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1 FLEXURAL LOAD AND DEFLECTION BEHAVIOR OF STRUCTURAL BAMBOO FILLED WITH CEMENT MORTAR

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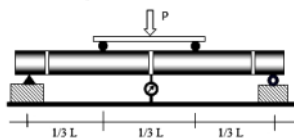
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Graphical abstract



Abstract

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Bamboo has been significantly and rapidly used to build temporal and permanent structures since time immemorial. However, this renewable natural material has a low bearing capacity, limiting its application to structures under light loads. Therefore, this research was carried out to determine an innovative scheme capable of enhancing bamboo's load-bearing by filling the cavity with cement mortar. Furthermore, a study was carried out to experiment flexural load carrying capacity and the deflection of mortar-filled structural bamboo by considering the diameter and node parameters. A total of 12 specimens were examined using a four-point bending protocol. The result showed the ultimate flexural load carrying capacity of mortar-filled bamboo specimens are higher than those of the conventional bamboo specimens. Specifically, mortar filled bamboo specimen with a diameter of 70 mm was significantly better, 41.10 and 47.06%, as compared than the conventional bamboo in terms of its flexural load carrying capacity for specimen without and with nodes, respectively. Increases in flexural load carrying capacity were also observed for the mortar-filled bamboo specimens having 80 and 90 mm diameter and these observed increases were recorded as 104.55 and 112.00%, and 48.72 and 60.74% respectively for specimen without and with nodes. Furthermore, the deflection of mortar-filled bamboo elements are substantially greater than those of conventional. Finally, the advantages of the bamboo diameter and bamboo nodes on the flexural load carrying capacity indicated that these essential findings need to be carefully considered in designing structural elements for both mortar-filled and conventional bamboos.

Keywords: Bamboo, mortar-filled bamboo, node, flexural load, deflection

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1.0 INTRODUCTION

Bamboos are some of the fastest-growing plants worldwide and have been widely used to build permanent and temporary structures since time immemorial. This plant is one of the sustainable materials that serve as an environmentally friendly and competitive alternative to nonrenewable as well as polluting materials, namely concrete and steel with mechanical properties similar to timber [1, 2, 3, 4]. Over the past few years, numerous experimental and analytical studies have been conducted on structural bamboo's mechanical properties [5, 6, 7]. For instance, Gotttron et al. [8] carried out a research to determine bamboo's creep behavior due to the specimen orientation. They found that bamboos loaded with outer culm-wall in tension (OT) indicated a larger modulus of rupture, as well as a lower residual strength and apparent modulus elasticity than those with outer culm-wall in compression (OC). A research carried out by Moran et al. [9] to determine the distribution of the circumferential elastic modulus through the wall and the associated failure strain and stress, mean effective moduli were found to be 1358.5 MPa, 662 MPa, and 862 MPa for bamboo species of Moso, Tre Gai, and Guadua, respectively.

Also, several studies have been conducted to investigate bamboo as reinforcement in structural concrete [10, 11, 12, 13, 14, 15]. One of such study is carried out by Haryanto et al. [16], who examined the performance of precast segmental bamboo reinforced concrete beams after exposing them to flexural loads. A flexural failure mechanism was indicated by the pattern of crack observed in the control beam. On the contrary, a shear failure mechanism was indicated in the precast segmental bamboo reinforced concrete beams. In comparison with the precast segmental bamboo reinforced concrete beams containing four bolted connections, the same containing six bolted connections demonstrated better performance. Furthermore, an experiment conducted by Haryanto et al. [17] with bamboo used as the reinforcing material in the slab specimen for the utilization of footplate foundations showed that compared to steel reinforced concrete (SRC) slabs, strength of 82% can be acquired by the bamboo reinforced concrete (BRC) slabs. Furthermore, ductility and stiffness demonstrated by the two types of specimens investigated were almost equivalent, with percentages of 93 and 72%, respectively.

