Screw Withdrawal Capacity of Full-Culm *P. edulis* Bamboo

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Abstract

The withdrawal capacity – as determined by a modified ASTM D1761 test – of screws embedded in *Phyllostachys edulis* bamboo culm walls is presented, demonstrating capacities and behaviour suitable for structural load bearing applications. This 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. For the better-performing screws, average withdrawal parameters exceeding f_{ax} = 40 N/mm^2 were achieved; twice that determined for three-ply plywood having comparable thickness. Comparison with a comparable dataset of screw withdrawal tests from *Guadua angustifolia* Kunth bamboo indicates that the value of f_{ax} is likely species-dependent. In order to mitigate splitting upon screw insertion into 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.

Keywords: bamboo, connection, screw, splitting, withdrawal

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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 (Widyowijatnoko and Harries 2019), few use conventional dowel connectors (screws and nails) driven in to the culm wall. Indeed, in original draft revisions to ISO 22156:2004 *Bamboo Structural Design*, 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 (2018) 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 (e.g., Morisco and Mardjono 1996) or pipe-sleeve (e.g., Forero 2003; Clavijo and Trujillo 2000) connections. Using screws in place of through-bolts in some connections may make these connections easier to fabricate, especially in a field environment. 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 (Clavijo and Trujillo 2000; Widyowijatnoko and Harries 2019).

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 (Gonzalez and Gutierrez 2006) 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 (AWC 2015). Screw (or nail or staple) withdrawal capacity from wood or wood-based engineered or composite materials can be determined based on ASTM D1761 (2012) or EN 1382 (2016) which are for most intents the same. In this paper, the screw withdraw capacity (in N) is denoted F_{ax} and the 'withdrawal parameter' normalizes F_{ax} by both screw diameter (d in mm) and depth of engaged threads (t in mm):

$$f_{ax} = F_{ax}/dt \qquad (1)$$

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 (e.g., Erdil et al. 2002) the withdrawal capacity for cases in which the screw protrudes sufficiently that only the full diameter threaded region of the screw is engaged in length t 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.

By convention, the characteristic value (denoted with an additional subscript k) for wood construction is defined as the 5th percentile value determined with 75% confidence (ASTM D2915 (2017); ISO 12122(2014)). In many studies only the characteristic value is reported; thus the mean and, importantly, the variation of data is obscured or lost.

Screw Withdrawal from Wood

Characteristic withdrawal capacity determined from analysis of 800 tests on Spruce having screw diameters ranged from 6 to 12 mm was reported by Blass et al. (2006) and adopted in EN 1995-1-1 (2008) (§8.7.2):

$$F_{ax,k} = (0.52d^{0.52}t^{0.9}\rho^{0.8})/(1.2\cos^2\alpha + \sin^2\alpha) \qquad (2)$$

$$f_{ax,k} = 0.52d^{-0.48}t^{-0.1}\rho^{0.8} \qquad (3)$$

Where ρ is the density of the wood (in kg/m^3 normalized at a moisture content of 12%) and α is the angle of screw insertion (for insertion perpendicular to the surface, $\alpha = 90^o$ and the denominator in Eq 2 is equal to unity).

Frese and Blass (2009) assessed a larger dataset of 1847 withdrawal tests and proposed the following logarithmic relationships.

$$ln(F_{ax,k}) = 6.54 + t(0.03265 - 1.173 \times 10^{-4}t) + 2.35 \times 10^{-4}d\rho \qquad (4)$$

$$ln(f_{ax,k}) = 2.182 - 0.04175d + 2.21 \times 10^{-3}\rho \qquad (5)$$

Frese and Blass go on to show that the simpler Eq. 6 yields similar values to Eq. 5.

$$f_{ax,k} = 0.0872d^{-0.4119}\rho \qquad (6)$$

Values determined from Eq. 4 for the case of $\alpha = 90^o$ are reported to be 108% of those of Eq. 2 (Frese and Blass 2009).

In North American practice (AWS 2015), design withdrawal strengths are tabulated and can be described as functions of d, t and ρ^2. Soltis (1999) reports that the withdrawal capacity of wood screws inserted into the side grain of seasoned wood used to calibrate the AWS tabulations is:

$$F_{ax} = 108.25dtG^2 \qquad (7)$$

Where G is specific gravity. Soltis also reports that the capacity of self-drilling screws (types A, H and K in this study, see below) is about 10% greater than comparable wood screws (B, J and L). For the plywood used in this study (see below), the allowable withdrawal strength (AWS 2015) would be approximately $F_{ax} = 5dt$, implying $f_{ax} = 5\ N/mm^2$. The 'allowable' strength is the characteristic strength to which an additional 'factor of safety' is applied.

Screw Withdrawal from Bamboo

There are multiple studies which report the screw withdrawal capacity of various engineered bamboo materials including reconstituted bamboo lumber (Chen et al. 2016) bamboo particle board (de Melo et al. 2014), bamboo OSB (Guo et al. 2018) and hybrid wood/bamboo materials (Nurhazwani et al. 2016; de Melo et al. 2014). All report a modest improvement in screw withdrawal capacity in bamboo materials as compared to wood and engineered wood products having similar material properties. However, due to the unique nature of each material, the capacities reported are not informative to the present study.

There is only a single known study reporting screw withdrawal capacity from full-culm bamboo (Trujillo and Malkowska 2018). This study reports 240 screw withdrawal tests (EN 1382) from the walls of

Guadua angustifolia Kunth culms having a reported density of 755 kg/m^3 (COV = 0.11) at MC = 8.6% (implying a density at MC = 12%, ρ_{12} = 779 kg/m^3). Five screw types were included in the study; a summary of screw parameters and test results are given in Table 1. Taking an approach similar to that reported for wood, Trujillo and Malkowska propose the following for *Guadua* bamboo:

$$F_{ax} = 0.03d^{0.53}\rho^{0.92}t^{1.19}MC^{-0.48} \qquad (8)$$

Where MC is moisture content of the test samples (reported as 8.6% with a COV = 0.09). The characteristic value is given as:

$$F_{ax,k} = 0.083d^{0.53}\rho^{0.92}t^{1.19} \qquad (9)$$

Comparing Eq. 9 for *Guadua* bamboo with those for wood prescribed by EN 1995 1-1 (Eq 2), one sees similar parametric effects likely indicating similar mechanisms engaged in the withdrawal of screws from wood and bamboo. Withdrawal capacity, F_{ax}, is a function of approximately the square root of screw diameter ($d^{0.5}$) and varies close to linearly with both density (ρ) and screw penetration (t).

