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Theoretical and experimental study on laterally loaded nailed bamboo connection

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ABSTRACT

The aim of the study was to create and verify a theoretical model for single-shear steel to bamboo nailed connections in natural bamboo. To this end, existing timber strength and fracture theories were used to model the brittle and ductile failure strength of the studied bamboo connection. Experimental tests of steel to bamboo nailed connection subjected to short-term loading in single shear parallel to fibre direction in Moso bamboo confirmed the suitability of the timber models to predict the connection behaviour. The findings constitute a basis for development of theory for screws, which is the advocated connector type by the authors. It is anticipated that the predictability of bamboo dowelled connection behaviour, along with the latest developments in bamboo design standardization, will enhance the designers confidence to implement dowelled bamboo connections in practice.

1. Introduction

Bamboo has been used as a construction material for centuries, and it is estimated that currently one billion people live in bamboo dwellings [1], which is testament to its abundance and versatility. In the context of the climate emergency, bamboo offers an attractive alternative to carbon intensive construction materials due to its smaller embodied carbon in terms of functional units, and its potential to act as a carbon sink [2,3].

Bamboo has very strong fibres, resulting in a relatively high longitudinal strength and stiffness properties. However, properties reliant on the matrix surrounding the fibres (shear and perpendicular to fibre tension) are much weaker. This makes bamboo very susceptible to longitudinal splitting and also results in the connections governing design. Moreover, the culm (bamboo stem) geometry defined by hollow inside, thin-walled round sections also poses difficulties in joining the culms.

Despite this, several connecting methods have been developed, with single-bolted joints being one of the most popular. The bolted joint provides simple and reliable transmission of forces, is cost-efficient, and provides high construction efficiency [4]. However, bolted joints are more likely to trigger shear failures and provide limited ductility to the connection and are therefore not favourable in seismic design. It is anticipated that a joint consisting of multiple small-diameter dowels, e.g. screws, would be a more favourable option providing higher joint ductility and stiffness.

The design guidance for dowelled connections in bamboo, as for any other structural aspect, is rather limited. The exception to this is the recently published ISO 22156:2021 [5], which arguably is the most comprehensive design code for bamboo. The standard provides equations based on allowable stress design for the principle structural members, as well as for connections. The allowable bearing capacity (Fig. 1a) $F_b$ of a single dowel according to the standard is given in Eq. (1) (using notations adopted in this publication):

$$ F_b = dt_f C_\theta $$

where: $C_\theta = 0.3$ – for dowel engaging single culm wall and $0^\circ < \theta \leq 5^\circ$.

The risk of brittle failure, including row shear (Fig. 1b) and splitting (Fig. 1c), is accounted for with Eqs. (2) and (3), respectively. Splitting is a failure mode that results in a single crack along the fibre direction caused by exceeded tensile strength perpendicular to fibre at the hole edge or at the loaded end, while row shear results in two cracks along the fibre direction due to exceeded shear strength at the hole edges.

$$ F_b \leq 1.6 dt_f $$

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Eqs. (2) and (3) include an additional factor of safety of 1.25.

Eq. (2), although not explicitly stated in the standard, represents the failure of rigid dowels that do not rotate within bamboo wall. For slender connectors, that rotate within the wall, the row shear is expected to be similar to a plug shear failure, where only a part of the wall thickness is effective in resisting stresses under the dowel (Fig. 2). Plug shear failure results in three shear planes (two sides + one bottom) rather than only two side planes in the case of row shear. The terms row shear and plug shear were adopted from literature (e.g. [6]), although other terms also exist, e.g. tear shear out or block shear.

Bamboo modelling is often based on theories developed for timber. A common timber theory of laterally loaded dowelled connections is the European Yield Model (EYM), which has been incorporated into design guidance in Eurocode 5 (EC5) [7] and NDS 2018 [8]. The theory was initially proposed by Johansen [9], who derived the yield shear capacity \( F_y \) through equilibrium of bending moments acting on the fastener and assuming plastic stress distribution along the fastener. The yield strength corresponds to ductile failure, and it is assumed in the EYM that brittle failure is prevented by adequate spacing rules.

The EYM theory distinguishes various failure modes that are a combination of embedment failure and/or dowel bending failure, depending on plate thickness. Connections with thin plates result in failure modes A and B, whereas connections with thick plates in modes C, D and E (Fig. 3). According to ECS, thin plates are defined as of thickness less or equal to half dowel diameter, whereas thick plates have thickness greater than or equal to dowel diameter.

