamboo scrimber is 3.

Table 4 also shows that the average withdrawal resistance of the STSs with α= 45°in the RA group is greater than that of the specimens with α= 0°. Comparison with the RD group and the T group implies that the withdrawal resistance of the STSs driven in the radial or tangential direction is greater than that of the STSs driven along the grain. This is consistent with experimental observations from the literature [37] in that the withdrawal resistance of the STSs increases as the angle α between the STSs and the bamboo fiber increases. The main reason is that with an increase of the angle more bamboo fibers become intertwined with the STSs, resulting in less grain-wise shear damage of bamboo fiber and more horizontal grain shear damage.

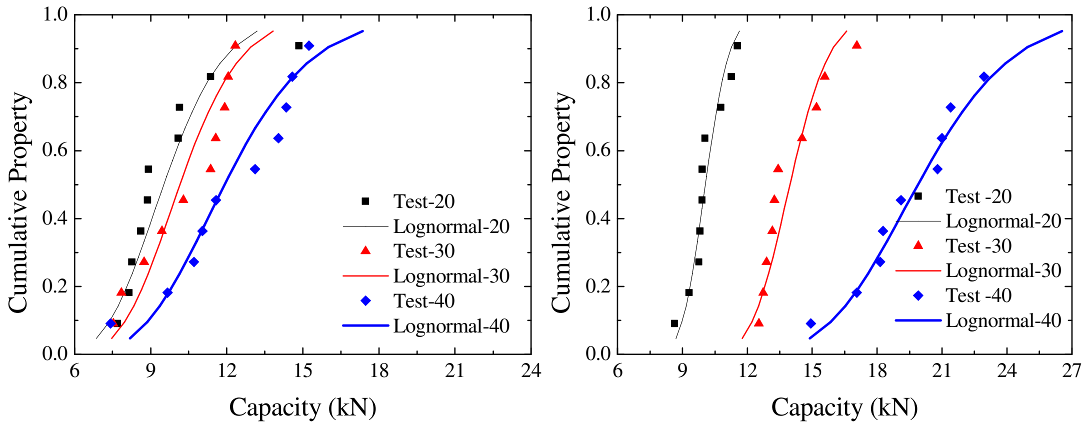
For group T, the average value and the 5th percentile value of the withdrawal resistance of the STSs in the tangential direction increase with the increase of the diameter. This is consistent with the increase of the contact area between the STSs and the bamboo scrimber.

However, it is noted that because the average density of the specimens with α=45° in the tangential direction is about 17% larger than that of the ones with α= 90° (Table 1), the average withdrawal resistance of the STSs with α=45° is higher. This shows that the density of bamboo scrimber has a certain effect on the anchoring capacity of self-tapping screws, similar to wood.

Table 4. Withdrawal resistance and stiffness of the STSs

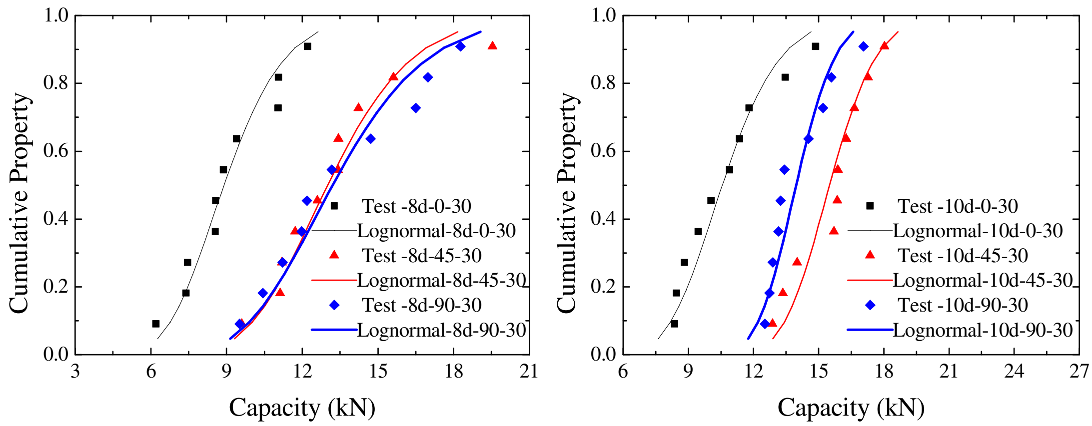
Test group	Test series	Mean		Withdrawal resistance (Lognormal distribution, kN)			Stiffness（Normal distribution, kN/mm）		
		Withdrawal resistance (kN)	Stiffness (kN/mm)	St.dev	Cov. (%)	5th	St.dev	Cov. (%)	5th
RD	R-6d-90-20	9.70	4.0	0.20	8.7	6.86	0.40	10.1	3.33
	R-6d-90-30	10.31	4.42	0.18	8.0	7.47	0.50	11.4	3.58
	R-6d-90-40	12.17	4.22	0.22	9.1	8.18	0.57	13.6	3.26
	R-8d-90-20	6.21	3.82	0.24	13.1	4.07	0.80	21.1	2.47
	R-8d-90-30	13.50	5.19	0.22	8.5	9.15	0.60	11.6	4.18
	R-8d-90-40	17.92	5.35	0.23	8.2	11.83	0.63	11.8	4.29
	R-10d-90-20	10.09	4.48	0.09	3.7	8.70	0.29	6.4	4.0
	R-10d-90-30	14.04	5.43	0.10	4	11.76	0.72	13.3	4.24
	R-10d-90-40	20.16	5.84	0.17	5.8	14.9	0.54	9.3	4.93
RA	R-6d-0-30	8.24	4.25	0.33	16.3	4.46	0.72	16.9	3.05
	R-6d-45-30	11.38	4.80	0.13	5.2	9.15	0.28	5.79	4.33
	R-8d-0-30	9.08	4.13	0.21	9.6	6.28	0.61	14.9	3.10
	R-8d-45-30	13.25	4.71	0.20	7.8	9.31	0.77	16.3	3.43
	R-10d-0-30	10.76	4.86	0.20	8.3	7.62	0.51	10.5	4.01
	R-10d-45-30	15.59	5.97	0.11	4.0	12.89	0.80	13.4	4.64
T	T-6d-90-30	10.72	4.85	0.25	10.6	6.88	0.49	10.2	4.02
	T-8d-90-30	13.36	5.31	0.23	8.8	8.94	0.66	12.4	4.21
	T-10d-90-30	14.62	5.27	0.12	4.4	11.92	0.51	9.6	4.42
	T-6d-45-30	14.98	5.74	0.15	5.6	11.54	0.41	7.2	5.05
	T-8d-45-30	17.25	6.40	0.17	5.8	13.1	0.79	12.4	5.25
	T-10d-45-30	21.94	7.15	0.13	4.2	17.6	0.54	7.6	6.25

