Determining the Distribution of the Dowel Bearing Strength of *Bambusa bluemana* Connections

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Abstract: Bamboo has long been utilized as a structural element, especially in low-rise structures. However, the dowel bearing strength that is used to connect structural bamboo elements has not been fully established. Studying bamboo connections is significant since it affects the structure's stability. In this study, the dowel bearing strength of a proposed bamboo connection is established through experimental tests (ASTM D5764). The species used in the tests is *Bambusa blumeana* with the following node presence: none, bottom, middle, and top. The dowel (rebar) diameters used are 3/8” and 1/2", which is where the compressive load is applied until ultimate failure is reached. The results show that a top node placement with a 1/2” dowel (rebar) diameter has the highest failure load of 25.1 kN. Furthermore, the maximum loads can be modeled as a lognormal distribution. The findings contribute to a better understanding of the dowel bearing strength of bamboo connections considering different nodal positions and dowel diameters. The paper also proposes a lognormal distribution of the maximum strength.

Keywords: *Bambusa blumeana*; bamboo connections; dowel bearing strength; ASTM D5764

1. INTRODUCTION

Bamboo is known in some parts of the world as “green gold,” as this fast-growing grass plant has been proven to combat land degradation, deforestation, unsustainable resources, and climate change (Bautista et al., 2021). Therefore, according to numerous studies, bamboo, particularly *Bambusa blumeana* (*B. blumeana*), is suggested as a material for construction. *B. bluemana*, known as *Kawayan Tinik*, is the most abundant and accessible bamboo species in the Philippines and is a viable alternative material for constructing cost-effective structures (Salzer et al., 2018). This is further proven in a life cycle assessment (LCA) study, which compares the use of some of the common materials in the construction of single and multi-story buildings, such as bamboo poles, brick, hollow blocks, and engineered bamboo. It was discovered that engineered bamboo construction systems have the lowest environmental impact, while the highest contributor arises from the transport and reinforcing materials (Bautista et al., 2021). Because of its versatility, resilience, and low weight, bamboo has become a popular construction. However, bamboo poles must be connected since bamboo connections play an essential role in a structure’s overall stability by bearing and transmitting load (Kou et al., 2022). Hence, studying its joint performance is linked to a building’s durability, ductility, security, and dependability.

Numerous studies have demonstrated standard methods of joining bamboo culms, such as authentic bamboo connections, the mechanical basis of screwed connections, bolted joints, nail and screw joints, and truss plate joints. It has been found that several failures, such as pullout resistance, were significantly influenced by the screw-in depth and hole diameter, leading to the weakness of joint strength (Hong et al., 2020). Additionally, according to Malkowska et al. (2022), a connection with several dowels, such as screws, is predicted to be a more practical solution, as other connection materials cause shear failures and provide little ductility. This was strengthened by Tang et al. (2019), whose results show that bamboo can be joined by screws with excellent and predictable mechanical properties and utilized as a connection material depending on the screw type, screw diameter, and steel plate thickness. However, more research and testing are needed to fully understand bamboo’s potential due to the complexity of the mechanical properties of bolted joints (Hong et al., 2020).

With that, we can see the lack of assessments on *B. bluemana* connections, specifically testing and analysis of the dowel bearing strength of bamboo connections considering (1) nodal placement and (2) dowel diameter. To address this, the paper aims to determine and analyze the dowel bearing strength of *B. blumeana* connections with rebars by achieving the following objectives:

1. To establish the strength (ultimate load) of *B. blumeana* connections by considering the following:
   a. no node (**N**),
   b. with nodes at the bottom (**B**), middle (**M**), or top (**T**) of the sample,
   c. different dowel (rebar) diameters – 3/8” and 1/2”;

2. To identify the type of failure that occurred during the testing of the proposed connections; and

3. To determine the distribution of the maximum load that the embedded *B. blumeana* connections can withstand based on dowel bearing capacity.

This paper analyzed the results of the study based on the following parameters: (1) the diameters of the rebars, (2) the nodal placements of the *B. blumeana* samples, and (3) the physical properties of the bamboo specimen, namely moisture content and oven-dry density. The temperature, sample size, and loading direction were not included in the study. Furthermore, the testing was conducted using ASTM D5764. Besides testing, ASTM D5764 was also followed to determine the failure of the sample. Additionally, ASTM D2395 was applied to prepare the samples for testing. ISO 22157-1 was also utilized to determine the density and moisture content of the bamboo samples.

2. METHODOLOGY

2.1. Data Collection Method

Testing was conducted following ASTM D5764, specifically the half-hole compression testing portion. The initial step in the data collection process was the preparation of samples, which followed ASTM D2395. See Figure 1 for the setup of the samples. However, instead of a threaded bolt, a rebar was utilized to ensure that the failure only occurred on the bamboo sample itself. A total of 240 samples were prepared following the parameters shown in Table 1.

