18th International Conference on
Non-Conventional Materials and Technologies
"Construction Materials & Technologies for Sustainability"
(18th NOCMAT 2019)
24th – 26th July 2019
Nairobi, Kenya

SCREW WITHDRAWAL CAPACITY IN FULL-CULM BAMBOO

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ABSTRACT

The use of screw connections in full-culm bamboo is often assumed to be limited, primarily due to the propensity for splitting of the culm. This study demonstrates that small diameter screws can be used effectively in full-culm bamboo. The study explores the withdrawal capacity of candidate screw types in order to identify those that may be used to achieve a high capacity while mitigating splitting failures. Twelve screw types of three standard sizes, ranging from hardwood screws, self-tapping wood screws and concrete anchors, are tested in conditions of both pre-drilled and self-tapping installation procedures. All tests are conducted on samples of P. edulis (Moso) having culm wall thickness on the order of 7 mm. The results of this study are intended to inform the applications for which screw connection to bamboo are viable.

Keywords: bamboo, bamboo connections, screws

INTRODUCTION

As interest in bamboo-based construction increases globally, significant efforts are underway to develop structural design codes and standards. Within this effort, developing efficient and economical connections for bamboo elements is of critical importance. While a large range of bamboo connections are possible [1], few use conventional dowel connectors (screws and nails) driven in to the culm wall. Indeed, in draft revisions to ISO 22156:2004 Bamboo Structural Design [2], the lead author of this paper proposed that screws and driven nails not be permitted in full-culm bamboo construction. This position, based on results presented by Trujillo and Malkowska [3] and those presented in this paper, has been reconsidered to permit screws but not driven nails. The study reported in this paper addresses the provision of screws for connecting bamboo in terms of the withdrawal capacity of screws embedded in the bamboo culm wall.

In full culm bamboo construction, screws may be used to secure gusset-plate [4] or pipe-sleeve [5, 6] connections. Using screws in place of through-bolts in some connections may make these connections easier to fabricate. As a secondary component of a bamboo connection, screws embedded in the culm wall may be used to secure lashing or other external confining or to secure a component of a connection. Helically-arranged screwed connections have also been proposed to transfer tension forces to a culm infill [1, 6].

Bamboo is also used in the form of strips split from a full culm requiring connections in which the use of screws would be beneficial. Connections in bahareque construction [7] are one example of this. Screwed connections to the exterior of glue-laminated bamboo also require quantification of screw withdrawal properties from the bamboo culm wall.

SCREW WITHDRAWAL

Screw withdrawal capacity derives from friction and/or mechanical interfaces for the transfer of axial (withdrawal) loads [7]. Screw (or nail or staple) withdrawal capacity from wood or wood-based engineered or composite materials can be determined based on ASTM D1761 [9] or EN 1382 [10] which are for most intents the same. In this paper, the screw withdraw capacity (in N) is denoted Fax and the 'withdrawal parameter' normalizes Fax by both screw diameter (d in mm) and depth of engaged threads (t in mm):

$$f_{ax} = F_{ax}/dt \tag{1}$$

Although many experimental programs are conducted otherwise, the thickness of the test specimen prescribed by ASTM D1761 is required to be greater than the depth of engaged threads t; that is, the screw does not protrude out the far side of the test specimen. There is limited data comparing the cases in which the screw protrudes through a thinner plywood or OSB specimen. Where such data exists [11] the withdrawal capacity for protruding cases is marginally greater than when the screw does not protrude. Such an effect is sufficiently small (and may not be statistically significant) that it should not be (and is not) considered in design.

Characteristic screw withdrawal capacity from wood is prescribed in EN 1995-1-1 [12] and, in North American practice, allowable capacity is prescribed by AWS [8]. Values of screw withdrawal are prescribed in terms of screw diameter, d, depth of embedment, t, and density of the material penetrated, ρ.

Screw Withdrawal from Bamboo

There are multiple studies which report the screw withdrawal capacity of various engineered bamboo materials [13-15] and hybrid wood/bamboo materials [14, 16]. All report a modest improvement in screw withdrawal capacity in bamboo materials as compared to comparable wood and engineered wood products.

There is only a single known study reporting screw withdrawal capacity from full-culm bamboo [3]. This study reports 240 screw withdrawal tests [10] from the walls of Guadua angustifolia Kunth culms having a reported density ρ = 755 kg/m3 (COV = 0.11) at MC = 8.6% and a wall thickness, t = 10.5 mm (COV = 0.24). Five screw types were included in the study; a summary of screw parameters and test results are given in Table 1.