From the comparison of the RD and RA groups in Fig. 10, it can be observed that the 5th percentile value of the withdrawal resistance of STSs with α=45° is close to that of specimens with α=90°. This is different from the behavior of the withdrawal resistance of STSs in wooden structures. Fig. 11 shows that the 5th percentile values of the withdrawal resistance of STSs in the radial and tangential directions are very close, and the average relative difference is less than 2.3% (Table 4).



(a) (b)

Fig.9. Comparison between a fitted distribution and test data in Group RD: (a) R-6d-90, (b) R-10d-90



(a) (b)

Fig. 10. Comparison between a fitted distribution and test data in Group RD and Group RA: (a) R-8d, (b) R-10d

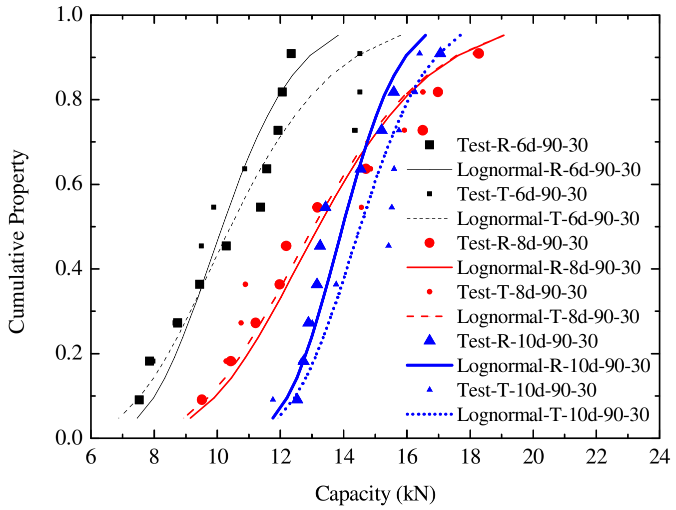


Fig.11. Comparison between a fitted distribution and test data in Group RD and Group RA

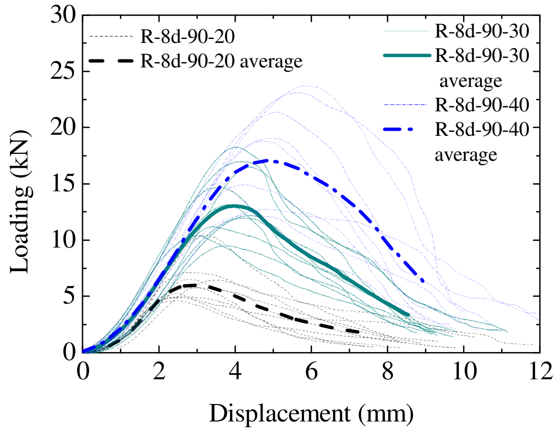
3.4 Load-displacement curves

The global performance of the STSs in the bamboo scrimber can be illustrated clearly in the load-displacement curves. Figs. 12 show the load-displacement curves of the three groups and the average curve of each series. In the initial stage of loading, the curves are approximately linear, indicating the withdrawal force is in the elastic stage. Nonlinear response develops as the displacement increases beyond a certain elastic limit. Approaching the peak load, the specimens generally exhibit a certain degree of permanent deformation.

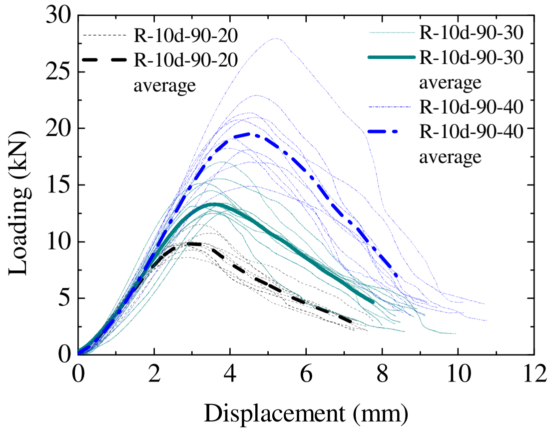
The RD group (Figs. 12a, 12b) shows that the withdrawal resistance capacity of STSs and the slope of the descending branch increases as the embedment length increases. The increase in the diameter of the STSs also causes similar effects. This is because with a larger diameter the contact area between an STS and the bamboo scrimber is larger, leading to a larger wedge body that is formed by the extrusion of the STS from the bamboo scrimber. Hence, the withdrawal resistance increases. In Fig. 12, a few curves with smaller embedment lengths appear above the curves with larger embedment lengths, and this is attributable to the scatter of the properties of the specimens.