Objective of Present Study

The objective of this study is to survey screw withdrawal capacity in full culm bamboo based on screw type and size. 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. This 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. Indeed, to address the latter issue, Trujillo and Malkowska (2018) considered only self-drilling screw types requiring no predrilling.

Experimental Program

A total of 216 screw withdrawal tests were conducted according to the method specified in ASTM D1761 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-centering 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. Displacement data, in this case, can only be used as a relative measure of performance and does not represent the actual slip of the screw.

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 (i.e., exiting through the interior surface of 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 characteristic value 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.

Materials

Bamboo

All tests in this study were made with *Phyllostachys edulis* (Moso) bamboo. The culms were obtained from a commercial importer and were borax treated (submerged in borax-boric acid solution) and kiln dried; they had been subsequently stored in an air-conditioned laboratory environment for almost two years. Samples ranged in diameter from approximately 65 mm to 100 mm. Diameter of the culm is not a parameter considered in this study as it only effects the curvature of the screw withdrawal sample and this was addressed by using a round test fixture (Figure 1). 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 for all tests reported.

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. Measured material properties determined for the same batch of bamboo are given in Table 2.

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. Allowable material properties inferred from design capacities (AWC 2015) are given in Table 3.

Screws

Twelve commercially available steel screw types were used; these are identified as A through M (excluding I) as indicated in Table 4. Screws were selected to capture a range of thread geometry. Material properties were not determined and are not expected to be relevant to the current study that focusses on withdrawal capacity. No screw rupture was observed in this study.

Most screw types are relatively easily found around the world. Schematic drawings of each screw type showing the tip geometry are shown in Figure 2. Screws A, H and K are self-drilling versions of conventional screws B, J and L, respectively; apart from the self-drilling point, these screws and thus their anticipated withdrawal properties are identical. For this reason, screws A, H and K were not tested in a 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 Trujillo and Malkowska (2018). Screw Type F is intended for use in plastics and plexiglass and has a dual height thread pattern. Type F has no point and therefore must be predrilled at a diameter similar to its inner diameter (diameter at root of threads).

Screw Insertion

Screening for Culm Splitting

Screws were inserted using a handheld rechargeable drill/screwdriver. Predrill diameters are given in Table 4. 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 might be expected, the larger diameter screws (J and L) resulted in bamboo splitting when inserted without predrilling. Sufficient samples were fabricated using screw type J for initial withdrawal testing while it was not possible to drive the larger #14 (6.3 mm diameter) screws without splitting the bamboo. As a result, no withdrawal data was obtained for screw type L with no predrilling. Interestingly, large diameter self-drilling screws (H and K) did not result in splitting.

Observations Regarding Screw Insertion

Bamboo has a very hard, silica-rich outer culm wall layer: the epidermis (Liese 1998). In general, this is easily drilled using a standard high speed drill bit. The drill point on the self-drilling metal screws (A, H and K), however, was not well suited to penetrating the bamboo. While it was possible to insert these screws in a laboratory environment, they had a tendency to 'wobble' while being installed. It is envisioned that these self-drilling screws may not be reliably installed in the field since the screws tend to take some effort to get the drill point to "bite" into the bamboo epidermis and wobble as they are drilled. Self-drilling hardwood screws (C) which have a very sharp auger tip, on the other hand, were very easy to drive without predrilling. Concrete screws (G and M) have a hardened although large four-sided (pyramidal) point – these were also not well suited to insertion without predrilling. All other screws, provided their point was sharp, could be inserted without predrilling although, as noted above, larger screw diameters resulted in undesirable splitting.

Screw Withdrawal Results

All data reported is in terms of the withdrawal parameter f_{ax} (Eq. 1); this normalizes for both screw diameter, d, and embedment length, t. Table 5 and Figure 3 provide a summary of all tests conducted in this study. Test data from all 216 samples indicating F_{ax} are provided in an Appendix at the end of this paper. Figure 4 shows the initial three tests of each screw type (predrilled and nonpredrilled); curves are offset 4 mm horizontally for clarity. The curves in Figure 4 show machine cross head travel which may be considered surrogate for, and interpreted in a manner similar to, load-extraction displacement curves. As seen in Figure 4, the withdrawal behavior 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. As noted above, screw type K was difficult to install and tended to 'wobble' as it was drilled.

As indicated in Table 5 and seen in Figure 3, the withdrawal parameters for bamboo exceeded those determined for 3/8 inch plywood by between 130 and 270%, depending on screw type.

Ranking of the withdrawal capacity of all screw types is given in Table 6. Based on initial results of three tests, the best performing screw types – B, B-P, D, D-P, J-P and L-P – were tested to determine characteristic withdrawal parameter values. Despite having the greatest withdrawal capacity, sheetrock screws (type E) were not considered further since these screws are intended for indoor use and have little resistance to corrosion.

In order to determine characteristic values, defined as the 5th percentile value determined with 75% confidence (ASTM D2915, ISO 12122), twenty samples were tested and the characteristic value reported in Table 5 was determined as:

$$f_{ax,k} = f_{ax} - 1.932 \text{ x standard deviation of } f_{ax} \qquad (10)$$

The factor 1.932 corresponds to the sample size n = 20 (ASTM D2915). Based on the greatest coefficient of variation (COV) observed (0.17 for screw type B-P), a minimum of 16 samples is required to establish the 5th percentile value with 75% confidence (ASTM D2915). Nonetheless, due to the relatively small sample size, the standard error (SE) is 0.385 times the standard deviation (ASTM D2915). The normalized standard error (NSE = NSE x COV) is also reported in Table 5.

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.

The nature of the embedment and withdrawal behavior 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.

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 fibers and parenchymal matrix (see Akinbade et al. 2019 for detailed description of bamboo culm wall structure).