TABLE 1 SCREW PARAMETERS AND SCREW WITHDRAWAL RESULTS [3] (COV IN BRACKETS IN ALL CASES)

test ID	screw type	d	n	F_{ax}	$f_{ax} = F_{ax}/dt$
		mm		N	N/mm^2
3.5-b1	self-drilling wood screw	3.5	60	1264 (0.28)	34.43 (0.17)
4.0-b1		4.0	60	1342 (0.29)	31.81 (0.11)
5.0-b1		5.0	30	1505 (0.29)	28.65 (0.12)
4.0-b2	serrated tip self-drilling wood screw	4.0	30	1296 (0.27)	30.87 (0.15)
4.8-b3	self-drilling roofing screw	4.8	60	1284 (0.24)	25.97 (0.17)

OBJECTIVE OF PRESENT STUDY

Among craftspeople working with bamboo, screws are used. These may be whatever screw type/size is available or the craftsperson may have a screw type/size which they (anecdotally) believe out performs others. The objective of this study is to survey screw withdrawal capacity in full culm bamboo based on screw type and size. The study considers twelve screw type-size combinations and considers whether these are predrilled or the screws are inserted without predrilling, resulting in 20 screw type-size-predrill combinations. The range of parameters selected recognizes that a) bamboo construction is often informal and therefore may utilize a range of screw types; and b) although predrilling may be good practice, it may not be followed if screws can be inserted without predrilling.

EXPERIMENTAL PROGRAM

A total of 216 screw withdrawal tests were conducted according to the method specified in ASTM D1761 [9] modified to account for the round geometry of the bamboo culm as shown in Figure 1. A round steel pipe section was used to support the bamboo culm wall section. The screw was centred in a 45 mm opening in the side of the pipe (Figure 1). The pipe was attached to the test machine in a manner that permitted the system to be self-centered upon application of load. For consistency, tests on plywood used a rectangular steel tube in the same test configuration as used for bamboo (Figure 1). All tests were conducted in a 4500 N capacity universal test machine equipped with a load cell providing precision of 0.1%. Tests were conducted in displacement control at a rate of 1.27 mm/min resulting in failures typically occurring in 2-3 minutes. Applied load and machine cross-head displacement was recorded.

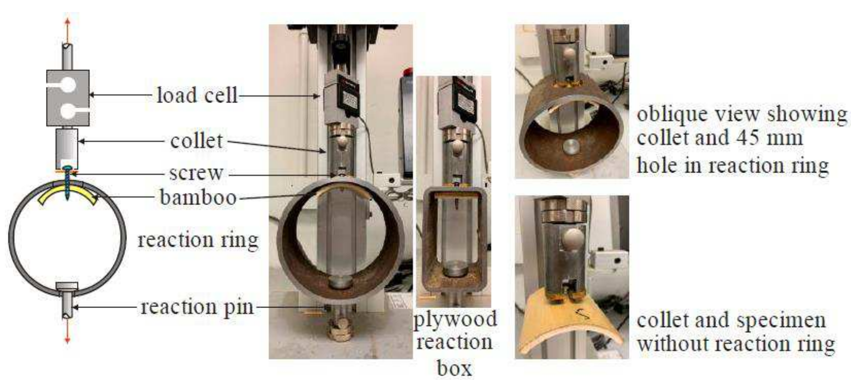

FIGURE 1 SCREW WITHDRAWAL TEST SET-UP.

All screws were installed from the outside of the culm wall, having to initially penetrate the tough bamboo epidermal layer. In a significant variation from ASTM D1761 practice, all tests were conducted with the screw completely protruding through the culm wall and engaged only over the region of the threaded full diameter of the screw. This condition would be typical of installations into bamboo culm walls.

An initial screening consisting of three tests of all 20 screw types (screw type and predrilling condition) was conducted to assess the performance of each screw type. Based on this screening, six types were selected for further testing of twenty samples each. Nineteen of the screw types were also tested using 3-ply 3/8 inch plywood to provide a comparison with typical results for wood.

Bamboo

All tests in this study were made with Phyllostachys edulis (Moso) bamboo. The culms were obtained from a commercial importer and were water treated and kiln dried. Samples ranged in diameter from approximately 65 mm to 100 mm. The culm wall thickness measured with a digital calliper, t, ranged from 4.8 mm to 10.4 mm having an average value of 7.0 mm (COV = 0.18). Moisture content determined by oven drying (ISO 22157-2019) at the time of screw insertion and testing was 7% with very little, if any, measureable variation. The bamboo was characterised as having a density, ρ = 730 kg/m3; compression strength [17], fc,0 = 48.1 MPa (COV = 0.20); a longitudinal shear strength [17], fv = 15.1 MPa (COV = 0.11) and transverse modulus of rupture [18], fr = 17.3 MPa (COV = 0.18).