A comparison of the load-displacement curves corresponding to the three angles in the RD and RA groups is presented in Figs. 12c, 12d. The ultimate bearing capacity increases as the angle increases. This is consistent with the failure mode of the STSs in the test in that the smaller the angle, the more likely that the bamboo fibers bundled around the STS will undergo shear failure along the grain, giving rise to the characteristics of more brittle failure.

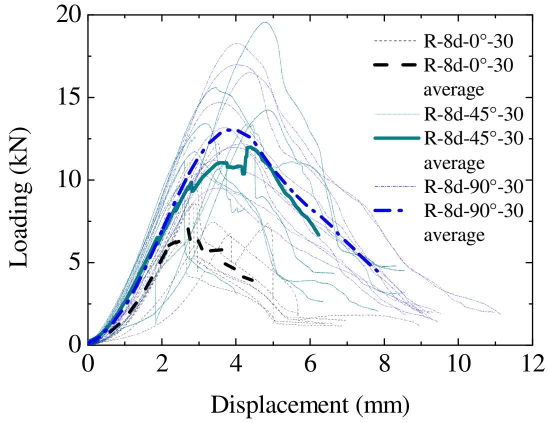
The load-displacement curves of the T group and the RD group are plotted in Figs. 12e, 12f. The main trend of load-displacement curves in the radial and tangential directions is similar. However, since the arrangement of bamboo fiber bundles is slightly different, the load-displacement curves in the tangential direction tend to be steeper than the radial curves.



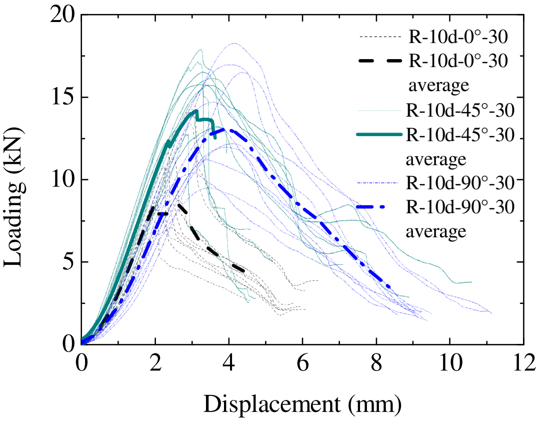
(a)



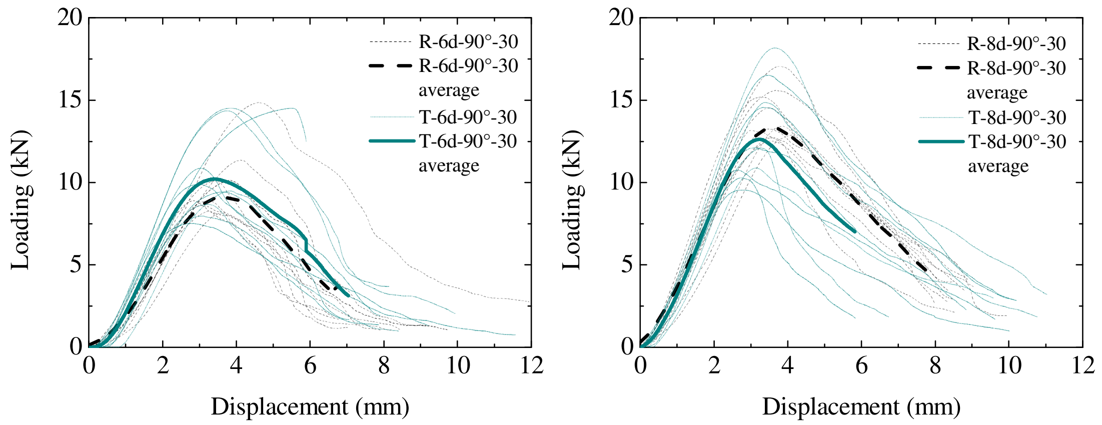
(b)



(c)



(d)

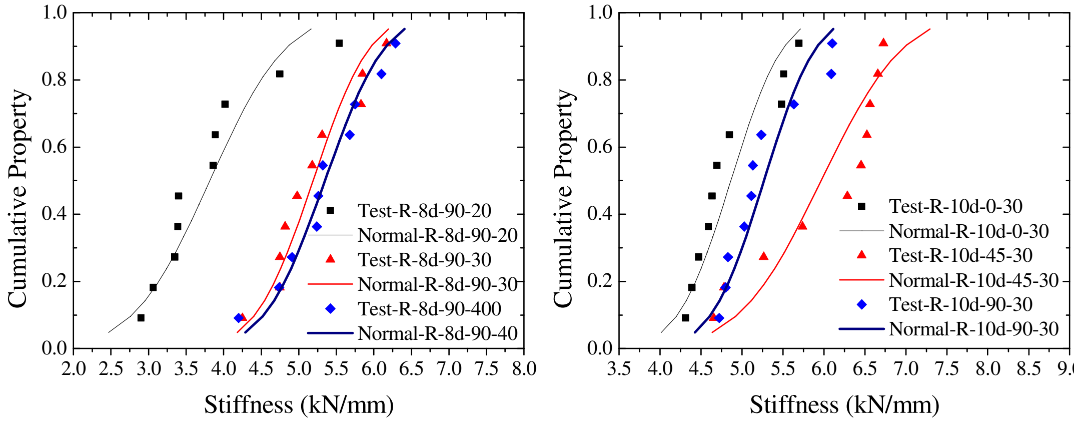


(e) (f)

Fig. 12. Load-displacement curves: (a) RD group, *d*=8mm, (b) RD group, *d*=10mm, (c) RD group, *d*=8mm with three angles, (d) RD group, *d*=10mm with three angles, (e) T group and RD group, *d*=6mm, (f) T group and RD group, *d*=8mm.