In addition, varieties of investigation have been carried out in recent years to improve the reinforced concrete structures using bamboo as the strengthening material [18, 19, 20]. Haryanto et al. [21] stated that the flexural strength of reinforced concrete beam with near-surface mounted (NSM) bamboo reinforcement increased by 41.7%, while the deflection ductility index reduced by 21.55% when compared to the control specimen. Furthermore, the research carried out on the finite element analysis (FEA) was similar to the experimental test. Hidayat et al. [22] also

conducted a nonlinear finite element analysis to evaluate concrete beams flexurally strengthened using bamboo and concluded that the load-carrying capacity improved due to the placement of bamboo plates.

In accordance with the above studies, bamboo is defined as an attractive and widely used material that is an alternate to steel because of the high tensile strength, that range between 100 MPa to 400 MPa [23]. In addition, some bamboo, have similar tensile strength to mild steel strength. However, bamboos compressive strength in the cylindrical section is lower than the tensile, which ranges between 12–65 MPa [24, 25, 26]. According to Li et al. [23], bamboo's low comprehensive strength, tends to limit its applications only to light load structures, namely low-rise houses, short footbridges, scaffolds, and roof structures.

Numerous studies have been conducted on structural bamboo's mechanical properties, and bamboo as reinforcement and strengthening materials in concrete members. However, little or no research has been carried out to improve conventional structural bamboo's load-carrying capacity in flexure. Therefore, this research improved the flexural capacity of bamboo, using an effective and easy scheme. The flexural capacity of structural bamboo was enhanced by filling cement mortar in the material's cavity. Hence, this exploratory research is used to verify the feasibility of the proposed scheme as well as the experimental behavior of structural bamboo, which is filled with cement mortar that is under flexural load.

2.0 EXPERIMENTAL PROGRAM

2.1 Test Specimen

A total of 12 specimens, comprising of 3 cement mortar-filled bamboo elements with nodes, 3 cement mortar-filled bamboo elements without nodes, and 6 conventional bamboo with and without nodes, with a nominal diameter of 70, 80, and 90 mm, were tested under four-point bending loading. The specimens' details are shown in Figure 1, while the properties are listed shown in Table 1.

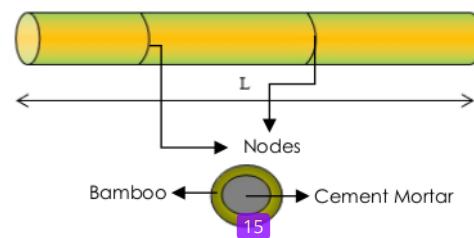


Figure 1 Details of test specimens

Table 1 Properties of specimens

Specimen	L (mm)	D (mm)	Material infilled	Node
SB-01	1350	70	-	without
SB-02	1350	70	-	with
SB-03	1350	70	Cement mortar	without
SB-04	1350	70	Cement mortar	with
SB-05	1350	80	-	without
SB-06	1350	80	-	with
SB-07	1350	80	Cement mortar	without
SB-08	1350	80	Cement mortar	with
SB-09	1350	90	-	without
SB-10	1350	90	-	with
SB-11	1350	90	Cement mortar	without
SB-12	1350	90	Cement mortar	with

The structural material used in this study is Java Black bamboo, also known as *Gigantochloa atroviolacea*, due to its suitability and use in furniture and interior artifacts [27]. In addition, cement mortar was selected as the infilled material due to its ability to be used as construction materials that is compressible and compatible with bamboo [23]. The bamboo diameter and nodes are key components that influences the flexural load of structural bamboo filled with cement. Therefore, this study also examined the attributes of the bamboo's nodes and diameter.

Table 1 shows that the total span of each test specimen (L) was 1350 mm, which are classified into three groups in accordance with the external diameters (D). These groups are as follows: specimens SB-01–SB-04, SB-05–SB-08, and SB-09–SB-12, with external diameters of 70, 80, and 90 mm. Furthermore, the bamboos used for the test were carefully picked from the 3 year old Java Black bamboo stems, which are 4 m in length and about 50–100 mm in wall thickness, in order to ensure the specimens have the right dimensions. All the bamboo culms utilized in this research were dried for 3 months to obtain a moisture content that is below 10%.