Plywood

In order to provide a basis of comparison, companion tests using three-ply, 8.5 mm thick (supplied as 3/8 inch plywood) were also carried out. This material was selected as it has a similar thickness to the bamboo tested. The properties of this commercially obtained material were not experimentally determined; the allowable material properties [8] are given as: compression strength, Fc = 4.4 MPa; and 0o modulus of rupture, Fb,0 = 6.1 MPa.

Screws

Twelve commercially available steel screw types were used; these are identified as A through M (excluding I) as indicated in Table 2. Screws were selected to capture a range of thread geometry while being easily obtained in most areas of the world. Schematic drawings of each screw type are shown in Figure 2. Screws A, H and K are self-drilling versions of conventional screws B, J and L, respectively; the former were not tested in the predrilled condition. Screws G and M are concrete anchor screws; these were selected for investigation due to their deep and widely spaced threads. Screw type C has a smaller pitch than conventional wood screws (D) and has a very sharp auger tip for installation into hardwood without predrilling. Screw type C in this study is similar to the 4.0-b1 specimens reported by [3]. Screw Type F is intended for use in plastics and has a dual height thread pattern; this screw required predrilling.

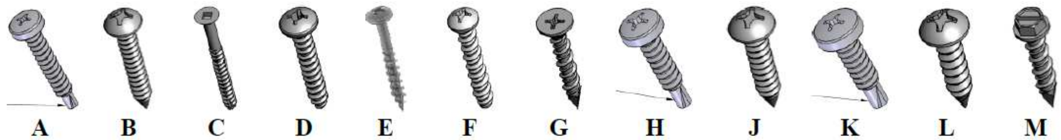

FIGURE 2 SCREW TYPES USED IN THIS STUDY (NOT TO SCALE).

Screening for Culm Splitting

Screws were inserted using a handheld rechargeable drill/screwdriver. Predrill diameters are given in Table 2. Initially, all screw types were inserted 25 mm from the cut end of a culm. There was no node between the screw and the end of the culm to arrest any splitting caused by screw insertion; inclusion of an end node is recommended in practice. The purpose of this was to screen the screw types for their likelihood of causing splitting of the culm upon insertion. None of the screw types caused splitting when they were inserted into predrilled holes. As expected, the larger diameter screws (J and L) resulted in bamboo splitting when inserted without predrilling. Interestingly, large diameter self-drilling screws (H and K) did not result in splitting.

SCREW WITHDRAWAL RESULTS

All data reported is in terms of the withdrawal parameter fax (Eq. 1). Figure 3 and Table 2 provide a summary of all tests conducted in this study. Figure 4 shows the initial three tests of each screw type (predrilled and non-predrilled); curves are offset 4 mm horizontally for clarity. The curves in Figure 4 may be considered surrogate for, and interpreted in a manner similar to, load-extraction displacement curves. As seen in Figure 4, the withdrawal behaviour is quite consistent for all screw types. The concrete anchor screws (G and M) both display more variable performance likely attributed to damage caused during insertion. The largest self-drilling screw (K) exhibits the least stiff response also suggesting damage during insertion. The withdrawal parameters for bamboo exceeded those determined for 3/8 inch plywood by between 130 and 270%, depending on screw type.