Figure 1

Samples with the Following Nodal Placements from Left to Right: (1) No node, (2) Bottom node, (3) Middle node, and (4) Top node

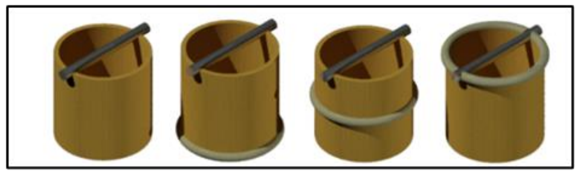


Table 1

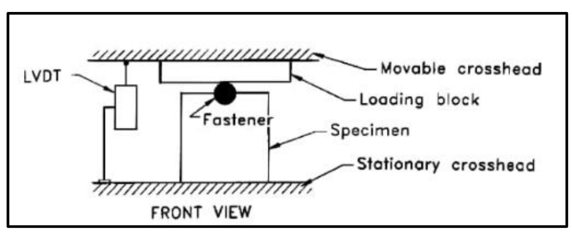
Parameters of B. blumeana connections

Dowel (Rebar) Diameter (in)	Node Placement
3/8	Top
½	Middle
	Bottom
	None

In accordance with ASTM D5764, the samples were subjected to half-hole compression testing using a Universal Testing Machine following the setup shown in Figure 2.

Figure 2

ASTM D5764 Half-hole Specimen Compression Testing Setup



Following ASTM D5764, the tests yielded the (1) maximum load and (2) modes of failure of each sample connection, with the loading kept constant at 2 mm/min. ISO 22157-1 was then followed to obtain the moisture content (ω) and density (ρ) of the bamboo samples. The moisture content and the oven-dry density were determined using Equations 1 and 2, respectively.

$$\omega\ (\%) = \left(\frac{m_i - m_f}{m_f}\right) \times 100 \quad (1)$$

$$\rho = \frac{m_i}{V} \quad (2)$$

where ω is the moisture content represented in %, m_f is the dry weight in g, m_i *is the* wet weight in g, ρ is the density in $\frac{kg}{m^3}$, and V is the volume in m^3.

2.2. Data Analysis Method

Force-Time graphs of each sample were obtained following Table 1. Furthermore, the probability density function of the maximum loads for each sample in a specific category was obtained. The maximum compressive stresses were determined using Equation 3.

$$\sigma = \frac{P}{A} \quad (3)$$

where σ is the compressive strength, P is the compressive force in N, and A is the area in mm^2.

3. RESULTS AND DISCUSSION

3.1. Strength (Ultimate Load) of the Connections

The maximum load each sample can sustain in a specific connection combination was determined and graphed. This was further filtered into samples that could sustain maximum load from all connection categories. The sample that showed the maximum load in each connection category was chosen as the representative sample, and their respective graphs are shown in Figures 3 and 4.

Figure 3

BB-1/2 Representative Samples with the Corresponding Plots: BB-1/2-B-S32 (Blue), BB-1/2-M-S29 (Red), BB-1/2-N-S33-2 (Yellow), BB-1/2-T-S8 (Purple)

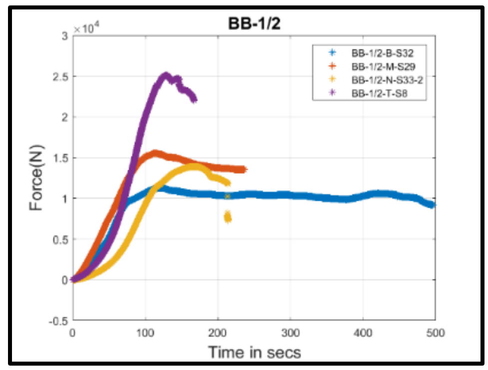
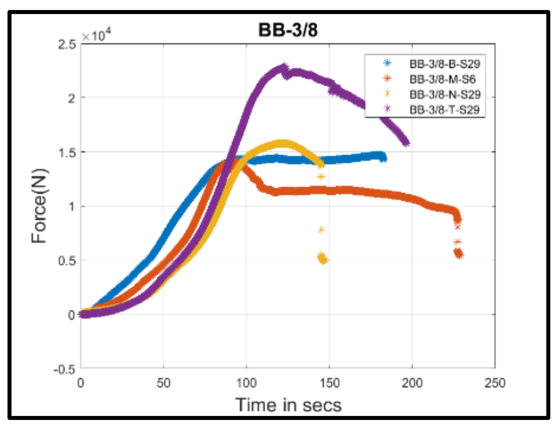