Due to the limited wall depth of bamboo the most likely failure modes are A, C and D. This was verified by comparing the theoretical ECS shear capacity \( F_{ps} \) of modes A – B for thin plate (Eq. (4)) and C – E for thick plate (Eq. (5)). The equations were compared within an assumed
range of embedment strength: 40–90 N/mm², dowel diameter 3–6 mm and wall thickness 6–15 mm, which represent a reasonable range of values for a bamboo dowelled connection. The yield moment \( M_y \) was assumed to be equal to the elastic bending capacity of a round dowel (Eq. (6)) with steel tensile strength \( f_y = 600 \) MPa. The withdrawal capacity \( F_{ax} \) was calculated according to Eq. (7), which was obtained experimentally for \textit{Phyllostachys edulis} (commonly known as Moso) by Harries et al. [10]. The term \( F_{ax}/4 \) in Eqs. (4) and (5) is a so-called rope effect, and according to EC5 for round nails this term should be limited to 15% of the Johansen part of the equation. In EC5 the terms \( f_y \), \( F_{ax} \) and \( M_y \) are characteristic values; however, in this comparison the values are mean, which is more representative when predicting experimental results.

\[
F_c = \min \begin{cases} 
0.4f_ytd & \text{a)} \\
1.15\sqrt{2M_yf_yd} + \frac{F_{ax}}{4} & \text{b)} 
\end{cases}
\]

\[
F_s = \min \begin{cases} 
f_ytd & \text{a)} \\
\sqrt{\left(\frac{4M_y}{f_ytd}\right)^2 - 1} + \frac{F_{ax}}{4} & \text{b)} \\
2.3\sqrt{M_yf_yd} + \frac{F_{ax}}{4} & \text{c)} 
\end{cases}
\]

\[
M_y = f_yd^3/32 \tag{6}
\]

\[
F_{ax} = 30.3f_y^{0.9}d^{1.11} \tag{7}
\]

The result of the comparison (Fig. 4) confirmed that the most likely failure mode for the thin plate is mode A, whereas for thick plate the most likely is mode D, followed by mode C. The modes B and E, which represent failure including bending of the dowel within the wall, are critical for only a small portion of the simulated sample, and may occur when the conditions that \( t \geq 12 \) mm and \( d < 4 \) mm are both met. This implies that, in theory, although bending of the fastener within the wall is unlikely, it can happen when the wall is thick, and the fastener diameter is small.

In terms of brittle failure, several models have been developed for timber. Cabrero et al. [6] compiled a thorough literature study of the existing methods. The authors compared the models with published experimental data and concluded that the best statistically performing models for splitting and row shear failure is the EC5 model (Eq. (8)) and the model presented by Hanhijärvi and Kevarinmäki [11] (Eq. (9)), respectively. The EC5 model is an implicit method, where the splitting is prevented by implementing an effective number of fasteners \( n_{ef} \), which is then multiplied by the shear capacity of a single fastener \( F_s \). This method follows from a study by Jorissen [12], who proposed Eq. (10) to predict the splitting capacity of bolted connections \( F_{spl} \).
Ef = \begin{cases} \frac{a_1}{13d} \text{ (dowels)} \\ n^{\text{nail}} \text{ (nails)} \end{cases} \quad (8)

\[ F_{rs} = 2k_{screw} \frac{\text{Ef}}{n} L t f_s \quad (9) \]

\[ F_{spl} = 2t \frac{G_E d \sin \alpha (b - d \sin \alpha)}{b} \quad (10) \]

Eqs. (9) and (2) predict the row shear capacity (two shear planes). An adaptation of those equations can be found in EC5 Annex A, which accounts for the plug shear failure (three shear planes). The ECS equation comprises a shear and a tensile component, and it accounts for multiple rows of fasteners (Eq. (11a)). For the case of a single row of fasteners, the tensile component \( A_{net,t} \) becomes zero and the equation reduces to Eq. (11b).

\[ F_{ps} = \max \left\{ \frac{1.5A_{net,fs}}{f_s}, 0.7A_{net,fs} \right\} \quad (11a) \]

\[ F_{ps} = 0.7A_{net,fs} \quad (11b) \]