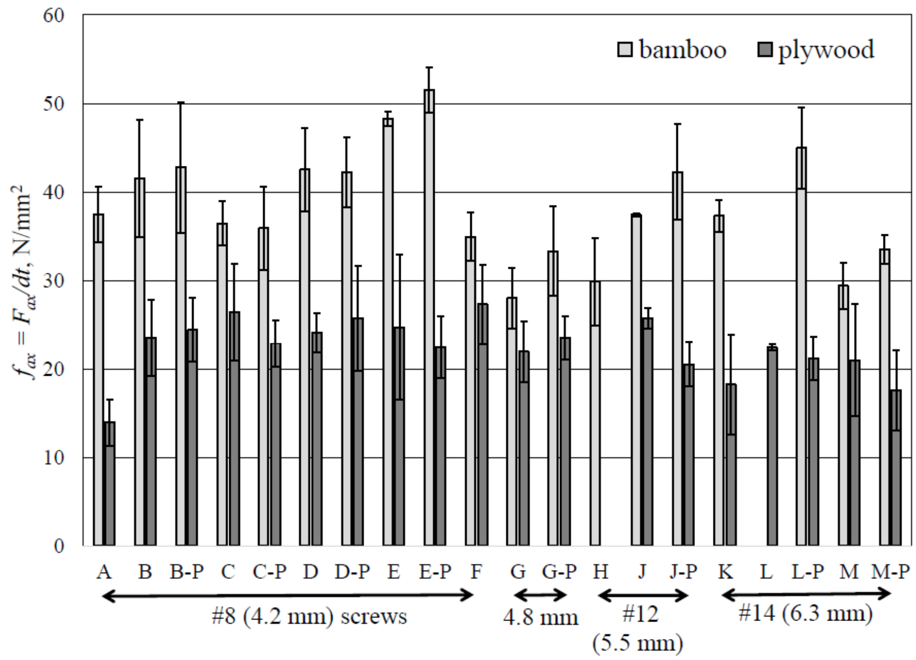

FIGURE 3 SUMMARY OF SCREW WITHDRAWAL TEST RESULTS.

TABLE 2 WITHDRAWAL TEST RESULTS.

ID	screw description	predrill dia.	d	pitch	*P. edulis*			3/8" plywood		
		mm	mm	mm	n	f_{ax} N/mm²	COV	n	f_{ax} N/mm²	COV
A	#8-18 – 1" self-drilling	none	4.166	1.41	3	37.5	0.08	3	13.9	0.19
B	#8-18 – 1" sheet metal	none	4.166	1.41	20	41.5	0.16	3	23.5	0.18
B-P		1.98			20	42.8	0.17	3	24.4	0.15
C	#8 – 1 5/8" auger point	none	4.166	1.69	3	36.5	0.07	3	26.4	0.21
C-P		1.59			3	35.9	0.13	3	22.9	0.11
D	#8 – 1" plywood/OSB	none	4.166	2.54	20	42.5	0.11	3	24.1	0.09
D-P		1.98			20	42.2	0.09	3	25.7	0.23
E	#8 – 1" sheetrock	none	4.166	2.54	4	48.2	0.02	3	24.7	0.33
E-P		1.98			3	51.5	0.05	3	22.5	0.15
F	#8 – 1" thread forming	2.38	4.166	1.41	3	34.9	0.08	3	27.3	0.16
G	3/16" – 1 ¼" concrete	none	4.775	2.54	3	28.0	0.12	3	22.0	0.16
G-P		2.38			3	33.3	0.15	3	23.5	0.10
H	#12 – 1" self-drilling	none	5.455	1.81	3	29.8	0.16	0	[2]	[2]
J	#12 – 1" sheet metal	none	5.455	1.81	3	37.4	0.00	3	25.7	0.05
J-P		3.18			20	42.3	0.13	3	20.5	0.12
K	¼" – 1 1/2" self-drilling	none	6.317	1.81	3	37.3	0.05	3	18.2	0.31
L	#14 – 1" sheet metal	none	6.317	1.81	3	[1]	[1]	3	22.4	0.02
L-P		3.18			20	45.0	0.10	3	21.2	0.12
M	¼" – 1 ¼" concrete	none	6.350	2.82	3	29.4	0.09	3	21.0	0.30
M-P		3.97			3	33.5	0.05	3	17.6	0.26

[1] screw insertion splits bamboo; no withdrawal test possible
[2] screw threaded length was inadequate to fully embed threads

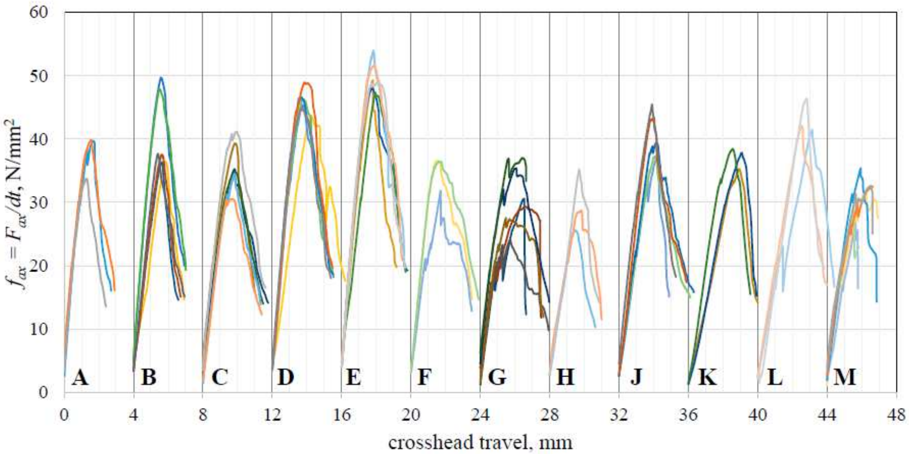

FIGURE 4 WITHDRAWAL PARAMETER VERSUS CROSSHEAD TRAVEL FOR THREE SCREENING WITHDRAWAL TESTS FOR ALL SPECIMENS. [HORIZONTAL AXES OFFSET 4 MM FOR EACH SERIES FOR CLARITY]