(a) Drilling a hole



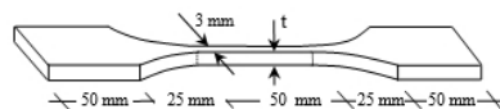
(b) Pouring cement mortar

Figure 2 Casting process

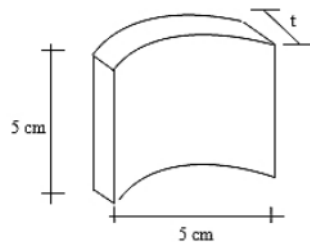
Specimens SB-02, SB-04, SB-06, SB-08, SB-10, and SB-12 were arranged with five bamboo nodes while others were without the nodes. For those with nodes, the traversal diaphragm was drilled to make a hole before casting cement mortar into the cavity, as shown in Figure 2. Furthermore, the cement mortar specimens were cured by covering their surfaces with wet gunny bags and tested after 28 days.

2.2 Material Properties

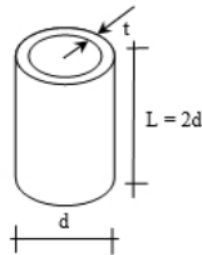
According to Ghavami [10], García *et al.* [2], Sharma *et al.* [5], Lee *et al.* [6], and Moran *et al.* [9], bamboo is a material with high and low strength in the parallel and perpendicular direction to the fibers, respectively. Furthermore, bamboo's compressive strength in the cylindrical section is lower than the tensile strength [24, 25, 26]. Therefore, the preliminary tests of bamboo material in this research were conducted to determine the physical properties such as the moisture content (MC) and specific density (SD), and the mechanical properties such as compressive strength, tensile strength, shear strength, and flexural strength. Since there is a lack of standardization of culm bamboo material as a construction material due to large number of bamboo species and geometry, this study refers to ISO 3129-1975 [28], the wood international standard for sampling method requirement of physical and mechanical testing by used small specimens. The specimens used are depicted in Figure 3.



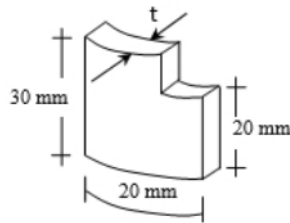
(a) Tensile strength specimen



(b) Moisture content and specific density specimen



(c) Compressive strength specimen



(d) Shear strength specimen

Figure 3 Detail specimens for material properties of bamboo

By measuring the moisture content of chosen bamboo culms for the development of mortar-filled bamboo specimens, a preliminary estimation of the required time to achieve a certain MC percentage suitable for processing of the raw bamboo and fabrication of the specimens became possible. The average MC of Java Black bamboo in this study was 7.28%. According to Javadina *et al.* [29], the average MC used for processing the bamboo needs to be less than 10% in order to reduce excessive delamination as well as long-term environmental negative impacts due to the degradation of the final composite product.

The average SD for Java Black bamboo used for this study was 0.572. Generally, bamboo culms have higher fiber density at top parts where the fibers are closely packed as has been shown by other studies on microstructure of bamboo culm of different species [30, 31]. As a result, the SD will be lower in the bottom parts where the culm diameter and wall thickness are much greater compared to the middle and top parts. In addition, the tensile strength and modulus of elasticity results in the tension tests of the Java Black bamboo samples along the fiber direction were 114.27 and 3682.20 MPa, respectively. According to Javadina *et*

al. [29], bamboo's high tensile capacity is significantly influenced by the cellulose fibers.