Experimental study of small-diameter connectors (\( d < 6 \text{ mm} \)) in bamboo are sparse. Trujillo and Malkowska [13] investigated embedment strength, stiffness, and withdrawal capacity of screws in Guadua bamboo. Harries et al. [10] investigated withdrawal capacity of screws in Moso, whereas Chen et al. [14] analysed multiple nailed connections in laminated Moso. The only known study on lateral resistance of screwed bamboo connections was carried out by Kou et al. [15]. Understandably, most studies of dowelled connections in natural bamboo focus on bolts, as it is the most common dowel connector type. Fu et al. [16] and Wang and Yang [17] investigated slotted-in bolted joint in Moso. Paraskeva et al. [18] and Pradhan et al. [19] tested a steel to bamboo bolted connection in Kao Jue bamboo. Oka et al. [20] investigated experimentally and analytically the critical end distance in Black bamboo. More recently, Correal et al. [22] developed an analytical model to predict the yield strength of bamboo-to-bamboo dowelled connections filled with cement-mortar.

To this end, this study aimed to create and verify a theoretical model for simple connections in natural bamboo. The analysis focused on single-shear steel to bamboo nailed connection. The authors do not suggest nailed connection as an appropriate connector for bamboo, conversely, nails have been proven to cause splitting. The choice to use nails rather than screws aimed to check the adequacy of the existing theoretical models, which were derived based on a smooth dowel assumption.

2. Theoretical considerations of bamboo dowel connection yield capacity

Various bamboo material properties have been proven to vary across bamboo wall thickness. Dixon and Gibson [23] verified experimentally that density, compression strength, elastic modulus and modulus of rupture of Moso increase radially outwards. The increase is caused by the number of fibres increasing in the direction towards the outer skin (Fig. 5). Although there appears to be no published results on...
embedment strength gradient through the bamboo wall, it could be postulated that, similar to compression strength, the embedment strength increases radially outwards. On this assumption, a theoretical study was carried out to assess the influence of the embedment strength gradient on the connection yield capacity \( F_y \). The embedment yield stress distribution was chosen as \( 0.8f_h \) at the inner wall surface and \( 1.2f_h \) at the outer surface (Fig. 6), which is an approximation of the gradient of axial compression strength as reported by Dixon and Gibson [23].

With the assumed embedment strength gradient through the wall, the approach proposed by Johansen [9] was used to derive the equation for the failure mode A in bamboo. The method is based on the equilibrium of forces and moments acting on the connection, and results in a set of equations from which the shear capacity \( F_y \) can be derived:

\[
\begin{align*}
    l_1 + l_2 + l_3 &= t \\
    A_1 &= A_3 \\
    M_y &= -A_1L_1 + A_2L_2 + A_3L_3 \\
    F_y &= A_3d
\end{align*}
\]

(12)

where: \( l_1 - l_3 \) are lengths as marked in Fig. 7, \( A_1 - A_3 \) represent the embedment strength \( f_h(x) \) acting over the length \( l \), e.g. \( A_1 = f_h(x)l_1 \), (Fig. 7), \( L_1 - L_3 \) are lever arms corresponding to areas \( A_1 - A_3 \) for the moment calculation.

The capacity of a dowel in bamboo was derived by solving Eq. (12) for the shear capacity \( F_y \), using the MATLAB equation solver. This resulted in Eq. (13), which is slightly higher than the timber prediction (Eq. (4)).

\[ F_y \approx 0.43fhd \]

(13)

The theoretical increase in capacity increases with further deviation from the mean embedment strength at the wall extremes, i.e. assuming e.g. yield stress \( 0.33f_h \) and \( 1.66f_h \) at the wall extremes result in further increase in the yield capacity of bamboo \( F_y \) with the factor 0.43 increasing to 0.46 (7% increase).

3. Experimental procedure

65 bamboo specimens with a nailed single-shear connection were tested. The sample used was commercially supplied Moso culms. The culms were stored in the Structures Testing Lab of the Queens Building at the University of Bristol in an environment with relative humidity in the range of 18–44% and temperature 21–26 °C, measured with a data logger for 2 weeks preceding the start of testing. The moisture content (MC) of each specimen was measured by oven-drying after the test, and the mean value for the sample was \( 8.9 \pm 0.7\% \). The sample density adjusted to 12% moisture content was \( 551 – 872 \, \text{kg/m}^3 \). The test set-up is shown in Fig. 8.

