Effects of Bolt Distance on Flexural Behavior of Bolt-Laminated Bamboo Beam

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***Abstract*—Bolt-laminated bamboo beam was utilized as an alternative to replace wood and it was used as structural and non-structural construction material. Bamboo material then has become the most popular non-wood material in construction field. Nowadays, bamboo material is not optimally utilized yet. Many studies showed the advantages of bamboo to be compared to the other materials. The diameter of *Gigantochloaatroviolacea* bamboo used in this study is ranged from 70 to 90 mm. The diameter of bolt is 12.7 mm. The improvement of strength and bending stiffness of beam can be conducted by arranging the full-culm bamboo with bolt as the shear connector. Variations of bolt distance in this study were 125 mm, 250 mm and 500 mm. The final product of the bamboo jointed segment is bolt-laminated bamboo beam. Setup test for bolt-laminated bamboo bemuses four point bending method. The strength and bending stiffness of bolt-laminated bamboo beam has increased as the bolt distance decreased.The shear connector distance that are greater than 500 mm has no significant affect to the strength and bending stiffness of the beam. Therefore, the distance of bolts is suggested to be less than 500 mm.**

***Index Terms*—Bamboo beam, bolt distance, strength, stiffness.**

I. Introduction

The need of wood in construction sharply increases. Therefore, it is difficult to obtain wood beams with large size and good quality. This problem can be solved by seeking an alternative material to wood substitution. Bamboo has immense opportunities to be used as wood alternative replacement material because it has rapid growth, can be harvested at age of 3-5 years, and has high mechanical properties [1].

Factors that affect the mechanical properties of bamboo are species of bamboo, age of bamboo, condition, moisture content, form and size of the specimens, node or internodes, position along the culm (bottom, middle and top) and testing speed [2].

Currently, the *Gigantochloa atroviolacea*bamboo has been used as a construction material in Yogyakarta, Indonesia, but the influence of mechanical properties, i.e. the species and age, height position, node or internode of the culm,has not been studied in detail [3]. In addition to the high ratio of strength to weight, bamboo also has relatively low cost and fast growth rate. Therefore, it is importat to have the mechanical and physical characteristic of all bamboo species, in order to have a more reliable understanding of their behavior for a better structural design and performance [4].

Regarding the structural design of bamboo building, when the span of structure is relatively long, the more strength and bending stiffness of bamboo materials is needed. The strength and bending stiffness of bamboo material can be improved by combining them vertically and jointed with bolt shear connector. Bolt-laminated bamboo beam is a bamboo structural component, which is arranged horizontally with bolt as its shear connector without void filled material. The horizontal friction between bamboos can be prevented using shear connector, i.e. bolts, with certain distance to achieve the required strength of full-bamboo beam layers. The strength and bending stiffness of bolt-laminated bamboo beam are affected by several factors such as number of bamboo used for the beam, specific gravity, bamboo diameter, bolt diameter and distance between bolts.

Some disadvantages of bamboo are 1) it is a Non-homogeneous material, 2) it has non-prismatic sectional form, 3) the straightness of the culms is not similar, 4) the culm has nodes and it has hollow inner section. Application of bamboo as building material is needed to understand its mechanical properties in order to be optimally utilized. Therefore, there is no surplus either shortage of bamboo [4]. The objective of these researches to determine the influence of bolt distance on strength and bending stiffness of bolt-laminated bamboo beam.

II. Materials and Method

Bamboo type that was used for bolt-laminated bamboo beam in this study was *Gigantochloaatroviolacea* (black bamboo). The culms were taken from the same culm. The bamboo culm was cut at 50 cm above the ground. Each culm was cut for 3.5 mof length. Specimens of moisture content were evaluated using samples in the form of split bamboo [5] and tested at 15% moisture content [6]. The form of specimens of moisture content can be prism look-alike, approximately 25 mm of width, 25 mm of height and the wall thickness of bamboo. In this study, the bolt diameter was 12.7 mm and bamboo diameter was 70-90 mm. This bamboo species has been widely used for many types of engineering construction such as frame, truss and roof system.