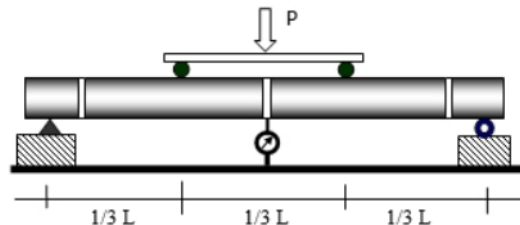
The compression and shear tests results of the Java Black bamboo in this study were 44.65 and 8.50 MPa, respectively. Meanwhile, the flexural and modulus of elasticity results in flexure tests of the Java Black bamboo were 93.29 and 4733.82 MPa, respectively. Cellulose fibers largely contribute to the increase in mechanical properties of bamboo, which is greater than the wall sections' outer layer and above the culms. Javadina *et al.* [29] stated that the Modulus of Rupture (MOR) or flexural strength increases with a rise in fiber and decreases the lignin content in the surroundings. Javadina *et al.* [29] further stated that the effect of the culm on the modulus is similar to MOR, which tends to increase the culm diameter with a decrease in average modulus. This observation is due to the culm sequential microstructure, which increases at the middle and bottom sections of the bamboo. Furthermore, the fiber density tends to decrease due to the high lignin content. Finally, Table 2 summarizes the physical and mechanical properties of Java Black bamboo used in this study in accordance with ASTM D143-94 [32].

Table 2 Physical and mechanical properties

Bamboo Properties	Average Value
Physical Properties	
Moisture content (%)	7.28
Specific density (gr/cm ³)	0.572
Mechanical Properties	
Compressive strength parallel to grain, $f_{c,0}$ (MPa)	44.65
Tensile strength parallel to grain, $f_{t,0}$ (MPa)	114.27
Shear stress parallel to grain, $f_{s,0}$ (MPa)	8.50
Flexural strength (MPa)	93.29
Modulus of elasticity in tensile, E_t (MPa)	3682.20
Modulus of elasticity in flexure, E_f (MPa)	4733.82

2.3 Instrumentation and Testing

Figure 4 shows a dial gauge's installation process placed in the mid-span and both ends of each mortar-filled bamboo specimen in order to monitor the flexural deformation. Furthermore, the specimens were examined under a 10,000 kN Universal Loading Machine and displacement control at a constant rate of 0.1 mm/min to provide the deflection behavior. The tested data were also gathered with a data logger.

**Figure 4** Test setup and instrumentation

3.0 RESULTS AND DISCUSSION

This section thoroughly presents the observed and measured results for the flexural load carrying capacity

and deflection behavior of the specimens due to the effect of infilled cement mortar, bamboo diameter, and bamboo nodes as listed in Table 3.

Table 3 Result of the maximum of flexural load and deflection

Specimen	Load (kN)	Deflection (mm)
SB-01	3.50	17.45
SB-02	4.25	16.80
SB-03	5.00	27.17
SB-04	6.25	15.48
SB-05	5.50	18.20
SB-06	6.25	15.80
SB-07	11.25	37.16
SB-08	13.25	33.32
SB-09	9.75	20.45
SB-10	10.75	18.94
SB-11	14.50	35.12
SB-12	17.25	24.10

3.1 Effect of the Infilled Mortar

Figure 5 shows the mortar's infilled effect on the flexural behavior of the specimens with the flexural load carrying capacity of mortar-filled bamboo was greater than the conventional. Mortar-infilled bamboo element with a 70 mm diameter was significantly better at 42.86 and 47.06%, compared to the conventional in terms of flexural load carrying capacity for specimen without and with nodes, respectively. Furthermore, an increase in flexural load

carrying capacity were observed for the mortar-filled bamboo element with diameters of 80 and 90 mm, and these observed increases were verified as 104.55/112.00%, and 48.72/60.74%, for specimen without and with nodes, as shown in Figure 5. This proves a direct relationship between the mortar-filled and the percentage increase in flexural load carrying capacity with a significant impact on both bamboo without and with nodes. The mortar enhanced the flexural capacity due to the increase in the specimens' moment of inertia.