The tested connection consisted of a 1.5 mm-thick steel plate fixed to the outer bamboo surface with 1 smooth, round steel nail. The plate thickness was selected with an aim to induce failure mode A, where fastener rotates within specimen wall, but it remains straight (does not bend). The fastener penetrated in full through the bamboo wall. The preredilled hole in bamboo matched the nail diameter. It was observed that the nail fitted snug in the hole and no undue force was required to insert it. It could be argued that the hole size could impact the results, especially in terms of the splitting resistance as tangential stresses would be introduced while the nail is inserted into a hole smaller than the nail diameter. This is one of the reasons why nails are not recommended fasteners for bamboo. The impact of the hole size was not investigated, and is therefore a limitation of this study. The summary of the tested configurations is shown in Table 1.

The connection was placed at one end of the bamboo internode. The other end of the internode was fixed to the testing machine with a 5-mm-thick steel plate and 3–5 screws. The specimen was fixed at the bottom with a 12 mm bolt penetrating through the tested connection plate. The displacement was applied to the specimen top through the fixing plate.
that was clamped in the machine. The specimens were obtained through saw-cutting culms to the required length (11–20 cm). Each saw-cut section of the culm accommodated between 4 and 8 consecutive tests. The sample included both split-free specimens as well as those with naturally pre-existing cracks with various depths, including both surface-deep and complete through-thickness splits. The tested connection was located as far as possible from any pre-existing cracks in tangential direction (min 20 mm at either side of the fastener). There were no pre-existing cracks in the longitudinal direction at the fastener location. There was no node at the loaded end. The specimens were hollow inside. The specimen wall thickness was measured at each fastener location after the test, by splitting the specimen with a chisel.

To eliminate the influence of the elastic deformations in the set-up, a set of two linear transducers (LVDT) was used to measure displacement at the bamboo surface and at the tested connection plate. The test was carried out using the Instron universal testing machine with a 25 kN loading cell, and the load was applied in tension (short-term) along the fibre direction at the rate 0.4 mm/min until ultimate failure occurred, i.e., either brittle failure or load dropped to 80% of its maximum value, according to EN 12512 [25].

4. Results and discussion

As anticipated, no bending of the tested fastener or the plate was observed, and all specimens resulted in yield failure mode A, followed by the ultimate failure, which was either plug shear, splitting or bearing failure. The bearing failure was followed by the nail withdrawal. The results are summarized in Table 2.

The failure mode due to exceeded shear strength was plug shear rather than row shear, and it occurred at the smallest end distances. The thickness of the failed section (radial direction) was on average 0.43 t, and the width (tangential direction) was on average 0.9 d (Fig. 9a). With increasing end distance, the failure mode changed to splitting. The split appeared slightly off the hole centre, and the crack was not only present at the loaded end but also extended in the direction of the unloaded end.

Table 2

<table>
<thead>
<tr>
<th>Ultimate failure mode</th>
<th>Number of tests</th>
<th>Ultimate loads ( F_{\text{ult}} ) [kN]</th>
<th>Yield loads ( F_y ) [kN]</th>
<th>( F_{\text{ult}} / F_y )</th>
<th>Ductility ( \mu ) [-]</th>
<th>Stiffness [kN/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug shear</td>
<td>9</td>
<td>1.58 ± 0.27</td>
<td>1.34 ± 0.27</td>
<td>1.21 ± 0.09</td>
<td>1.50 ± 0.78</td>
<td>1.83 ± 0.59</td>
</tr>
<tr>
<td>Splitting</td>
<td>7</td>
<td>2.24 ± 0.12</td>
<td>1.76 ± 0.10</td>
<td>1.28 ± 0.09</td>
<td>1.79 ± 0.79</td>
<td>2.54 ± 0.23</td>
</tr>
<tr>
<td>Bearing</td>
<td>49</td>
<td>1.39 ± 0.44</td>
<td>0.98 ± 0.44</td>
<td>1.41 ± 0.26</td>
<td>1.28 ± 0.67</td>
<td>5.01 ± 4.73</td>
</tr>
</tbody>
</table>

Fig. 8. Test set-up.

Fig. 9. Examples of observed failure modes: a) plug shear, b) splitting, c) bearing.