Figure 4

BB-3/8 Representative Samples with the Corresponding Plots: BB-3/8-B-S29 (Blue), BB-3/8-M-S6 (Red), BB-3/8-N-S29 (Yellow), BB-3/8-T-S29 (Purple)



The representative force-time graphs of each dowel (rebar) diameter have similar plots to those of load-deformation graphs presented by Milch et al. (2017) and Chaowana et al. (2021). The load-deformation graphs of Milch et al. (2017) were generated based on the testing of Norway Spruce with different dowel diameters (see Figure 5). Meanwhile, the load-deformation graphs generated by Chaowana et al. (2021) utilized results from the compressive testing of the top, middle, and bottom portions of five bamboo species: *Dendrocalamus asper*, *Dendrocalamus sericeus*, *Dendrocalamus membranaceus*, *Thyrsostachys oliveri*, and *Phyllostachys makinoi* (see Figure 6). Both studies display similar behavior in each part of the plot. The first being the initial non-linear deformation in the form of an exponential curve, then (2) the linear load-deformation, and lastly, (3) the non-linear and ductile load-deformation leading to failure as a logarithmic curve (Chaowana et al., 2021). The same behavior can be observed in Figures 4 and 5. Furthermore, the graphs presented by Milch et al. (2017) showed an increase in the maximum load the sample could withstand as the dowel diameter increased. Similarly, it is evident that the samples with a top node or a middle node and a 1/2" dowel (rebar) diameter resisted a larger force (see Figures 4 and 5). Additionally, the similarity between the force-time graphs and the load-deformation graphs by Milch et al. (2017) and Chaowana et al. (2021) can be attributed to the loading rate being consistently held at 2 mm/min.

Figure 5

Milch et al.'s (2017) Load-slip Curves per Dowel Diameter

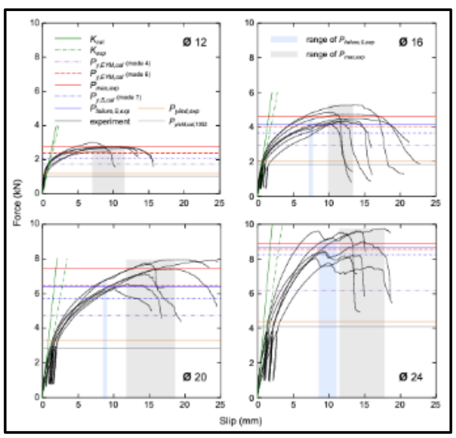
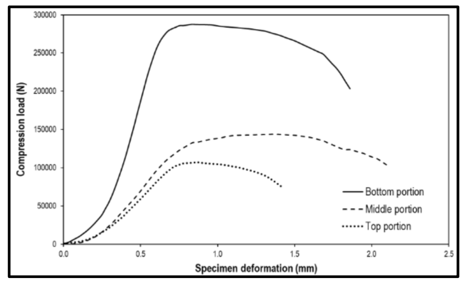


Figure 6

Chaowana et al.'s (2021) Load-deformation Curve of All Bamboo Specimens from the Top, Middle, and Bottom Portion of the Culm



Overall, the bamboo sample with the top nodal placement and a 1/2" dowel (rebar) diameter withstood the largest maximum load compared to all the other samples. This was exemplified by ½-T-S8, which withstood a maximum force of 25.1 kN. However, the result does not agree with Chaowana et al. (2021) that the bottom of a bamboo culm will resist the greatest ultimate load due to "having a bigger culm diameter and thicker culm wall," thus a greater cross-sectional area. Yet, according to Salzer et al. (2018) and Javadian et al. (2019), the top part of a bamboo culm is naturally the strongest due to the increase in fiber densities towards the top of a bamboo culm. Therefore, bamboo samples with a top nodal placement combined with a 1/2" dowel diameter dowel or rebar are the strongest among the connections tested. Furthermore, the ultimate load withstood by the bamboo samples is comparable to the compressive strengths of timber species, which range from 30 to 60 MPa (Harte, 2009, p. 4). This further supports that *B. blumeana*, with a top nodal placement and a dowel diameter of 1/2", shows good potential as a connection material.

3.2. Types of Failure

In testing the *B. blumeana* samples utilizing the ASTM D5764 testing protocol, failure can be observed in the load-deformation curve graph (see Figures 3 and 4). As each sample reached its maximum force, the curve reached its highest point and declined sharply. This indicates that the bamboo connection had already cracked or split and had received enough force it could tolerate.

The mode of failure observed at the highest maximum force of each *B. blumeana* sample was shear failure—specifically bamboo dowel-bearing failure.