Discussion of Results

Table 7 provides a matrix of *p*-values determined from t-tests on the withdrawal parameter results for bamboo samples (Table 5) of all test conditions compared to the others. *p*-values less than 0.05 indicate data that is statistically different with 95% confidence. The data shown in Table 7 clearly indicates that withdrawal parameter is affected by screw type. Two inserts in Table 7 highlight informative results. Firstly, there is no statistical difference between non predrilled and predrilled cases. This is contrary to what is typically found in wood, for instance, where predrilling results in marginally increased withdrawal capacity (e.g. Erdil et al. 2002). 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 tested for characteristic withdrawal capacity (B, B-P, D, D-P, J-P and L-P) there is no significant difference 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 (Soltis 1999), 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 highly isotropic nature of the bamboo fibres, compared to the inter-winding of fibres in wood, may contribute to the poorer behaviour of the self-drilling screws. 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 the relatively smaller thread depth (Table 4).

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; see Table 7) suggesting an effect of screw surface treatment on withdrawal capacity. This parameter requires further study.

Analysis of variation (ANOVA) analysis was conducted on all bamboo withdrawal data (159 tests) using commercial software Minitab (2018). While admittedly a small sample, ANOVA confirmed that error distribution is normal and only screw diameter, d, and depth of embedment, t, had significant effects on the withdrawal capacity. Subsequent independent regression analysis resulted in:

$$F_{ax} = 30.3d^{0.9}t^{1.23} \qquad R^2 = 0.80 \qquad NMAE = 0.124 \qquad (11)$$

When the product $d \times t$ is considered a similar correlation results:

$$F_{ax} = 29.3(dt)^{1.1} \qquad R^2 = 0.80 \qquad NMAE = 0.130 \qquad (12)$$

Eq. 12 suggests that adopting the simpler AWS approach (Eq 7) results in an equally satisfactory result:

$$F_{ax} = 41.1dt \qquad R^2 = 0.78 \qquad NMAE = 0.125 \qquad (13)$$

Where NMAE is the normalised mean absolute error. The coefficients include the effects of bamboo density which were not varied in this study. Since the correlation is close to $(dt)^{1.0}$, the predicted withdrawal parameter, f_{ax}, is essentially constant. Indeed, the average value obtained in this study is f_{ax} = 41.2 N/mm^2 (COV = 0.16). It must be noted that in this study d ranged from only 4.2 to 6.4 mm; smaller diameters are not felt to be appropriate for meaningful load-carrying connections while splitting upon insertion becomes a concern with larger diameters. The culm wall thickness, t, ranged from 4.8 to 10.4 mm; bamboo used for construction may have wall thicknesses exceeding this range.

Eq. 8, proposed for *Guadua* bamboo, is a poor predictor of the *P. edulis* data reported in this study, resulting in $R^2 = 0.17$ and NMAE = 0.25. Indeed, Eq. 2, adopted for wood in EN 1995-1-1 is a better predictor ($R^2 = 0.62$, NMAE = 0.16) than Eq. 8. Regression analysis was subsequently conducted on the data reported by Trujillo and Malkowska (2018; see Table 1) resulting in a relationship similar to Eq 13:

$$F_{ax} = 30.8dt \qquad R^2 = 0.59 \qquad \text{NMAE} = 0.134 \qquad (14)$$

Eq. 14 has poorer correlation than Eq. 13; however the bamboo density in the Trujillo and Malkowska data varied to a greater extent than it did in the present data. Including the density, ρ (in kg/m^3), improves the correlation:

$$F_{ax} = 0.041\rho dt \qquad R^2 = 0.68 \qquad \text{NMAE} = 0.131 \qquad (15)$$

A similar regression analysis for the 3 ply 3/8 inch plywood tested indicated a variation with screw diameter proportional to $d^{0.66}$ but with relatively poor correlation ($R^2 = 0.23$). Both thickness and density were constant in these companion tests.

When interpreting the results presented it is important to recall that these are presented for single bamboo species (*P. edulis*) from a single batch having both uniform density (ρ = 730 kg/m^3) and moisture content (MC = 7%). Moisture content, for instance is well known to affect bamboo material strengths (Janssen 1981). Typically normalized at MC = 12%, most bamboo material strengths and moduli increase with decreased MC below the fibre saturation point (FSP; typically about MC = 30%). There are two notable exceptions to this trend: tensile strength parallel to grain and impact toughness. Both of these properties could have an effect on screw withdrawal capacity and both are reported to decrease with decreasing MC (JG/T 199-2007).

Greater withdrawal capacities are reported in the present study than were reported by Trujillo and Malkowska (2018) for *Guadua* bamboo. Typically, the density of *P. edulis* is reported as being 116% that of *Guadua* (Correal 2016) although the densities reported in this (730 kg/m^3) and the Trujillo and

Malkowska study (755 kg/m^3) were similar (t-test p-value = 0.45). Comparing essentially identical screw type C from this study and 4.0-b1 from Trujillo and Malkowska (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.

Cost and Availability

The realty of most bamboo construction is that the craftsman will use materials that are readily available and/or least expensive. The unit cost – from a North American industrial supply company – of each screw type is reported in Table 4. The results of this study are encouraging in so far as less expensive, and often more readily available screw types – B and D – are also the better performers.

Recommendations

Based on the limited available data, it is proposed that screw connectors intended for softwood, OSB or plywood can be used in bamboo culm walls when the screws are subject to withdrawal forces. Although greater withdrawal capacities have been observed in bamboo, without characterisation testing, withdrawal capacities recommended for plywood having a thickness comparable to the bamboo culm wall appear to be appropriately conservative. Screws should not exceed 6.5 mm in diameter and may be self-drilling or inserted into predrilled holes provided the insertion is shown to not split the bamboo. Screws should fully penetrate the culm wall, engaging the full diameter (d) threaded portion of the screw through the entire culm wall thickness (t).

Conclusion

A series of screw withdrawal tests from *P. edulis* bamboo has demonstrated capacities and behaviour suitable for structural applications. Withdraw capacities for a particular bamboo species having similar density and moisture content may be expressed in terms of a linear function of the product of screw diameter and embedded depth (i.e., $d \times t$), making the withdrawal parameter constant. For the better-performing screws, average withdrawal parameters exceeding f_{ax} = 40 N/mm^2 were achieved; greater than twice that determined for 3/8 inch, 3 ply plywood. Additionally, less variation was observed in bamboo withdrawal tests than in plywood tests. Comparison with a comparable dataset of screw withdrawal tests from *Guadua* bamboo indicates that the value of f_{ax} is likely species-dependent; a value of f_{ax} = 30.8 N/mm^2 was observed in the *Guadua* tests. The variation in withdrawal capacity was similar for both species; COV of f_{ax} was 0.16 for *P. edulis* and 0.17 for *Guadua*.