<table>
<thead>
<tr>
<th>Range of ( t ) [mm]</th>
<th>Number of tests with ( d ) [mm]</th>
<th>Number of tests with ( a_2/d )</th>
<th>Total number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 ≤ ( t ) ≤ 9</td>
<td>3, 3.8, 4.0, 4.5</td>
<td>3, 4, 6</td>
<td>37</td>
</tr>
<tr>
<td>9 &lt; ( t ) ≤ 12</td>
<td></td>
<td>3, 4, 6</td>
<td>14</td>
</tr>
<tr>
<td>12 &lt; ( t ) ≤ 16</td>
<td></td>
<td>3, 4, 6</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>7, 7, 44, 7</td>
<td>13, 13, 23, 13</td>
<td>65</td>
</tr>
</tbody>
</table>
In some tests, the crack appears on the opposite edges of the hole (Fig. 9b). Further increase of the end distance resulted in the bearing failure (Fig. 9c). The load–displacement behaviour varied between the tests. Most commonly, the stiffness was linear up to the bearing failure (yield), after which it decreased until the load–displacement reached plateau (Fig. 10B), or the load dropped abruptly (Fig. 10C). In most tests (39 out of 65) a sudden uptake in load occurred as the nail slipped and started withdrawing (Fig. 10A). The load–displacement plots were grouped into distinctive types (A–F) based on their plot shape (Fig. 10). A representative example for each type and its frequency with regard to a particular failure mode type is shown in Table 3, where it can be noted that each of the three failure mode types can be characterized by various load–displacement shapes. It should be noted that in almost all cases the splitting failure happened after a sudden load uptake (Fig. 10A), which could imply that the nail was hindered from withdrawing at this point. This behaviour could be an effect of a thicker than average wall, with mean wall thickness of 12.3 ± 1.59 mm for the split specimens and 9.3 ± 2.52 mm for the whole sample. The higher thickness is also responsible for higher capacities, as shown in Table 2, where the mean ultimate and yield capacity for the splitting failure is higher than for the plug shear and bearing failure. The yield load was assessed according to ASTM D 5764-97a [26], at 0.05d offset from the initial linear portion of the graph.

<table>
<thead>
<tr>
<th>Load-displacement plot type</th>
<th>Plug shear</th>
<th>Splitting</th>
<th>Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>6*</td>
<td>31</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>–</td>
<td>–</td>
<td>8</td>
</tr>
<tr>
<td>F</td>
<td>–</td>
<td>–</td>
<td>2</td>
</tr>
</tbody>
</table>

*The split occurred just after the nail slippage and load uptake.

In some tests, the crack appears on the opposite edges of the hole (Fig. 9b). Further increase of the end distance resulted in the bearing failure (Fig. 9c).

The load–displacement behaviour varied between the tests. Most commonly, the stiffness was linear up to the bearing failure (yield), after which it decreased until the load–displacement reached plateau (Fig. 10B), or the load dropped abruptly (Fig. 10C). In most tests (39 out of 65) a sudden uptake in load occurred as the nail slipped and started withdrawing (Fig. 10A). The load–displacement plots were grouped into distinctive types (A–F) based on their plot shape (Fig. 10). A representative example for each type and its frequency with regard to a particular failure mode type is shown in Table 3, where it can be noted that each of the three failure mode types can be characterized by various load–displacement shapes. It should be noted that in almost all cases the splitting failure happened after a sudden load uptake (Fig. 10A), which could imply that the nail was hindered from withdrawing at this point. This behaviour could be an effect of a thicker than average wall, with mean wall thickness of 12.3 ± 1.59 mm for the split specimens and 9.3 ± 2.52 mm for the whole sample. The higher thickness is also responsible for higher capacities, as shown in Table 2, where the mean ultimate and yield capacity for the splitting failure is higher than for the plug shear and bearing failure. The yield load was assessed according to ASTM D 5764-97a [26], at 0.05d offset from the initial linear portion of the graph.

Fig. 10. Load-displacement plot types.

Table 3
Frequency of the load–displacement plot types.

<table>
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<th>Load-displacement plot type</th>
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<th>Splitting</th>
<th>Bearing</th>
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<tbody>
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<td>A</td>
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<td>31</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>–</td>
<td>–</td>
<td>8</td>
</tr>
<tr>
<td>F</td>
<td>–</td>
<td>–</td>
<td>2</td>
</tr>
</tbody>
</table>

*The split occurred just after the nail slippage and load uptake.

Fig. 11. Observed and predicted yield load.
4.1. Yield load prediction model

The yield load was predicted with the ISO equation (Eq. (1)), the EYM equation (Eq. (4)) and the revised EYM equation (Eq. (13)). The axial compressive strength in Eq. (1) was assumed 55 MPa following EYM equation (Eq. (4)) and the revised EYM equation (Eq. (13)). The coefficient of determination results for Moso reported by Deng et al. [27]. The embedment strength axial compressive strength in Eq. (1) was assumed 55 MPa following EYM equation (Eq. (4)) and the revised EYM equation (Eq. (13)).