3.5 Withdrawal stiffness

The slope of the load-slip curves from 2kN to 4kN, within the generally linear range, is adopted to represent the stiffness of the specimens. Again with reference to the law of lognormal distribution of the stiffness of wood [54], the withdrawal stiffness of STSs is analyzed using normal distribution herein. The withdrawal stiffness results of the test specimens and the distribution parameters are included in Table 4. It can be seen that the withdrawal stiffness of the STSs increases with the increase of the embedment length, the diameter of the STSs, and the screw angle. This is similar to the rule of the withdrawal resistance as shown in Fig. 12 and Fig.13.



(a) (b)

Fig.13. Comparison between a fitted distribution and test data of withdrawal resistance: (a) R-8d-90, (b) R-10d

4 Calculation of withdrawal resistance of STSs in bamboo scrimber

4.1 Existing calculation methods for withdrawal resistance of STSs in wood and raw bamboo

At present, Eurocode 5 [41] and industry standards (e.g. CCMC 13677-R [42]) provide the calculation formulas for the 5th percentile value of withdrawal resistance of STSs in wood for application in the design. The calculation formula in Eurocode 5 [41] are as follows:

$$F_{\mathrm{ax,k,Rk}} = \frac{n_{\mathrm{ef}} f_{\mathrm{ax,k}} d \cdot l_{ef} \cdot k_{\mathrm{d}}}{1.2\cos^2\alpha + \sin^2\alpha} \tag{1}$$

$$f_{\mathrm{ax,k}} = 0.52 d^{-0.5} l_{ef}^{-0.1} \cdot \rho_{\mathrm{k}}^{0.8} \tag{2}$$

where $F_{ax,k,\ Rk}$ is the characteristic withdrawal force capacity of the connection at an angle α to the grain, in N; $f_{\mathrm{ax,k}}$ is the characteristic withdrawal resistance perpendicular to the grain, in N/mm^2; n_{ef} is the effective number of screws; l_{ef} is the penetration length of the threaded part, in mm; ρ_{k} is the characteristic density, in kg/m^3; α is the angle between the screw axis and the grain direction; k_{d} is the diameter parameter, taking the smaller value of 1 and d/8, in mm.

The calculation formula specified in CCMC 13677-R [42] is expressed as:

$$P_{rw,\alpha} = \phi \frac{0.8\delta(b \cdot 0.84 \cdot \rho)^2 \cdot d \cdot l_{ef} \cdot 10^{-6}}{\sin^2\alpha + \frac{4}{3}\cdot\cos^2\alpha} \cdot K_D \cdot K_{SF} \quad (3)$$

where $P_{\mathrm{rw},\alpha}$ is factored withdrawal resistance for installation angle α; ϕ is the resistance factor for design purpose, ϕ=0.9; 0.8 is load duration normalization factor and is applied to adjust to standard term loading; δ is material adjustment factor: δ=82 for $\rho \geq$440kg/m^3, δ =85 for ρ <440kg/m^3; b is the material factor: b=1 for D-Fir-L, SPF, SYP, STP, WRC, Hem-Fir, b=0.75 for Parallam (PSL); ρ=mean oven-dry relative density (CSA O86, Table A.10.1) x10^3 kg/m^3; 0.84 is the adjustment of mean oven-dry relative to fifth percentile value; d is the outside screw diameter (mm); l_{ef} is the effective embedment length into the member: l_{ef} = thread length - tip length (=d) (mm); K_{D} and K_{SF} are the load duration factor and service condition factor, respectively.

For the withdrawal resistance of STSs in the raw bamboo, an empirical formula has been proposed [43], which is similar to the calculation formula given by Eurocode 5 [41] but with improved accuracy when applied to calculate the screw withdrawal capacity in raw bamboo [43].

4.2 Calculation of the withdrawal resistance of STS in bamboo scrimber

Based on the analysis of the experimental performance and the withdrawal resistance of STSs in bamboo scrimber in Section 3.3, the effects of the pertinent parameters, including the embedment length, screw diameter and embedment angle, are very similar to the situation with STSs in wood. Therefore, the formulas of Eurocode 5 and CCMC (2013) are firstly used to calculate the characteristic value of the withdrawal resistance of STS in bamboo scrimber. The calculation results are compared with the 5$^{\mathrm{th}}$ percentile value of withdrawal resistance of

STSs in the tests. Considering the dispersion of the bamboo scrimber properties, a lognormal distribution with a coefficient of variation of 20% is assumed in this paper [35]. Based on this coefficient, the average value of the withdrawal capacity is estimated.

The above two calculated values are compared with the test results in Table 5. Note that the comparisons are given for cases with $\lambda \geq 3$, taking into consideration that smaller λ appeared to be inadequate to ensure an effective withdrawal resistance of STSs, as mentioned earlier in Section 3.4. Furthermore, in the calculation of the withdrawal resistance of STS using Eq. (3), factors for the purpose of design, including the resistance factor ϕ and service condition factor K_{SF}, are set equal to 1.0. The material factor b is set equal to 0.75, which is taken from the engineering wood SPL. Since the experiment involved short-term loads, the load duration adjustment factor K_D is set at 1.25 for short-term loading [55].