Bolt-laminated bamboo beam material was made in two groups, i.e. Layers Double Beam (LDB) and Layers Triple Beam (LTB) as shown in Fig. 1 and Fig. 2. Each group of LDB and LTB beam was made in five models. The first model was the beams with combination of adhesive and bolt with the distance of 125 mm. The second, third and fourth model used bolt with the distance of 125 mm, 250 mm and

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500 mm. The fifth model is beam without shear connector. The first beam model was labeled as LDB.A.125. And LTB. A. 125. The second beam model is labeled as LDB.125. And LTB. 125. The third beam model is labeled as LDB.250. and LTB.250. The fourth beam model is labeled as LDB.500 and LTB.500. The last beam model is labeled as LDB-NS and LTB-NS. Bamboo jointed segment was shaped from full-bamboo culms with bolt as the shear connector without void filler material to make bolt-laminated bamboo beam.

Fig. 1. Specimens of LDB beam.

Fig. 2. Specimens of LTB beam.

The curvature of beam can be determined with Finite Difference Method. Curvature line can be determined by used of Taylor series if the points that traversed a function are known [7]. Finite Difference Method can be applied to determine the curvature of beam using 3 LVDT in Fig. 3.

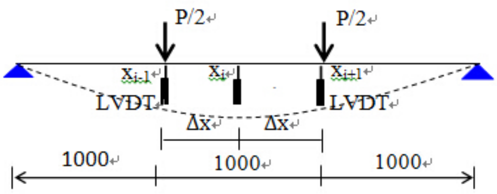

Fig. 3. The curvature of beam.

$$f(x_{i+1}) = f(x_i) + f'(x_i)\frac{\Delta x}{2!} + f''(x_i)\frac{(\Delta x)^2}{2!} + f'''(x_i)\frac{(\Delta x)^3}{3!} + f''''(x_i)\frac{(\Delta x)^4}{4!} \quad (1)$$

$$f(x_{i-1}) = f(x_i) - f'(x_i)\frac{\Delta x}{2!} + f''(x_i)\frac{(\Delta x)^2}{2!} - f'''(x_i)\frac{(\Delta x)^3}{3!} + f''''(x_i)\frac{(\Delta x)^4}{4!} \quad (2)$$

Equation (1) and equation (2) is added to obtain:

$$k = f''(x_i) = \frac{f(x_{i+1}) - 2f(x_i) + f(x_{i-1})}{(\Delta x)^2} \quad (3)$$

Equation (3) is the magnitude of function curvature, and then this equation is presented to determine the magnitude of beam curvature.

Stiffness is the capacity of beam to restrain the change of its form due to an external load. Beam bending stiffness is calculated using moment and beam curvature, as it is shown in equation (4).

$$EI = \frac{M}{K} \quad (4)$$

Dimension of LDB beam specimen is 3000 mm of length and 2 bamboo jointed segments, as shown in Fig. 1, while dimension of the LTB beam specimen is 3000 mm of length and 3 bamboo jointed segments, as shown in Fig. 2. The equipment was used in this study, i.e. hydraulic jack, load cell, LVDT and data logger. Setup test used the configuration of four bending points of LDB and LTB beam in Fig. 4 and Fig. 5. The test of beam is performed by monotonic loading method. Load is performed by load cell using a hydraulic jack. Deflection is conducted using 3 LVDTs on center span and at the load point. The measurement of displacement was conducted step by step, because the capacity of LVDT was limited as 50 mm and displacement of bolt-laminated bamboo beam was larger. Base on of all mechanical properties at bamboo modulus elasticity is small.

Fig. 4. Setup test of LDB beams.

Fig. 5. Setup test of LTB beams.

III. Results and Discussion

There are various results of moisture content teston the specimens, from 12.95% to 16.16% with an average value of 14.59% from 24 bamboo specimens. Base on of requirement BSN standard as building material is moisture content 15% [5].