In order to mitigate splitting upon screw insertion into 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; additionally self-drilling screws are more expensive and may be less easily obtainable in some locations. 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.

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Table 1 Screw parameters and screw withdrawal results reported by Trujillo and Malkowska (2018). (COV in brackets in all cases)

test ID	screw type		d	d_1	pitch	n	F_{ax}	$f_{ax} = F_{ax}/dt$	$f_{ax,k}$
			mm	mm	mm		N	N/mm^2	N/mm^2
3.5-b1	self drilling wood screw		3.5	2.6	1.8	60	1264 (0.28)	34.43 (0.17)	23.92
4.0-b1			4.0	2.7	1.9	60	1342 (0.29)	31.81 (0.11)	25.53
5.0-b1			5.0	3.5	2.2	30	1505 (0.29)	28.65 (0.12)	22.22
4.0-b2	serrated tip self-drilling wood screw		4.0	2.5	2.3	30	1296 (0.27)	30.87 (0.15)	22.22
4.8-b3	self drilling roofing screw (tabs removed)		4.8	3.8	1.6	60	1284 (0.24)	25.97 (0.17)	18.04
for all data, t = 10.5 mm (0.24); MC = 8.6% (0.09) d_1 is diameter at root of thread									

Table 2 Material properties of *P. edulis* bamboo used in this study. (COV in brackets in all cases)

property		test method
gross section fibre volume ratio, V_f	0.27	image analysis (Akinbade et al. 2019)
measured culm wall thickness, t	7.02 mm (0.18)	measured with calliper
transverse modulus of rupture, f_r	17.3 MPa (0.18)	flat ring flexure (Virgo et al. 2017)
full culm compression strength, $f_{c,0}$	48.1 MPa (0.20)	ISO 22157-2019
longitudinal shear, f_v	15.1 MPa (0.11)	ISO 22157-2019 ("bowtie" test)
moisture content at time test, MC	7%	ISO 22157-2019 (oven dry)
density (at MC = 7%), ρ density at MC = 12%, ρ_{12}	730 kg/m^3 (0.08) 764 kg/m^3	ISO 22157-2019

Table 3 Allowable properties of three-ply 3/8 inch plywood used in this study.

property	
measured thickness, t	8.5 mm
nominal thickness	9.5 mm
0^{o} modulus of rupture, $F_{b,0}$	6.1 MPa
90^{o} modulus of rupture, $F_{b,90}$	1.3 MPa
compression strength, F_c	4.4 MPa

Table 4 Screws used in this study

ID	description provided by US-based supplier	unit cost	surface condition	major dia., d	minor dia., d_1	thread depth $0.5(d-d_1)$	pitch	predrill test cases	
								none	dia.
		US¢		mm	mm	mm	mm		mm
A	#8-18 – 1" self-drilling screws for metal	6.4	Zn plated	4.166	2.486	0.84	1.41	y	[3]
B	#8-18 – 1" sheet metal screws	6.6	Zn plated	4.166	2.486	0.84	1.41	y	1.98
C	#8 – 1 5/8" auger point hardwood screws	33.4	18-8 SS	4.166	2.789	0.69	1.69	y	1.59
D	#8 – 1" plywood/OSB screws	7.4	Zn plated	4.166	2.692	0.74	2.54	y	1.98
E	#8 – 1" sheetrock screws	7.8	black oxide	4.166	2.692	0.74	2.54	y	1.98
F	#8 – 1" thread forming (plastic) screws	23.0	Zn plated	4.166	2.486	0.84	1.41	n[1]	2.38
G	3/16" – 1 ¼" concrete screws	17.2	blue[4]	4.775	3.222	0.78	2.54	y	2.38
H	#12 – 1" self-drilling screws for metal	15.4	Zn plated	5.455	3.294	1.08	1.81	y	[3]
J	#12 – 1" sheet metal screws	8.6	Zn plated	5.455	3.294	1.08	1.81	y[2]	3.18
K	¼" – 1 1/2" self-drilling screws for metal	20.1	Zn plated	6.317	4.157	1.08	1.81	y	[3]
L	#14 – 1" sheet metal screws	10.8	Zn plated	6.317	4.157	1.08	1.81	n[2]	3.18
M	¼" – 1 ¼" concrete screws	22.1	blue[4]	6.350	4.189	1.08	2.82	y	3.97

[1] screw type has no point; must be predrilled
[2] screw insertion splits bamboo without predrilling
[3] self-drilling screws were not tested in predrilled condition
[4] proprietary coating reported as "ultra-corrosion resistant"

Table 5 Summary of screw withdrawal test results

ID	predrill dia	*P. edulis* bamboo					3/8" plywood			bam/ply
		n	$f_{ax} = F_{ax}/dt$	COV	$f_{ax,k}$	NSE	n	$f_{ax} = F_{ax}/dt$	COV	
	mm		N/mm^2		N/mm^2			N/mm^2		
A	none	3	37.5	0.08	-	-	3	13.9	0.19	2.69
B	none	20	41.5	0.16	28.7	0.06	3	23.5	0.18	1.77
B-P	1.98	20	42.8	0.17	28.5	0.07	3	24.4	0.15	1.75
C	none	3	36.5	0.07	-	-	3	26.4	0.21	1.38
C-P	1.59	3	35.9	0.13	-	-	3	22.9	0.11	1.57
D	none	20	42.5	0.11	33.4	0.04	3	24.1	0.09	1.76
D-P	1.98	20	42.2	0.09	34.6	0.03	3	25.7	0.23	1.64
E	none	4	48.2	0.02	-	-	3	24.7	0.33	1.95
E-P	1.98	3	51.5	0.05	-	-	3	22.5	0.15	2.29
F	2.38	3	34.9	0.08	-	-	3	27.3	0.16	1.28
G	none	3	28.0	0.12	-	-	3	22.0	0.16	1.27
G-P	2.38	3	33.3	0.15	-	-	3	23.5	0.10	1.42
H	none	3	29.8	0.16	-	-	0	[2]	[2]	-
J	none	3	37.4	0.00	-	-	3	25.7	0.05	1.45
J-P	3.18	20	42.3	0.13	31.8	0.05	3	20.5	0.12	2.06
K	none	3	37.3	0.05	-	-	3	18.2	0.31	2.04
L	none	3	[1]	[1]	-	-	3	22.4	0.02	-
L-P	3.18	20	45.0	0.10	36.0	0.04	3	21.2	0.12	2.12
M	none	3	29.4	0.09	-	-	3	21.0	0.30	1.40
M-P	3.97	3	33.5	0.05	-	-	3	17.6	0.26	1.91

COV = coefficient of variation; NSE = SE x COV = normalised standard error
[1] screw insertion splits bamboo; no withdrawal test possible
[2] screw threaded length was inadequate to fully embed threads

Table 6 Ranking of screw withdrawal capacities.