The comparison results in Table 5 show that, in terms of the characteristic values, the withdrawal resistance calculated by Eurocode 5 (equations 1-2) exhibit an average error of 26% relative to the test results, whereas the results calculated using the CCMC 13677-R formula (equation 3) give an average relative error of 16%. In terms of the average withdrawal resistance, the results calculated using Eurocode 5 (equations 1-2) give an average error of about 18% as compared to an average error of 12% when equation 3 is employed.

Besides, the average relative error between the characteristic value calculated with the empirical formula for raw bamboo [43] and the test result of the first three series of specimens with α=90° in the RD group and the T group is 18%. The average relative error between the average value calculated with the same empirical formula [43] and the test result is 6% and the maximum relative error is 39%. This suggests that the accuracy of equation 3 for the withdrawal resistance of STS in bamboo scrimber is better than the Eurocode 5 formula and empirical formula for raw bamboo [43].

Table 5 Comparison of withdrawal resistance between calculated values and test results [kN]

Specimens	Test result		EN1995				CCMC			
	5^{th} percentile	mean	$F_{ax,k,Rk}$	Δ^{a}	Estimated average	Δ^{b}	$P_{rw,\alpha}$	Δ^{a}	Estimated average	Δ^{b}
R-6d-90-20	6.86	9.7	4.36	0.36	6.50	0.33	6.68	0.03	9.96	0.03
R-6d-90-30	7.47	10.31	5.95	0.20	8.86	0.14	8.07	0.08	12.03	0.14
R-6d-90-40	8.18	12.17	7.45	0.09	11.10	0.09	10.76	0.32	16.04	0.24
R-8d-90-30	9.15	13.5	9.01	0.02	13.42	0.01	9.96	0.09	14.84	0.09
R-8d-90-40	11.83	17.92	11.39	0.04	16.98	0.05	14.08	0.19	20.98	0.15
R-10d-90-30	11.76	14.04	8.29	0.30	12.35	0.12	12.70	0.08	18.92	0.26
R-10d-90-40	14.9	20.16	11.24	0.25	16.75	0.17	17.60	0.18	26.23	0.23
R-6d-0-30	4.46	8.24	4.19	0.06	6.24	0.24	5.94	0.33	8.85	0.07
R-8d-0-30	6.28	9.08	4.73	0.48	7.05	0.38	6.89	0.10	10.27	0.12
R-10d-0-30	7.62	10.76	6.15	0.02	9.16	0.01	9.90	0.30	14.75	0.27
R-6d-45-30	6.88	10.72	6.94	0.25	10.34	0.22	8.07	0.17	12.03	0.11
R-8d-45-30	8.94	13.36	6.75	0.11	10.07	0.06	10.76	0.20	16.04	0.17
R-10d-45-30	11.92	14.62	7.82	0.39	11.66	0.25	13.20	0.11	19.67	0.26
T-6d-90-30	6.88	10.72	4.92	0.29	7.33	0.32	7.46	0.18	11.11	0.02
T-8d-90-30	8.94	13.36	7.70	0.14	11.47	0.14	8.54	0.08	12.72	0.04
T-10d-90-30	11.92	14.62	8.18	0.31	12.19	0.17	10.67	0.17	15.90	0.02
T-6d-45-30	11.54	14.98	5.32	0.42	11.38	0.25	9.65	0.16	14.38	0.04
T-8d-45-30	13.11	17.52	8.24	0.11	13.25	0.24	12.52	0.05	18.66	0.06
T-10d-45-30	17.59	21.94	8.90	0.31	15.59	0.26	14.81	0.16	22.08	0.01

Compared with natural and engineered wood, the bamboo scrimber belongs to a different biomass composite material. It is therefore reasonable to expect that, while the basic form of the CCMC 13677-R formula may be applied, appropriate modifications are needed so that the formula can predict better the withdrawal resistance of STS in bamboo scrimber. Following a statistical analysis, a new pair of coefficients for the sine and cosine terms are determined, and subsequently the formula is modified into the following expression:

$$P_{rw,\alpha} = \frac{1.25\delta(b \cdot 0.84 \cdot \rho)^{2} \cdot d \cdot l_{ef} \cdot 10^{-6}}{1.08\sin^{2}\alpha + 1.55\cos^{2}\alpha} \tag{4}$$

where, $P_{rw,\alpha}$ represents the factored withdrawal resistance of STS at an angle of α to the bamboo scrimber fiber; 1.25 is the load duration factor of Eq. (3) converted into the test short-term for the standard period; δ is the material adjustment parameter, and the value is 82; b=0.75 is the material parameter for the bamboo scrimber; ρ is the average density in kg/m^3; 0.84 is the adjustment of mean to fifth percentile value; d is the outside screw diameter of the STS in mm; l_{ef} is the effective embedment length into the member in mm.

The relative errors in the calculation results using Eq. (4) relative to the test results for angles α = 90° and 0° are 7% for the 5th percentile value and 8% for the average value, as illustrated in Fig. 14. A marked improvement of the accuracy as compared to using the Eurocode 5 and CCMC 13677-R formulas is observed. Therefore, it is recommended that the modified Eq. (4) be used to calculate both the 5th percentile and the average values of the withdrawal resistance of STS in bamboo scrimber for α=90° and α= 0°.