Fig. 6 shows the relationship between load and deflection of all LDB beam specimens, while Fig. 7 shows the relationship between load and deflection of all LTB beam specimens. Base on of test result on LDB and LTB beam was obtained of maximum beam strength at first model between adhesive and bolt. The strength and bending stiffness of bolt-laminated bamboo beam has increased as the bolt distance decreased. The displacement of bolt-laminated bam bu beam is relatively large, because bamboos have got of modulus elasticity that relatively small between

5000-30000 MPa. If in building structure is needed of material capacity and span length that larger, so that beam is made as bolt-laminated bamboo beam. Beside of shear connector distance is affected of strength and bending stiffness that is bamboo uniqueness. The strength of LDB and LTB beam is showed to increase as bolt distance decreased. The unique behavior of bamboo is larger diameter, so the wall thickness is not necessarily of large. All mechanical properties are varied from bottom to top and bamboo is non-prismatic material.

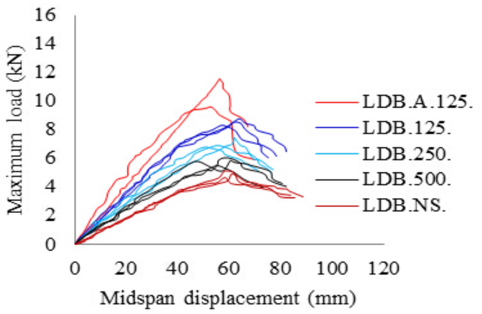

Fig. 6. Load and deflection relationship of LDB beams.

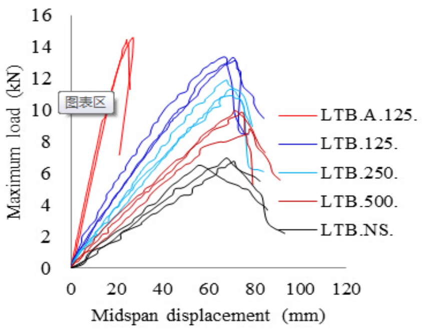

Fig. 7. Load and deflection relationship of LTB beams.

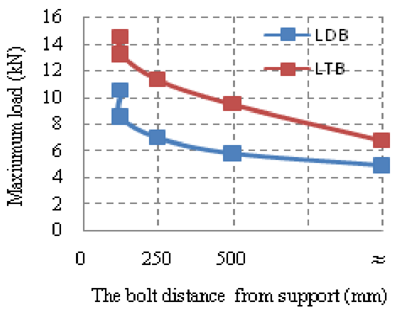

Fig. 8. Comparison of LDB and LTB beam strength.

This research uses28 beam specimens, Layer Double Beam (LDB) has 14 specimens and Layer Triple Beam (LTB) has 14 specimens. Test resultof Layers Double Beam (LDB) is shown in Table I, for strength and bending stiffness of beam, while strength and bending stiffness of Layer Triple Beam (LTB) is shown in Table II. The maximum strength of LDB beam specimens that were evaluated is various, with average value of 11,05 kN, 8.55 kN, 6.90 kN, 6.03 kN and 4,50 kN, while the maximum strength of LTB beam has average value of 14,54 kN, 13.24 kN, 11.38 kN, 10,07 kN and 7,70 kN. The proportional bendingstiffness of LDB beam specimens is various, with average value of 0.600×10^{11} Nmm^2, 0.489×10^{11} Nmm^2, 0.447×10^{11} Nmm^2, 0.388×10^{11} Nmm^2 and 0.274×10^{11} Nmm^2, while the proportional stiffness of LTB beam has average value of 1.482×10^{11} Nmm^2, 1.239×10^{11} Nmm^2, 0.999×10^{11} Nmm^2, 0.874×10^{11} Nmm^2 and 0.773×10^{11} Nmm^2. The strength and bending stiffness of LDB and LTB beam increase as the bolt distance decreases. Comparison of LDB and LTB beam strengths is shown in Fig. 8, while comparison of LDB and LTB beam bending stiffness is shown in Fig. 9.

Factors that affect strength and bending stiffness of bolt-laminated bamboo beam are non-homogeneous bamboo, difference culms straightness, culms contained node and has void inner cross-section. Height position of non-homogeneous bamboo is various with different mechanical properties. The different culm straightness of the beam causes gapon the beam strength decreases. Node was affected by mechanical properties of bamboo as bolt-laminated material. The bamboo is easily split due to the hollow inner section. Beside of bamboo uniqueness and mechanical properties are affected of strength and bending stiffness, i.e. species and age of bamboo, topography, node and inter node, high position (bottom, middle and top), moisture content, shape and size of bolt-laminated bamboo beam. The beam geometry shape is affected of strength and bending stiffness, i.e. specific gravity, number of bamboo component, member jointed shape, bamboo diameters, bamboo wall thickness, bolt diameters and distance as beam parameters.