Rank	bamboo		plywood	
	ID	f_{ax}	ID	f_{ax}
highest	**E-P**	51.5	**F**	27.3
2	**E**	48.2	**C**	26.4
3	**L-P**	45.0	**D-P**	25.7
4	**B-P**	42.8	**J**	25.7
5	**D**	42.5	**E**	24.7
6	**J-P**	42.3	**B-P**	24.4
7	**D-P**	42.2	**D**	24.1
8	**B**	41.5	**B**	23.5
9	**A**	37.5	**G-P**	23.5
10	**J**	37.4	**C-P**	22.9
11	**K**	37.3	**E-P**	22.5
12	**C**	36.5	**L**	22.4
13	**C-P**	35.9	**G**	22.0
14	**F**	34.9	**L-P**	21.2
15	**M-P**	33.5	**M**	21.0
16	**G-P**	33.3	**J-P**	20.5
17	**H**	29.8	**K**	18.2
18	**M**	29.4	**M-P**	17.6
19	**G**	28.0	**A**	13.9

Table 7 t-test *p*-values for bamboo withdrawal tests

	B	B-P	C	C-P	D	D-P	E	E-P	F	G	G-P	H	J	J-P	K	L-P	M	M-P
A	0.32	0.24	0.68	0.65	0.09	0.06	0.001	0.004	0.35	0.02	0.29	0.09	0.97	0.15	0.93	0.01	0.03	0.12
B	1	0.57	0.21	0.18	0.58	0.68	0.06	0.02	0.11	0.003	0.05	0.01	0.31	0.69	0.30	0.06	0.01	0.05
B-P		1	0.17	0.14	0.90	0.77	0.16	0.06	0.09	0.003	0.05	0.01	0.23	0.81	0.22	0.27	0.01	0.05
C			1	0.86	0.04	0.02	0.0003	0.002	0.52	0.03	0.39	0.11	0.54	0.09	0.67	0.01	0.03	0.16
C-P				1	0.04	0.02	0.003	0.01	0.78	0.08	0.55	0.20	0.61	0.07	0.66	0.01	0.11	0.45
D					1	0.84	0.03	0.004	0.01	0.0001	0.05	0.0003	0.08	0.88	0.08	0.10	0.0001	0.004
D-P						1	0.01	0.001	0.01	0.0001	0.002	0.0001	0.05	0.97	0.05	0.05	0.0001	0.001
E							1	0.06	0.0002	0.0001	0.002	0.001	0.0001	0.04	0.0001	0.18	0.0001	0.0001
E-P								1	0.002	0.001	0.01	0.003	0.001	0.01	0.001	0.03	0.001	0.001
F									1	0.05	0.64	0.19	0.19	0.03	0.28	0.002	0.06	0.47
G										1	0.21	0.62	0.01	0.0003	0.01	0.0001	0.60	0.06
G-P											1	0.45	0.23	0.01	0.27	0.001	0.30	0.95
H												1	0.06	0.001	0.07	0.0001	0.90	0.29
J													1	0.14	0.92	0.01	0.01	0.01
J-P														1	0.14	0.10	0.001	0.01
K															1	0.01	0.01	0.06
L-P																1	0.0001	0.0004
M																	1	0.08

non-predrilled versus predrilled	
B-BP	0.57
C-CP	0.86
D-DP	0.84
E-EP	0.06
G-GP	0.21
J-JP	0.14
M-MP	0.08

characteristic value tests (n =20)					
	B-P	**D**	**D-P**	**J-P**	**L-P**
B	0.57	0.58	0.68	0.69	0.06
B-P	1	0.90	0.77	0.81	0.27
D		1	0.84	0.88	0.10
D-P			1	0.97	0.05
J-P				1	0.10

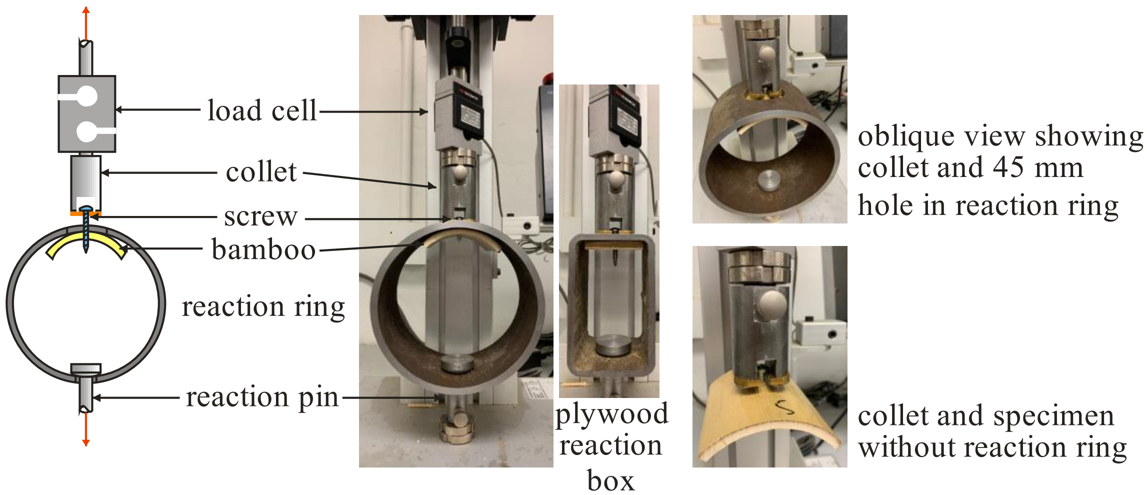

Figure 1 Screw withdrawal test set-up.