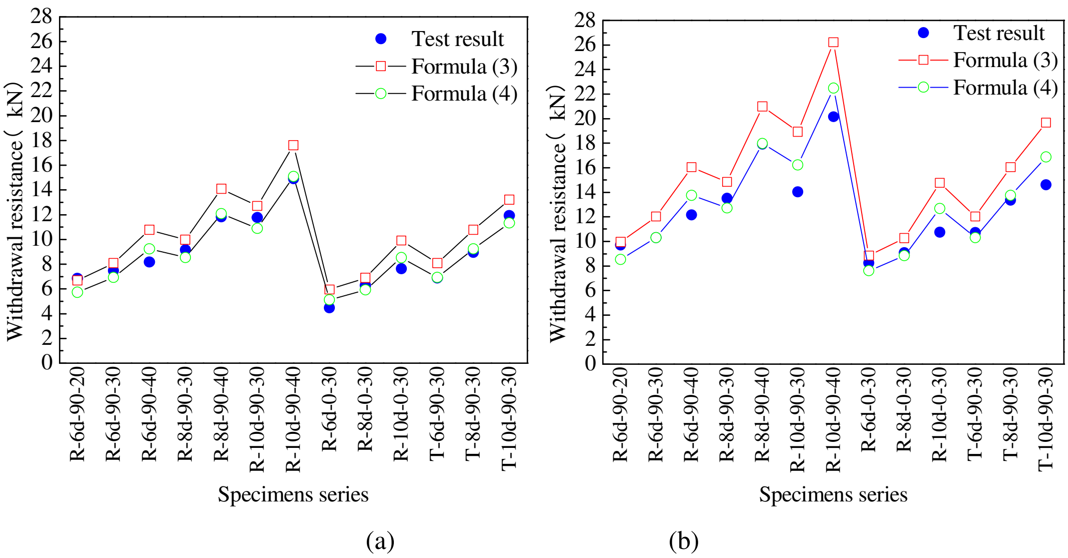


Fig.14 Comparison of the experimental and calculated withdrawal resistance results: (a) 5th percentile value, (b) Average

4.3 Verification of the calculation formula

To further examine the accuracy of Eq. (4), the experimental results of the withdrawal resistance for three kinds of STSs in bamboo scrimber in the literature [21] are selected for comparison and verification. The outer diameter of the STSs from the experimental study [21] was 3.5mm. Since the ratio of the pre-drilled hole to the outer diameter of STS has been set at approximately 0.6 in the present tests, the test results from the literature with a ratio of the pre-drilled hole to the outer diameter close to 0.6 are selected for comparison. Furthermore, it is assumed that the coefficient of variation of the withdrawal resistance of the STSs is 20% [35].

The experimental results of the withdrawal resistance of cross-head screws, slotted screws and wall panels screws are 2.12 kN, 1.57 kN and 0.86 kN, respectively. The calculation results of these three types of screws using Eq. (4) are found to be 2.06 kN, 1.43 kN and 0.77 kN, respectively, giving rise to an average error of 8% and maximum error of 12%, as shown in Fig. 15. This comparison shows that the modified formula in Eq.(4) can predict the withdrawal resistance of STSs in bamboo scrimber with good accuracy.

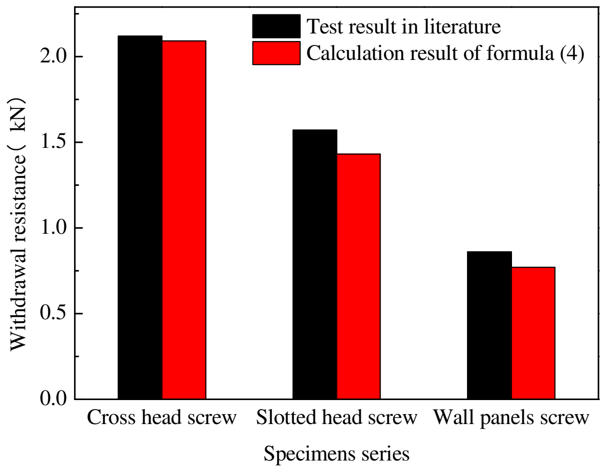


Fig. 15 The comparison of the test result and the calculation result in literature [21]

5 Conclusions

The withdrawal performance of STSs in bamboo scrimber has been investigated experimentally and analytically. In the experimental programme, 210 specimens have been tested to evaluate the effects of three key parameters on the withdrawal resistance of STSs, namely the embedded length, the screw penetration angle and the self-tapping screw diameter.

The applicability of the calculation formulas for the withdrawal resistance of STSs in wood and original bamboo to STSs in bamboo scrimber has been examined. On this basis, a modified calculation formula for STSs in bamboo scrimber is proposed. From the results presented in the paper, the following conclusions may be drawn:

(1) Preliminary experimental results from STSs-bamboo scrimber specimens suggest a critical embedment slenderness (λ) value of around 7.5; larger λ will lead to a failure mode with rupture of the STSs, while smaller λ tends to lead to STS pull-out failure. Furthermore, the material property test shows that the radial and tangential compressive strengths of bamboo scrimber are very close, therefore the bamboo scrimber may be generally assumed as a horizontally homogeneous material.

(2) Overall, the withdrawal resistance and rigidity of the STSs in the bamboo scrimber are similar to those of the STSs in wood. Both properties increase with the increase of the diameter of the STSs and the density of bamboo scrimber. Unlike the wood, however, the tensile strength and stiffness of STSs in the radial and tangential directions of the bamboo scrimber are very similar, so a unified calculation formula is recommended.

(3) From the test results, the 5^{th} percentile value of the withdrawal resistance of STSs with α=45° appears to be close to or greater than that of STSs with α=90°. This observation is not in line with the trend in wooden structures. The specific relationship between the withdrawal resistance and the embedment angle in the bamboo scrimber requires further experimental evidences.

(4) Comparative analyses using different withdrawal resistance formulas suggest that the withdrawal capacity results of STSs calculated by the CCMC formula (Eq. 3) achieve better

accuracy. The CCMC (Eq. 3) formula is best suited as a basis for the calculation of the 5th percentile value of the withdrawal resistance of STSs in bamboo scrimber with α=45°.