TABLE I: STRENGTH AND STIFFNESS OF LDB BEAM

Specimens label	Load	Bending Stiffness
	P_{max} (kN)	EI_{pro} (10^{11} Nmm^2)
LDB.A.125.1.	11.50	0.648
LDB.A.125.2.	10.60	0.551
LDB.125.1.	8.32	0.482
LDB.125.2.	8.77	0.495
LDB.125.3.	8.55	0.491
LDB.250.1.	7.27	0.464
LDB.250.2.	6.97	0.444
LDB.250.3.	6.45	0.436
LDB.500.1.	5.90	0.399
LDB.500.2.	6.15	0.365
LDB.500.3.	6.05	0.399
LDB.NS.1.	4.67	0.294
LDB.NS.2.	4.35	0.274
LDB.NS.3.	4.47	0.256

TABLE II: STRENGTH AND STIFFNESS OF LTB BEAM

Specimens label	Load	Bending Stiffness
	P_{max} (kN)	EI_{pro} (10^{11} Nmm^2)
LTB.A.125.1.	14.47	1.446
LTB.A.125.2.	14.60	1.518
LTB.125.1.	13.27	1.167
LTB.125.2.	13.57	1.334
LTB.125.3.	12.87	1.217
LTB.250.1.	11.32	0.951
LTB.250.2.	11.90	1.064
LTB.250.3.	10.92	0,981
LTB.500.1.	9.97	0.881
LTB.500.2.	9.82	0.854
LTB.500.3.	10.42	0.887
LTB.NS.1.	7.41	0.802
LTB.NS.2.	7.72	0.784
LTB.NS.3.	7.96	0.734

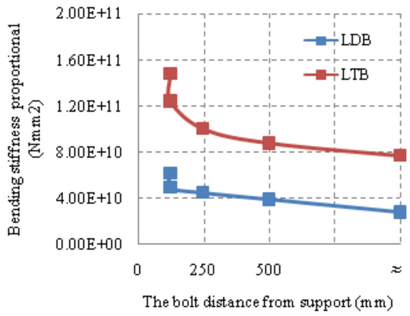

Fig. 9. Comparison of LDB and LTB beam bendingstiffness.

Base on of Tabel I and Table II present a summary of the load at time of the ultimate load that is LDB.A.125 and LTB.A.125. The average results of ultimate strength were showed 11.5 kN and 14.47 kN for LDB.A.125 and LTB.A.125 beam respectively. In general for all the materials ultimate load test results of the test have trend increased as bolt distance decreased. In addation adhesive (LDB.A.125 and LTB.A.125), beams bending strength increased. It is the result of a combination between adhesive and bolt of commulatively increasing the bending strength of the LDB.125 (LTB.125), LDB.250 (LTB.250), LDB.500 (LTB.500), LDB. NS (LTB.NS) at ultimate load. Base on Fig.8 of beam ultimate strength difference is small relatively, so that the distance of bolts is suggested to be less than 500 mm. Base on Fig. 6 and Fig. 7 can be concluded that beam is adhesive addition give advantages can be increased of beam strength and bending stiffness. Comparison ratio between LDB.A.125 beam strength with LDB.125, LDB 250, LDB.500 and LDB.NSbeam strength is 0.77, 0.62, 0.55, 0.41 respectively, while comparison ratio between LTB.A.125 beam strength with LTB.125, LTB.250, LTB.500, LTB.NS beam strength is 0.91, 0.78, 0.69, 0.53 respectively. Base on of comparison ratio between LDB.A.125 beam strength with LDB.125, LDB.250, LDB.500, LDB.NS is showed to decrease as bolt distance increased, while comparison ratio between beam strength with LDB.125, LDB.250, LDB.500, LDB.NS is showed to increase of bolt distance increased. Increasing of beam strength from LDB beam to LTB beam is 131, 58%, 154.85%, 164.93%, 167.00%, 171.11% respectively.