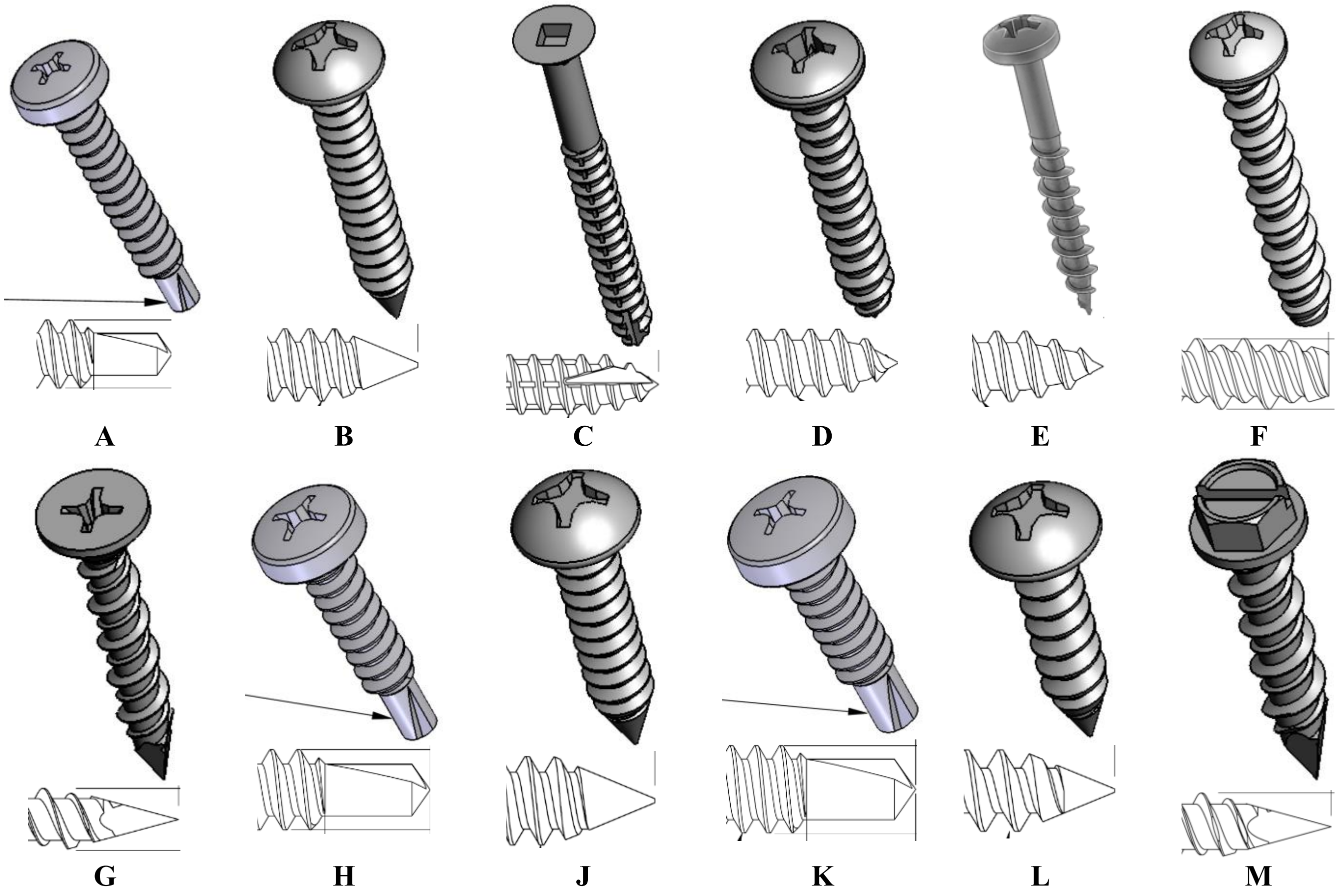

Figure 2 Screw types used in this study (not to scale; images from supplier-provided CAD drawings).

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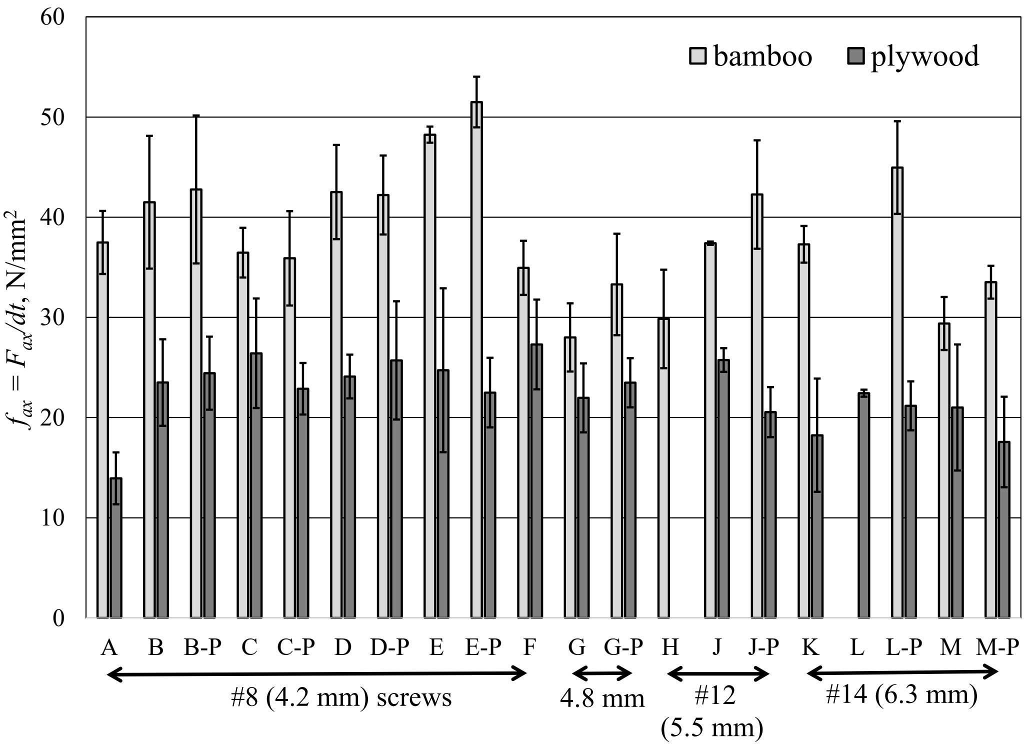

Figure 3 Summary of screw withdrawal test results.