(5) Based on the CCMC (Eq. 3) formula, a modified formula (Eq. 4) is proposed taking into account of the present experimental data. The proposed formula is further verified by the relevant test data from the literature, showing satisfactory accuracy. It should be noted that the applicability of the proposed formula for the withdrawal resistance of STSs in bamboo scrimber with other angles still requires further investigation.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (51908291), the Nanjing Forestry University Youth Science and Technology Innovation Fund (CX2019002) and the Personal Scientific Research Start-up Funds (163020125, 163020657) from NFU.

References

[1] P. Van der Lugt, A. Van den Dobbelsteen, J. J. A. Janssen. , Constr. Build. Mater. 20 (9) (2006) 648-656.

[2] D. Yu, H. Tan, Y. Ruan. A future bamboo-structure residential building prototype in China: Life cycle assessment of energy use and carbon emission, Energ. Buildings. 43 (10) (2011) 2638-2646.

[3] Y. Xiao, R. Z. Yang, B. Shan. Production, environmental impact and mechanical properties of glubam, Constr. Build. Mater. 44 (2013) 765-73.

[4] B. Sharma, A. Gatóo, M. Bock, M. Ramage. Engineered bamboo for structural applications.

Constr. Build. Mater. 81 (2015) 66-73.

[5] M. Ahmad, F. A.Kamke. Properties of parallel strand lumber from Calcutta bamboo (Dendrocalamus strictus). Wood Sci Technol, 45(1) (2011) 63–72.

[6] P. Malanit, M. C.Barbu, A. Frühwald. Physical and mechanical properties of oriented strand lumber made from an Asian bamboo (Dendrocalamus asper Backer). Eur J Wood Wood Prod. 69(1) (2011) 27–36.

[7] D. Huang, Y. Bian, A. Zhou, B. Sheng. Experimental study on stress-strain relationships and failure mechanisms of parallel strand bamboo made from phyllostachys. Constr. Build. Mater. 77 (2015) 130–138.

[8] H. Li, H. Zhang, Z. Qiu, J. Su, D. Wei, R Lorenzo, C. Yuan, H. Liu, C. Zhou. Mechanical properties and stress strain relationship models for bamboo scrimber. J Renew Mater. (2020) 13-27.

[9] P. Xie, W. Liu, Y. Hu, X. Meng, J. Huang. Size effect research of tensile strength of bamboo scrimber based on boundary effect model, Eng. Fract. Mech. 239 (2020) 107319.

[10] X. Sun, M. He, F. Liang, Z. Li, L. Wu, Y. Sun. Experimental investigation into the mechanical properties of scrimber composite for structural applications, Constr. Build. Mater. 276 (2021) 122234.

[11] Y. Yu, R. Zhu, B. Wu, W. Yu. Fabrication, material properties, and application of bamboo scrimber, Wood Sci. Technol. 49 (1) (2015) 83-98.

[12] L. M. Tian, B. B. Jin, J. P. Hao. Research and application of modern bamboo structures, Engineering Mechanics. 5(36)(2019) 1-18.(in Chinese)

[13] Y. Xiao, Y. Wu, J. Li, R. Z. Yang. An experimental study on shear strength of glubam, Constr.

Build. Mater. 150 (2017) 490-500.

[14] Y. Huang, Y. Ji, W. Yu. Development of bamboo scrimber: a literature review, J. Wood Sci. 65 (1) (2019) 1-0.

[15] G. Chen, Y.F. Yu, X. Li, B. He, Mechanical behavior of laminated bamboo lumber for structural application: an experimental investigation, Eur. J. Wood Prod. 78 (2020) 53–63,

[16] H. Li, B. J. Wang, L. Wang, P. Wei, Y. Wei, P. Wang. Characterizing engineering performance of bamboo-wood composite cross-laminated timber made from bamboo mat-curtain panel and hem-fir lumber, Compos. Struct. 266 (2021) 113785.

[17] B. Fei, R Liu, X. Liu, X. Chen, S. Zhang. A review of structure and characterization methods of bamboo pits. Journal of Forestry Engineering, 4(2) (2019) 13–18.

[18] C. Hong, H. Li, Z. Xiong, R. Lorenzo, I. Corbi, O. Corbi, D. Wei, C. Yuan, D. Yang, H. Zhang, Review of connections for engineered bamboo structures, J. Build. Eng. 30 (2020) 101324,

[19] B. Sharma, A. Gatoo, M. Bock, H. Mulligan, M. Ramage, Engineered bamboo: state of the art, Constr Mater, 168(2) (2014) 57-67.

[20] Y. Fu, H. Fang, F. Dai. Study on the properties of the recombinant bamboo by finite element method, Compos. Part B-Eng. 115 (2017) 151-159.

[21] X. Liu, X. Liu, J. Li. The test and analysis of nail holding power about recombinant bamboo used in furniture, Wood processing machinery. 28 (5) (2017) 10-12. (in Chinese)

[22] Y. Xiao, Q. Zhou, B. Shan. Design and construction of modern bamboo bridges, J. Bridge Eng. 15 (5) (2010) 533-541.

[23] H. Li, Z. Qiu, G. Wu, Li, O. Corbi, D. D. Wei, L. B. Wang, I. Corbi, and C. G. Yuan. Slenderness Ratio Effect on Eccentric Compression Properties of Parallel Bamboo Strand Lumber

Columns, J. Struct. Eng. 145 (8) (2019) 04019077.