Additionally, the types of shear failure identified were (1) splitting failure and (2) bearing failure (see Figure 7). These findings were consistent with those of previous studies, as seen in the works of Chahrour et al. (2021) and Chaowana et al. (2021).

In this case, the occurrences of failure can be identified by analyzing the force-time graphs depicted in Figures 3 and 4, where a sudden decrease is evident for each sample. To elaborate further, the splitting failure is characterized by a noticeable and abrupt decline in the graph, as exemplified by the curve of ½-N-S33-2. Conversely, the bearing failure is distinguished by a more subtle drop in the curve, as demonstrated by ½-B-S32.

Figure 7

Splitting (left) and Bearing (right) Failure of Bamboo Samples

3.3. Distribution of Maximum Load of *Bambusa blumeana* Connections

This study proposes a lognormal distribution as a model for the maximum strength of bamboo connections, as proven by comparing the normal and lognormal probability plots of each category (see Figures 8 and 9). See Table 2 for the parameters of the lognormal distribution of all samples.

Figure 8

Normal and Lognormal Probability Plot of BB-1/2 (a) B, (b) M, (c) N, and (d) T

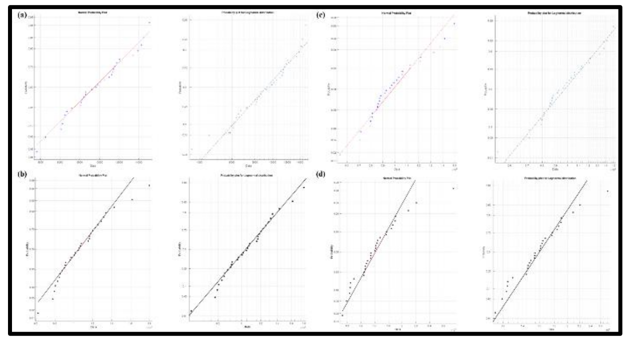


Figure 9

Normal and Lognormal Probability Plot of BB-3/8 (a) B, (b) M, (c) N, and (d) T

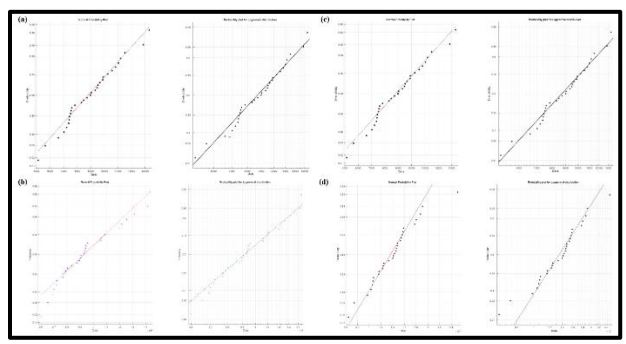


Table 2

Parameters of the Lognormal Distribution

Category	Mean (μ)	Std dev (σ)	Cov (δ)
½-B	9.05	0.27	0.030
½-M	9.13	0.24	0.026
½-N	9.08	0.39	0.043
½-T	9.63	0.28	0.029
⅜-B	9.29	0.26	0.028
⅜-M	9.18	0.25	0.027
⅜-N	9.21	0.38	0.041
⅜-T	9.50	0.31	0.033

4. CONCLUSIONS

The bamboo sample with a top node and a 1/2" dowel (rebar) diameter sustained the maximum load compared to all other samples. This was exemplified by ½-T-S8, which withstood a maximum load of 25.1 kN. On the other hand, the bamboo sample with a bottom node and a 1/2" dowel (rebar) diameter withstood the least maximum load out of all the other samples. This was exemplified by ½-B-S32, with a maximum load of 11.3 kN. Therefore, bamboo with top nodal placements shows good potential as a connection. This is due to the increase in fiber density towards the top of the bamboo culm, thus having the highest resistance to load. However, other connections can also be used, namely connections with a middle nodal placement and 1/2" dowel (rebar) diameter. It was also identified that the samples would either experience a splitting failure or a bearing failure at the highest maximum load. Therefore, these types of failure can be considered once bamboo connections are applied to structures. Moreover, the distribution of the maximum loads was also determined. The maximum loads of all bamboo samples can be modeled after a lognormal distribution.

The findings of this study will contribute to the study of bamboo connections. By understanding the mechanical properties of *B. blumeana* as a connection considering nodal placement and dowel diameters, bamboo connections can be further developed and improved upon.

For future studies, it is recommended to conduct compressive tests of other economically important local bamboo, such as *Bambusa vulgaris*, *Dendrocalamus asper*, and *Bambusa merriliana*. Furthermore, a different set of dowel diameters could also be considered. Through these modifications, a comparison of dowel bearing strengths can be established.

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