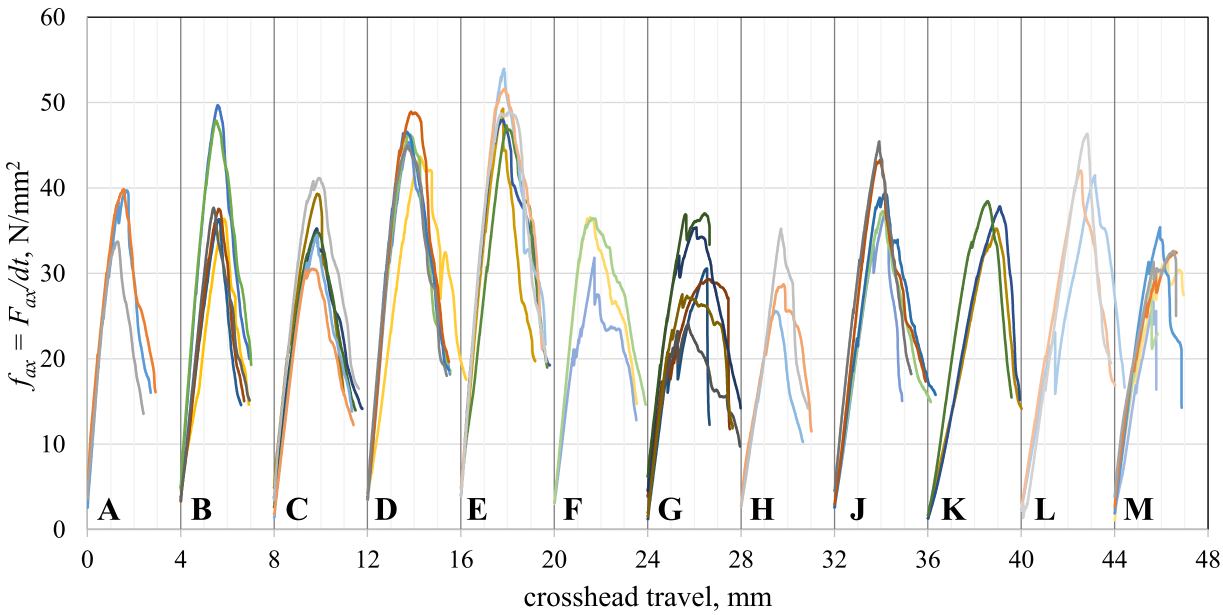

Figure 4 Withdrawal parameter versus crosshead travel for three screening withdrawal tests for all specimens. [Horizontal axes offset 4 mm for each series for clarity]

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

Figure 5 Typical screw withdrawal tests (samples split following test to show embedment).

Appendix – Screw withdrawal test data

The following tabulates the results of all 216 screw withdrawal tests conducted.

test condition		bamboo results			plywood results t = 8.53 mm	
ID	predrill dia.	t	F_{ax}	$f_{ax} = F_{ax}/dt$	F_{ax}	$f_{ax} = F_{ax}/dt$
	mm	mm	N	N/mm2	N	N/mm2
A	0.00	5.33	882.3	39.71	390.8	9.4
A	0.00	5.33	863.3	38.85	563.8	13.5
A	0.00	6.10	860.7	33.89	532.6	12.8
B	0.00	6.60	1001.3	36.40	774.6	18.6
B	0.00	5.08	1052.1	49.71	721.6	17.3
B	0.00	5.59	1114.6	47.88	1010.5	24.3
B	0.00	6.60	965.3	35.09		
B	0.00	6.35	1133.2	42.84		
B	0.00	7.11	1136.5	38.36		
B	0.00	6.60	977.8	35.54		
B	0.00	7.11	1131.7	38.20		
B	0.00	6.60	1178.5	42.84		
B	0.00	6.60	1048.7	38.12		
B	0.00	6.60	1172.2	42.61		
B	0.00	6.86	1119.3	39.18		
B	0.00	6.86	1261.7	44.16		
B	0.00	6.35	650.6	24.59		
B	0.00	6.60	1078.6	39.21		
B	0.00	6.35	1204.2	45.52		
B	0.00	6.35	1038.0	39.24		
B	0.00	8.64	1628.4	45.26		
B	0.00	8.64	1862.8	51.78		
B	0.00	8.89	1979.7	53.45		
B	1.98	6.35	961.1	36.33		
B	1.98	6.86	1072.4	37.54	720.9	17.3
B	1.98	7.11	1115.7	37.66	921.6	22.1
B	1.98	7.37	1593.6	51.93	963.3	23.1
B	1.98	7.37	1324.3	43.15		
B	1.98	7.87	1102.2	33.60		
B	1.98	7.62	1722.7	54.27		
B	1.98	8.64	1592.7	44.27		
B	1.98	8.13	1652.2	48.79		
B	1.98	7.87	1611.1	49.11		
B	1.98	8.38	1849.6	52.97		
B	1.98	7.62	1572.6	49.54		
B	1.98	9.65	1327.9	33.02		
B	1.98	10.41	2148.5	49.52		
B	1.98	10.41	1170.0	26.97		
B	1.98	6.86	1129.9	39.55		
B	1.98	7.11	1279.2	43.18		
B	1.98	6.86	1236.9	43.29		
B	1.98	7.37	1242.0	40.47		
B	1.98	6.60	1108.4	40.29		
C	0.00	8.13	1331.1	39.31	1123.3	27.0
C	0.00	7.11	1044.3	35.25	735.6	17.7
C	0.00	6.86	995.1	34.83	959.3	23.0
C	1.59	7.37	1058.8	34.50	885.4	21.3
C	1.59	7.11	949.5	32.05	844.5	20.3
C	1.59	6.60	1132.2	41.15	710.7	17.1
D	0.00	5.59	1017.0	43.69	790.2	19.0
D	0.00	5.84	1104.0	45.36	942.4	22.6
D	0.00	5.84	1126.4	46.28	837.6	20.1
D	0.00	6.86	1088.8	38.11		
D	0.00	6.86	1091.4	38.20		
D	0.00	6.10	1027.7	40.47		
D	0.00	6.35	1093.0	41.32		
D	0.00	6.10	981.6	38.65		
D	0.00	6.35	1100.5	41.60		