In the current study the sample was expanded with new data to 44 specimens in total. The mean embedment strength was found to be 75.7 ± 16.0 MPa (CoV = 0.21). Multiple linear and non-linear regression analyses were used to derive the equation outputting the highest coefficient of determination $R^2 = 0.82$ (Eq. (14)), which is a statistical measure of how well the observed outcomes are replicated by the model. All strength parameters in Eq. (1), (4) and (13) are mean values, as it was deemed to be more representative to compare means rather than characteristic values. The comparison of the three models is shown in Fig. 11. The ratio of observed to predicted values was 1.88, 0.94 and 0.91 (CoV = 0.23, 0.17 and 0.17), respectively, which indicates that the increase in yield capacity as predicted with the revised EYM equation (Eq. (4)) was not observed in the experimental results, where, contrary to the prediction, the yield capacity was found to be slightly lower than the EYM prediction (Eq. (4)). The ISO model (Eq. (1)) appears to provide a conservative solution, which is expected for such a simplistic model.

These findings may indicate that the fibre volume gradient across the bamboo wall thickness does not affect the connection yield strength, and that the prediction model with uniform embedment stress distribution along the dowel is an appropriate model for bamboo. Therefore, the EYM equation for yield strength prediction in timber is proposed as the prediction model for bamboo (Eq. (4)).

$$f_y = -54.43 - 1.33t - 3.44d^2 + 28.37d + 0.12\rho_{12}$$

(14)

All strength parameters in Eq. (1), (4) and (13) are mean values, as it was deemed to be more representative to compare means rather than characteristic values. The comparison of the three models is shown in Fig. 11. The ratio of observed to predicted values was 1.88, 0.94 and 0.91 (CoV = 0.23, 0.17 and 0.17), respectively, which indicates that the increase in yield capacity as predicted with the revised EYM equation (Eq. (4)) was not observed in the experimental results, where, contrary to the prediction, the yield capacity was found to be slightly lower than the EYM prediction (Eq. (4)). The ISO model (Eq. (1)) appears to provide a conservative solution, which is expected for such a simplistic model.

4.2. Plug shear prediction model

The prediction of the plug shear capacity was made with the EC5 equation (Eq. (11b)) and the ISO equation (Eq. (2)) assuming mean shear strength $f_s = 13.6$ MPa as reported by Deng et al. [27] for 4-year-old and 6-year-old Moso. It should be noted that the ISO prediction if for row shear failure, rather than plug shear and it is therefore not expected to match the observed values. It was however decided to include it in this comparison, to verify its suitability in terms of a safe prediction for slender-fastener connections failing due to shear stress parallel to the fibre. Equation (2) was calculated excluding the safety factor 1.25 for the purpose of the comparison, resulting in Eq. (15):

$$F_s \leq 2\pi f_s$$

(15)

The shear area in Eq. (11b) was calculated as:

$$A_{w,s} = 2\pi a_1 + d a_2$$

(16)

where: $y$ is the thickness of the plug shear failed section (in radial direction), calculated as Eq. (17), according to the formula proposed by Jorissen [12], although not explicitly for plug shear but rather for splitting failure for slender dowels in softwood.

$$y = \left(1 + \frac{C - \frac{t}{t_1}}{t}\right)t_1$$

(17)

where $C = 0.3 \frac{2y}{d}$ is an experimental parameter determined for slender dowels in softwood, $y_1 = F_s / (d f_s)$. For the specimens that failed in plug shear, according to Eq. (17): $y = 0.43t$, which corresponds to the observed values. The results of the comparison are shown in Fig. 12.

As apparent in Fig. 12, the EC5 model (Eq. (11b)) appears to be applicable to bamboo, although the sample was small, and more research is required to confirm it. The ISO model (Eq. (15)), which does not represent the observed failure mode due to the rigid dowel assumption, appears to overestimate the observed capacity with the predicted to observed values ratio of 2.3 ± 0.6, making it an unsafe model for bamboo. It should be therefore stressed that the ISO row shear prediction should not be used for the prediction of the brittle failure due to shear stress in connections with slender fasteners.