Characterization of Failures

Observed failures were dominated by a pull-out mode of failure (Figure 5). Due to the anisotropic nature of bamboo, this was typically followed by splitting following the peak capacity being achieved. In Figure 4, pull-out failures are characterized by a small drop in apparent stiffness prior to the peak capacity being reached and a somewhat ductile post-peak ascending curve. Splitting failures are brittle and characterized by little (if any) drop in stiffness prior to the peak load being achieved and an abrupt loss of load carrying capacity. Few specimens exhibited splitting dominated failures.

a) screw type D (t = 6.9 mm) b) screw type B-P (t = 7.9 mm) c) screw type D following removal

FIGURE 5 TYPICAL SCREW WITHDRAWAL TESTS (SAMPLES SPLIT FOLLOWING TEST TO SHOW EMBEDMENT).

The nature of the embedment and withdrawal behaviour is evident in Figure 5. Withdrawal capacity is primarily affected by mechanical interaction between the screw and the bamboo. The anisotropic nature of the bamboo results in interlaminar splitting, presumably initiated at the threads. Depending on thread engagement, the portions of the culm wall continue to delaminate (Figure 5a) or the outer laminates bend (Figure 5b) as the withdrawal progresses. Care should be taken examining Figure 5; these images were taken following continued post-peak displacement (Figure 4). The relatively 'soft' nature of the bamboo in terms of engaging threads is evident in Figure 5c. Here the threads are clearly seen as having engaged and cut across both the bamboo fibres and parenchymal matrix.

Discussion of Results

ANOVA evaluation of all test results was conducted. This clearly indicated that withdrawal parameter is affected by screw type. Two results in particular are informative: Firstly, there is no statistical difference between non predrilled and predrilled cases. This finding is useful in that not having to predrill screw connections into bamboo would be a preferable condition in field applications. Secondly, among the best performing screw types – those subsequently subject to 20 tests (B, B-P, D, D-P, J-P and L-P) – there is no significant difference in performance except when comparing L-P to D-P. In general, screw type L-P exhibits a greater characteristic withdrawal capacity than the other conditions tested.

Contrary to the trend reported for wood construction [19], self-drilling screws (types A, H and K) exhibited lower capacities than comparable regular-point screws (B, J and L) whether the latter was predrilled or not. This observation suggests that the drilling tip on self-drilling metal screws is inappropriate and may cause damage to the culm wall. The auger tip on screw type C, on the other hand appeared to perform well, easily penetrating the bamboo epidermis. The performance of screw type C, however, may have been limited by it relatively smaller thread depth.

Screw types D and E have identical geometry. Screw type D is zinc-plated steel to resist corrosion in wet environments while type E is black oxide steel suitable only for dry environments. The difference in performance between D and E is statistically significant ($p < 0.03$ for all variations) suggesting an effect of screw surface treatment on withdrawal capacity. This parameter requires further study.

When interpreting the results presented it is important to recall that these are presented for a single bamboo species (P. edulis) from a single batch having both uniform density (ρ = 730 kg/m3) and moisture content (MC = 7%). Greater withdrawal capacities are reported in the present study than were reported previously [3] for Guadua bamboo. Comparing essentially identical screw type C from this study and 4.0-b1 from [3] (Table 1), the former is observed to have a withdrawal parameter 115% the latter (t-test p-value = 0.03). The difference is hypothesized to be attributable to species morphology.

CONCLUSION

A series of screw withdrawal tests from P. edulis bamboo has demonstrated capacities and behaviour suitable for structural applications. For the better-performing screws, average withdrawal parameters exceeding fax = 40 N/mm2 were achieved; twice that determined for 3/8 inch, 3 ply plywood. Additionally, less variation was observed in bamboo withdrawal tests than in plywood tests. In order mitigate splitting upon screw insertion in to bamboo, screw diameters generally less than 6 mm were required unless the screws are inserted into predrilled holes. There was no advantage observed to using self-drilling screws; indeed, the self-drilling screw tip may cause more damage to the bamboo than a simple sharp screw of the same size. The lubricating and/or friction effect of the screw coating is a factor not considered widely in this study although results suggest that this is a factor that should be included in further study.

ACKNOWLEDGEMENTS

This research was partially funded through National Science Foundation Award 1634739 Collaborative Research: Full-culm Bamboo as a Full-fledged Engineering Material.

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