test condition		bamboo results			plywood results t = 8.53 mm	
ID	predrill dia.	t	F_{ax}	$f_{ax} = F_{ax}/dt$	F_{ax}	$f_{ax} = F_{ax}/dt$
	mm	mm	N	N/mm2	N	N/mm2
D	1.98	6.86	1154.3	40.40		
D	1.98	7.87	1229.5	37.48		
D	1.98	6.86	1107.4	38.76		
D	1.98	7.62	1317.2	41.49		
D	1.98	7.62	1234.3	38.88		
D	1.98	7.37	1119.0	36.46		
D	1.98	7.62	1265.1	39.85		
E	0.00	5.33	1094.7	49.26	1213.3	29.1
E	0.00	5.59	1117.1	47.99	739.6	17.8
E	0.00	5.59	1101.6	47.32	684.5	16.4
E	0.00	5.59	1126.8	48.40		
E	1.98	5.33	1199.2	53.97	798.2	19.2
E	1.98	5.33	1147.1	51.62	677.1	16.3
E	1.98	5.59	1138.9	48.92	923.9	22.2
F	2.38	7.11	1083.8	36.58	1081.1	26.0
F	2.38	6.86	909.4	31.83	788.5	18.9
F	2.38	6.86	1040.7	36.43	1042.6	25.0.
G	0.00	5.84	852.5	30.56	906.1	19.0
G	0.00	6.10	852.9	29.30	1030.4	21.6
G	0.00	6.35	731.9	24.14	749.9	15.7
G	2.38	6.35	834.4	27.52	845.0	17.7
G	2.38	6.10	1029.2	35.36	1037.8	21.7
G	2.38	5.59	987.4	37.00	987.7	20.7
H	0.00	6.10	850.6	25.58		
H	0.00	5.59	875.8	28.73		
H	0.00	5.59	1073.9	35.23		
J	0.00				1154.2	21.2
J	0.00	6.86	1403.9	37.53	1180.5	21.6
J	0.00	7.11	1446.8	37.29	1260.0	23.1
J	3.18	6.60	1418.1	39.36	835.0	15.3
J	3.18	6.83	1590.8	42.68	1066.1	19.5
J	3.18	6.35	1498.7	43.27	968.6	17.8
J	3.18	6.72	1513.4	41.29		
J	3.18	6.60	1637.0	45.44		
J	3.18	7.14	1857.7	47.71		
J	3.18	7.34	1976.5	49.36		
J	3.18	5.31	1144.1	39.51		
J	3.18	8.03	2280.5	52.09		
J	3.18	8.12	2421.5	54.70		
J	3.18	7.51	1463.5	35.74		
J	3.18	6.65	1364.7	37.59		
J	3.18	6.69	1533.4	42.00		
J	3.18	5.18	1020.0	36.09		
J	3.18	5.41	1078.9	36.56		
J	3.18	5.49	1065.5	35.60		
J	3.18	6.52	1554.0	43.73		
J	3.18	8.92	1892.0	38.90		
J	3.18	8.70	1931.0	40.69		
J	3.18	8.79	2062.6	43.02		
K	0.00	8.41	1872.1	35.25	862.2	13.6
K	0.00	8.59	2052.3	37.84	1329.9	21.1
K	0.00	8.64	2116.2	38.79	757.8	12.0
L	0.00				1204.4	19.1
L	0.00				1230.0	19.5
L	0.00				1192.8	18.9
L	3.18	6.35	1663.7	41.48	1155.5	18.3
L	3.18	8.76	2678.7	48.39	1002.9	15.9
L	3.18	6.86	1821.2	42.04	1265.6	20.0

test condition		bamboo results			plywood results t = 8.53 mm	
ID	predrill dia.	t	F_{ax}	$f_{ax} = F_{ax}/dt$	F_{ax}	$f_{ax} = F_{ax}/dt$
	mm	mm	N	N/mm2	N	N/mm2
D	0.00	6.10	1007.5	39.67		
D	0.00	5.84	1011.9	41.58		
D	0.00	9.40	1543.1	39.41		
D	0.00	8.89	1290.0	34.83		
D	0.00	8.89	1838.0	49.63		
D	0.00	8.64	1531.4	42.56		
D	0.00	9.40	1888.9	48.25		
D	0.00	9.65	2008.2	49.94		
D	0.00	9.65	1433.7	35.66		
D	0.00	8.89	1632.5	44.08		
D	0.00	9.91	2102.3	50.94		
D	1.98	5.59	1084.3	46.58	671.6	16.1
D	1.98	5.33	1087.4	48.94	1037.9	24.9
D	1.98	5.84	1094.2	44.96	1032.3	24.8
D	1.98	8.38	1683.7	48.22		
D	1.98	7.62	1527.4	48.11		
D	1.98	8.38	1469.6	42.09		
D	1.98	8.13	1467.0	43.32		
D	1.98	8.38	1296.5	37.13		
D	1.98	8.13	1535.2	45.34		
D	1.98	8.64	1625.1	45.17		
D	1.98	8.13	1451.6	42.87		
D	1.98	6.86	1135.6	39.75		
D	1.98	6.86	1102.7	38.60		

test condition		bamboo results			plywood results t = 8.53 mm	
ID	predrill dia.	t	F_{ax}	$f_{ax} = F_{ax}/dt$	F_{ax}	$f_{ax} = F_{ax}/dt$
	mm	mm	N	N/mm2	N	N/mm2
L	3.18	8.94	2716.2	48.09		
L	3.18	6.60	1933.6	46.35		
L	3.18	8.79	2838.4	51.13		
L	3.18	8.69	2562.1	46.69		
L	3.18	8.81	2643.0	47.47		
L	3.18	7.26	1650.6	35.97		
L	3.18	7.06	1983.5	44.47		
L	3.18	5.38	1416.3	41.64		
L	3.18	6.30	1426.8	35.86		
L	3.18	8.83	2845.3	51.03		
L	3.18	9.40	2788.0	46.96		
L	3.18	8.53	2742.7	50.87		
L	3.18	9.09	2491.9	43.38		
L	3.18	8.94	2574.4	45.58		
L	3.18	8.97	2550.1	45.02		
L	3.18	7.39	2276.0	48.75		
L	3.18	5.49	1316.7	37.99		
M	0.00	5.08	1031.0	31.96	1268.8	20.0
M	0.00	5.59	946.6	26.68	1395.2	22.0
M	0.00	5.08	953.2	29.55	751.2	11.9
M	3.97	4.83	1084.9	35.40	1232.9	19.4
M	3.97	5.33	1101.5	32.52	783.1	12.3
M	3.97	5.08	1052.0	32.61	840.8	13.3