4.3. Splitting failure prediction model

Splitting failure resulted in a crack originating either at the hole location or at the loaded end (origin of the crack was not investigated). The crack appearing slightly off the hole centre could be possibly explained by high tangential strain in this location, which was verified by Reynolds et al. [29] in embedment testing on laminated Moso.

The equation on which basis the EYM splitting model was derived

Fig. 12. Observed and predicted plug shear load.
(Eq. (10)) and the ISO equation (Eq. (3)) were used to predict the splitting capacity. The results of the comparison are shown in Fig. 13. Eq. (3) was calculated excluding the safety factor 1.25 for the purpose of the comparison, resulting in Eq. (18):

$$F_b \leq 1.25 \frac{\pi td_f t_{90}}{2(1 - d/D)^2}$$

(18)

The fracture energy $G_f$ was assumed 360 J/m$^2$ according to results reported by Shao et al. [30] on fracture mode I (tensile) energy of Moso. The elastic modulus follows from a study by Dixon et al. [31], who found through empirical analysis that for Moso it can be correlated to density as:

$$E_0 = 0.0296\rho_{4}^{0.65}$$

(19)

Tests on friction between bamboo and steel nail do not appear to have been reported in the literature. Reynolds et al. [29] suggest that the friction coefficient of 0.4, equivalent to $\alpha = 22^\circ$, may be an appropriate value for laminated Moso. Specimen width $b$ in Eq. (10) was assumed equal to the external bamboo diameter. Tensile strength perpendicular to fibre $f_{t,90}$ was assumed 2.4 MPa following from split-pin tests on Moso by Richard et al. [32].

As shown in Fig. 13, it appears that Eq. (10) provides a good estimation of the observed values, whereas the ISO model (Eq. (18)) is over-conservative, although again, the sample was rather small, and more tests would be required to further confirm those findings. Also, Eq. (10) was derived for timber assuming a uniform stress distribution along the section thickness, which is true for bolted connection. Although the equation appears to correlate well for nails in bamboo, its applicability is questionable, since the physical behaviour of nailed connections differs from the assumption of uniform stress distribution under fastener.

4.4. Ultimate failure mode prediction

The ultimate failure mode was found to be a function of end distance $a_3$ (EC5 nomenclature) and wall thickness $t$ (Fig. 14a). With increasing end distance, the failure mode changed from plug shear, through splitting until bearing. As seen in Fig. 14a, at small end distances thicker walls tend to be more prone to plug shear failure, while thin sections exhibit bearing failure. The predicting models for the three ultimate failure modes were combined in Eq. (20) to estimate the critical ultimate capacity. The equations corresponding to plug shear and splitting are based on theoretical models, and therefore are independent of the test results, while the equation for bearing failure is based on the observed

![Fig. 13. Ultimate capacities of tests with splitting failure mode.](image)

![Fig. 14. Ultimate failure mode as function of end distance and wall thickness, a) observed failure, b) predicted failure mode.](image)
ultimate capacity being 40% higher than the observed yield load (Table 2). Therefore, the presented model is not entirely independent of the test results.

The mode corresponding to the lowest predicted capacity (plug shear, splitting or bearing) calculated with Eq. (20) for each test is plotted in Fig. 14b.

\[
F_{\text{pred}} = \min \begin{cases} 
0.7 \lambda \sigma_b f_t \sqrt{\frac{G_f E_d \sin \alpha (b - d \sin \alpha)}{b}} & 
\end{cases}
\] (20)

The prediction confirms the observed lack of plug shear failure for thin sections at small end distance. This observation is further supported by plotting the prediction for bearing and plug shear failure for two assumed end distances as a function of wall thickness (Fig. 15). As apparent in Fig. 15, the ductile failure due to bearing may become critical for thinner sections at lower end distance. This is due to the fact that the end distance affects the predicting equation of the plug shear capacity (shear area increases with increasing end distance), whereas the predicting equation for bearing is independent of the end distance value.

The lowest predicted capacity calculated with Eq. (20) was plotted against the observed capacity in Fig. 16. The model appears to predict the capacity relatively well, with the ratio of observed to predicted values 1.05 ± 0.17 (CoV = 0.17).