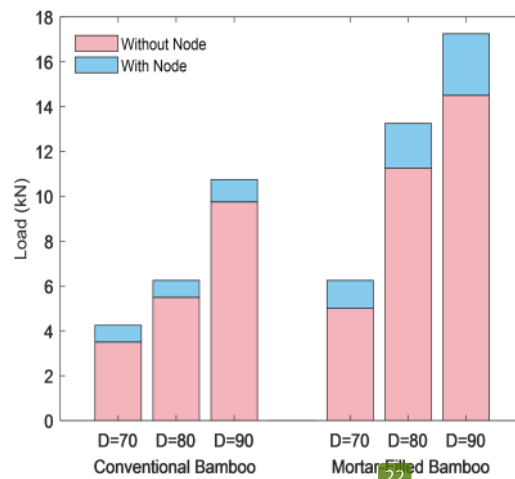


Figure 5 Effect of the infilled mortar on the specimens' flexural load carrying capacity

3.2 Effect of Bamboo Diameter

This study also explored the effect associated with bamboo diameter on the performance of mortar-filled

bamboo elements, as also shown in Figure 5. The figure indicated that the specimen with a 70 mm diameter has the lowest flexural load carrying capacity compared to those with a diameter of 80 and 90 mm.

Figure 5 also confirmed that the increase in the conventional bamboo's flexural load carrying capacity with a diameter of 80 and 90 mm were 57.14 and 178.57%, respectively, in comparison with a diameter of 70 mm. Furthermore, for the specimen with nodes, the increase in the conventional bamboo's flexural load carrying capacity with a diameter of 80 and 90 mm was 47.06 and 152.94% compared to a diameter of 70 mm, respectively. It can be observed from Figure 5 that the increase in the mortar-filled bamboo's flexural load carrying capacity with a diameter of 80 and 90 mm was 125 and 190% for the specimen without nodes, over the specimen with a diameter of 70 mm. In addition, for the specimen with nodes, the increase in the flexural load carrying capacity of the mortar-filled bamboo with a diameter of 80 and 90 mm was 112 and 176% over a diameter of 70 mm. These essential findings need to be taken into account to design the structural elements for conventional bamboo and those filled with cement mortar.

3.3 Effect of Bamboo Nodes

also shown in Figure 5, bamboo nodes' beneficial effect on the flexural load carrying capacity of the specimens can be found in both conventional and mortar-filled bamboo. The flexural load carrying capacity of specimens with nodes were higher than those without nodes. In particular, conventional bamboo element with nodes was meaningfully higher, 21.43, 13.64, and 10.26%, as compared to the conventional bamboo in regards of its flexural load carrying capacity for specimen having diameter of 70, 80, and 90 mm, respectively. Increases in flexural load carrying capacity were indicated for the mortar-infilled bamboo with nodes, and these observed increases

were noted as 25.00, 17.78, and 18.97%, respectively for specimen having diameter of 80, and 90 mm. These results illustrate that the nodes' integrity is imperative for the flexural load carrying capacity both of conventional and mortar-filled bamboo elements.

3.4 Deflection Behavior

Figure 6 shows the deflection value for all specimen types, including conventional and mortar-filled bamboo elements. Furthermore, the figure indicates that the deflection values of mortar-filled bamboo specimens are higher than those of the conventional bamboo specimens. The mortar-filled bamboo element with a 70 mm diameter was significantly greater, by 55.70 and 44.51%, compared to the conventional bamboo in terms of the deflection for specimen without and with nodes, respectively. An increase in the deflection value was also observed for the mortar-filled bamboo element having 80 and 90 mm diameter, which increased by 104.18 and 110.86% and 71.74 and 27.24%, respectively for specimen without and with nodes. Therefore, this indicates a direct relationship between the mortar-filled with a percentage increase in deflection value for both bamboos without and with nodes. Mortar-filled causing enhancement in deflection value, attributed to the fact that the mortar-filled results in a change of the physical form of the specimens that has considerable influence on the total deflection to be expected [33]. Finally, the increase of bamboo diameter that provides additional stiffening enhances the resistance of the specimens to loading, leading to greater deflection in the specimens. Unfortunately, in some cases, the benefit of this stiffening is unpredictable [33].