Base on of Table I and Table II show a summary of proportional bending stiffness of LDB.A.125 and LTB.125 beam is conducted of larger bending stiffness value. It is the result of a combination between adhesive and bolt of cumulatively increasing the bending stiffness from beam model as such the LDB.125 (LTB.125), LDB.250 (LTB.250), LDB.500 (LTB.500), LDB.NS (LTB.NS) at proportional bending stiffness. In general Fig. 9 of beam bending stiffness the difference is small relatively, so that the bolt distance is suggested to be less than 500 mm. The beam of LDB.NS and LTB.NS is intended as compored of LDB and LTB beam. Comparison ratio between LDB.A.125 beam strength with LDB.125, LDB 250, LDB.500 and LDB.NS beam strength is 0.82, 0.75, 0.63, 0.45 respectively, while comparison ratio between LTB.A.125 beam strength with LTB.125, LTB.250, LTB.500, LTB.NS beam strength is 0.84, 0.767, 0.59, 0.52 respectively. Base on of comparison ratio between LDB.A.125 beam bending stiffness with LDB.125, LDB.250, LDB.500, LDB.NS is showed to decrease as bolt distance increased, while comparison ratio between beam bending stiffness with LDB.125, LDB.250, LDB.500, LDB.NS is showed to increase of bolt distance increased.Increasing of beam bending stiffness fromLDB beam to LTB beam is 246.67%, 253.06%, 222.22%, 228.95%, 285.18% respectively.

In general, the pattern of failure model of Layer Double Beam (LDB) and Layer Triple Beam(LTB) is shown in Fig. 10 and Fig. 11. The flexural failure model began to occur when the force stress exceeds the compression strength at upper part of bamboo material. The addition of the adhesive dan bolt can be increased of beam strength and bending stiffness. The biggest strength and stiffness beams is obtained on the beam combination of adhesive and distance a bolt at 125 mm.Majority of failure modeloccurs on the upper beam fiber during form split, while the bolt has not experienced a form change(elasticity behavior) showed in Fig. 12. The failure Model of LDB and LTB beam is splitted on upper part and this isbeam compression part.This difference can be showed from compression and tensile strength value diferrenceis 54.68 MPa and 187.34 MPa respectively [4]. The solution of splitted bamboo is made load support coated with rubber.The support shape of circumference is avoided to occur oftwisting at beam test.

Fig. 10. Failure model of LDB beam.

Fig. 11. Failure model of LTB beam.

Fig. 12. Failuremodel of bolt.

IV. Conclusions

A study on flexural behavior of bolt-laminated bamboo beam using LBD and LTB beam test configuration has been conducted. The average strength of LDB beam are 11.05 kN, 8.55 kN, 6,90 kN, 6.03 kN and 4.50kN, while the stiffness proportional of LDB beam are 0.600×10^{11} Nmm^2, 0.489×10^{11} Nmm^2 , 0.447×10^{11} Nmm^2, 0.388×10^{11} Nmm^2 and 0.274×10^{11} Nmm^2. The average strengths of LTB beam are 14.54 kN, 13.24 kN, 11.38 kN, 10,07 kN and 7.70 kN, while the stiffness proportional of LTB beam are 1.482×10^{11} Nmm^2, 1.239×10^{11} Nmm^2, 0.999×10^{11} Nmm^2, 0.874×10^{11} Nmm^2 and 0.773×10^{11} Nmm^2. This study shows that the bolt distance is a combination of adhesive and a 125 mm, 125 mm, 250 mm, 500 mm and non-shear connector.Comparison ratio between LDB.A.125 beam strength with LDB.125, LDB 250, LDB.500 and LDB. NSbeam strength is 0.82, 0.75, 0.63, 0.45 respectively, while comparison ratio between LTB.A.125 beam strength with LTB.125, LTB.250, LTB.500, LTB.NS beam strength is 0.84, 0.767, 0.59, 0.52 respectively. Comparison ratio between LDB.A.125 beam strength with LDB.125, LDB 250, LDB.500 and LDB. NSbeam strength is 0.82, 0.75, 0.63, 0.45 respectively, while comparison ratio between LTB.A.125 beam strength with LTB.125, LTB.250, LTB.500, LTB.NS beam strength is 0.84, 0.767, 0.59, 0.52 respectively.

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