[24] H. Li, G. Wu, Q. Zhang, A J Deeks, J Su. Ultimate bending capacity evaluation of laminated bamboo lumber beams, Constr. Build. Mater. 160 (2018) 365-375.

[25] Y. R. Shen, D. S. Huang, A. P. Zhou, D. Hui. An inelastic model for ultimate state analysis of CFRP reinforced PSB beams, Compos. Part B-Eng. 115(2017) 266-274.

[26] Y. Wei, S. Tang, X. Ji, K. Zhao, G. Li. Stress-strain behavior and model of bamboo scrimber under cyclic axial compression, Eng. Struct. 209 (2020) 110279.

[27] Z. Cui, M. Xu, Z. Chen, F. Wang. Experimental study on bearing capacity of bolted steel-PSB-steel connection. Engineering Mechanics. 36(1) (2019)96-103,118. (in Chinese)

[28] X. Li, Q. Mou, H. Ren, X. Li, Y. Zhong. Effects of moisture content and load orientation on dowel-bearing behavior of bamboo scrimber, Constr. Build. Mater. 262 (2020) 120864.

[29] G. Chen, W. Yang, T. Zhou, Y. Yu, J. Wu, H. Jiang, et al. Experiments on laminated bamboo lumber nailed connections. Constr Build Mater. 269 (2021) 121321.

[30] R. Tomasi, A. Crosatti, M. Piazza. Theoretical and experimental analysis of timber-to-timber joints connected with inclined screws, Constr. Build. Mater. 24(9) (2010) 1560-1571.

[31] L. Righetti, M. Corradi, A. Borri. Shear resistance of screwed timber connections with parallel to grain FRP reinforcements, The14th World Conference on Timber Engineering (WCTE2016), 2016.

[32] H. M. Li, F. Lam, H. Qiu. Flexural performance of spliced beam connected and reinforced with self-tapping wood screws, Eng. Struct. 152 (2017) 523-34.

[33] H. M. Li, F. Lam, H. Qiu. Comparison of glulam beam-to-beam connections with round dovetail and half-lap joints reinforced with self-tapping screws, Constr. Build. Mater. 227 (2019)

116437.

[34] T. Tannert, F. Lam. Self-tapping screws as reinforcement for rounded dovetail connections, Struct. Control Hlth. 16 (3) (2009) 374-384.

[35] A. Hossain, D. Ilana, T. Tannert. Cross-Laminated Timber Shear Connections with Double-Angled Self-Tapping Screw Assemblies. J. Struct. Eng. 142(11) (2016) 04016099.

[36] S.Y. Huang, A Study on the Design of New-Sino-Style Furniture Made of Recombinant Bamboo, Nanjing Forestry University, Nanjing, China, 2011.

[37] Y. Chen, S. Zhu, Y. Guo, S. Liu, D. Tu, H. Fan. Investigation on withdrawal resistance of screws in reconstituted bamboo lumber. Wood Research, 61 (5) (2016) 799-810.

[38] K. A. Harries, Morrill P, Gauss C, et al. Screw withdrawal capacity of full-culm P. edulis bamboo, Constr. Build. Mater. 216 (2019) 531-541.

[39] J.Q. Li, L.H. Chen, T. Su, Study on bolt joint intensity of laminated bamboo for furniture, J.Fujian.Fujian.For 31 (3) (2011) 271–275.

[40] H.W. Zhang, Study on the Optimize Design for Parameters of Screw Thread Used in Glued Laminated Bamboo and the Mechanical Property, Nanjing Forestry University, Nanjing, China, 2012.

[41] BS EN 1995-1-1, Eurocode 5: Design of timber structures-Part 1-1: General-common rules and rules for buildings. London: British Standards Institution, 2004

[42] CCMC. Evaluation report CCMC 13677-R SWG ASSY and VG plus and SWG ASSY 3.0 self-tapping wood screws. Canadian Construction Material Center, Ottawa, 2013

[43] Trujillo D J A, Malkowska D. Empirically derived connection design properties for Guadua bamboo, Constr. Build. Mater. 2018, 163: 9-20.

[44] JG/T 199-2007. Testing methods for physical and mechanical properties of bamboo used in building. Beijing, China：China Standard Press, 2007 (in Chinese).

[45] GB/T1935-2009 Method of testing in compressive strength parallel to grain of wood (in Chinese).

[46] GB/T 1939-2009 Method of testing in compressive strength perpendicular to grain of wood. (in Chinese).

[47] GB/T 1936.2-2009. Method for determination of the modulus of elasticity in static bending of Wood. Chinese national standard. China Standard Press, 2009 (in Chinese).

[48] D. Huang, Y. Bian, A. Zhou, B. Sheng. Experimental study on stress–strain relationships and failure mechanisms of parallel strand bamboo made from phyllostachys. Constr Build Mater. 77 (2015) 130-8.

[49] Lv H. The renovation and demonstration of the traditional rural dwellings construction technology. Beijing：China architecture and building press，2018.09:60-62. (in Chinese).

[50] ASTM D1761 Standard test methods for mechanical fasteners in wood. Philadephia, PA, 2006.

[51] LY/T 2377-2014, Test methods for the joint performance with dowel type fasteners used in wooden structural material. 2012 (in Chinese).

[52] CAN, CSA-O86.09. Engineering design in wood (limit states design). Canadian Standards Association (CSA), Mississauga, 2014.

[53] ASTM D5652 Standard test methods for bolted connections in wood and wood-base.

[54] Barrett J D, Jones E D, Lau W. Canadian lumber properties. Ottawa: Canadian Wood Council, 1994.

[55] Canadian Wood Council (CWC). Wood design manual. Ottawa:2015.