![Fig. 15. Predicted capacity comparison for plug shear and bearing ultimate failure at two end distances.](image1)

![Fig. 16. Observed ultimate capacity plotted against predicted ultimate capacity.](image2)

![Fig. 17. a) Ductility corresponding to each ultimate failure mode, b) ductility plotted against \(a_3/d\).](image3)
Although the capacity prediction is relatively good, the predicted type of failure mode was correct only for 33 out of 65 tests (Fig. 14b). However, where it was incorrect, the ratio $a/b$, where $a$ - predicted capacity of the observed failure mode and $b$ - minimum of all three predicted capacities (for the three failure modes) was on average 0.92 ± 0.04 (CoV = 0.04), meaning that the predictions are very similar. This explains why the capacity prediction is relatively good (Fig. 16), but the predicted failure mode for as much as half of the sample differs from the observed. The misprediction occurs mostly for tests where ductile failure was observed but splitting failure was predicted. It may be argued that the equations therefore err on the side of caution.

ISO 22156 [5] requires the ultimate brittle capacity to be at least 25% higher than the critical component of the joint (yield load), which was satisfied for all tests except those with the plug shear failure: $F_{pl}/F_y = 1.21$ (Table 2). All tests that failed in plug shear had the end distance of 3d, therefore it could be argued that brittle failure modes can be avoided if greater end distances are observed.

The standard also requires that the displacement ductility $\mu$ of any brittle failure mode must not be $<1.25$. The ductility was calculated according to EN 12512 [25] as a ratio of the ultimate displacement over the yield displacement, and value of $\mu$ was 1.83 ± 0.59, 2.54 ± 0.23 and 5.01 ± 4.73 for plug shear, splitting and bearing, respectively (Table 2 and Fig. 17a). As expected, ductility appears to increase with increasing end distance adjusted for dowel diameter $a_3/d$ (Fig. 17b). The average $\mu$ values for each ultimate failure mode appear to exceed the ISO 22156 [5] minimum requirements ($\mu > 1.25$), although for the main seismic force resisting system the requirement is $\mu \geq 2.5$.

The connection stiffness was calculated as the slope of the initial linear portion of the load–displacement graph and was found to be in the range 0.6 – 4.74 kN/mm (Table 2), which appears to be substantially lower than values reported for Guadua: 8.59 kN/mm (GoV = 0.51) [13]. This finding is not unexpected since the stiffness obtained from a connection test is expected to be lower due to the additional displacement caused by fastener rotation and deformation in the connection test. The ECS stiffness prediction for timber-to-timber connections (Eq. (21)) appears to overestimate the results found in this study (Fig. 18). According to the ECS, Eq. (21) could be further multiplied by a factor of two for steel to timber joints, making the prediction even more inaccurate for bamboo. The high stiffness prediction could potentially be explained by the fact that the ECS model was derived based on: 1) assumed timber-to-timber failure mode where the fastener bends within both timber members and 2) an empirical formula to estimate displacement at 40% of the maximum load [33]. Those assumptions make the ECS formula too generic and therefore not applicable to bamboo.

$$K_{stiff} = p_{mc}^{1/3}d/23$$ (21)

5. Conclusions

The study provides a fundamental basis to understand the mechanics of laterally loaded dowelled connections in bamboo. It was found that the connection strength can be reliably predicted with existing models for timber. The yield load appears to correlate well with predictions of the European Yield Model, whereas splitting capacity can be modelled with fracture mechanics and plug shear strength with a simple equation contained in the Eurocode 5 [7]. Variations in end distance proved that the ultimate failure mode changes from plug shear through splitting until bearing along with increasing end distance. The key findings from this study are:

1. In order to assess the yield capacity, there is no need to consider the fibre volume gradient, assuming it is homogeneous is adequate.
2. ISO 22156 [5] in general provides equations that err on the side of safety, except for shear, because it assumes row shear will occur (possibly true for larger diameter dowels). However, this failure mode is infrequent, provided a minimum end distance is provided.
3. Brittle ultimate failure modes can be avoided if an end distance of 15d is adopted for small diameter dowels.
4. Yielding occurs prior to other failure modes, with adequate levels of ductility even when the ultimate failure mode was brittle. For connections that failed in bearing of the nail a reserve capacity of 40% was observed.

The findings apply only to Moso within the range of tested parameters. This is a preliminary research into nailed connection, which may be expanded to screws in the future. Driven nails should not be used in bamboo due to the risk of splitting. The reported results are based on mean values and should not be used for the design purposes.

CRediT authorship contribution statement

Dominika Malkowska: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. James Norman: Conceptualization, Methodology, Resources, Writing – review & editing, Funding acquisition. David Trujillo: Conceptualization, Methodology, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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