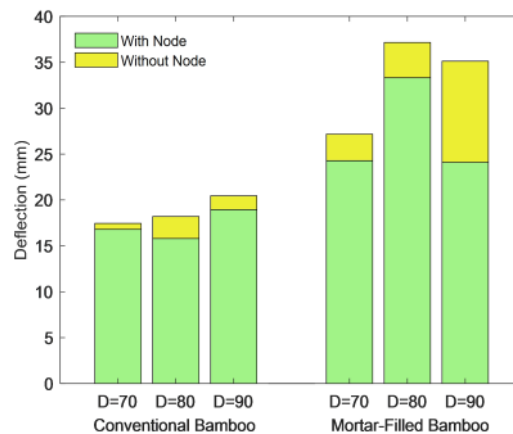


Figure 6 Deflection value

3.5 General Failure Modes

Failure modes in flexural elements are classified into two major types: flexural failure and shear failure. The former occurs when the imposed load exceeds the flexural capacity of the materials of the beam, while the latter occurs due to deficiency in shear resistance between different materials of the beam. In this study, the general failure trend in specimens with nodes present consistently originated from the node scar located at the tension side where the diaphragms were once present. Upon further loading, it initiated a lateral shearing failure while reaching its ultimate flexural load carrying capacity. Comparatively, for the specimens without nodes, the failure mode also showed a transverse failure on the tension side with some lateral shear. Furthermore, after removing the covering bamboo, it was observed that infilled mortar were crushed, showing that the strength of infilled material was fully utilized. The general failure modes of the specimens are illustrated in Figure 7.



(a) Failure due to flexural load



(b) Infilled mortar

Figure 7 General failure modes of the specimens

4.0 CONCLUSIONS

This research examined the flexural performance of structural bamboo filled with cement mortar. The study was carried out by testing a total of 12 specimens under four-point bending protocols to ascertain the aftermath of the infilled materials, bamboo diameter, as well as the nodes on the flexural load carrying capacity and deflection behavior of the specimens. Therefore, the following conclusions were made:

Mortar-infilled bamboo element with a diameter of 70 mm was significantly better, 41.10 and 47.06%, as compared to the conventional bamboo in terms of its flexural load carrying capacity for specimen without and with nodes, respectively. Increases in flexural load carrying capacity were also observed for mortar-infilled bamboo element having 80 and 90 mm diameter by 104.55 and 112.00%, and 48.72 and 60.74%, respectively for specimen without and with nodes. This finding verified the feasibility of the proposed stiffening scheme for conventional structural bamboo. In addition, it is efficient to increase the flexural load carrying capacity by filling cement mortar. The experimental flexural load carrying capacities of conventional and mortar-filled bamboo elements tend to rise with an increase in diameter. Therefore, the bamboo diameter is significant and cannot be ignored. The beneficial effect of the nodes on the flexural load carrying capacity is present in both conventional bamboo and mortar-filled bamboo elements, thereby indicating that the bamboo nodes' integrity is essential for their load carrying capacity. The distance between nodes need to be further considered in the future work.

The deflection of mortar-filled bamboo elements is significantly greater than those of conventional bamboo. This is attributed to the fact that the mortar-infilled bamboos change the physical form of the specimens that influence the total deflection to be expected. Furthermore, the increase of bamboo diameter that provides additional stiffening enhances the resistance of the specimens to loading, leading to greater deflection in the specimens. The load-displacement responses need to be further analyzed in the future study. After removing the covering bamboo, it was observed that infilled mortar were crushed, showing that the strength of infilled material was fully utilized.

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