Australian Journal of Basic and Applied Sciences, 8(16) October 2014, Pages: 428-433

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Characteristics of mechanics of box-section beam made of sliced-laminated dendrocalamus asper under bending

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ARTICLE INFO

Article history:
Received 20 August 2014
Received in revised form
19 September 2014
Accepted 23 October 2014
Available online 16 November 2014

Keywords:
flexure, four-point bending, Modulus of elasticity, shear, urea formaldehyde

ABSTRACT

Background: A box-section beam more efficient than a solid cross section due to placing all materials along the periphery. Thus, the box-section beam will provide a greater moment of inertia than the solid cross-section for the same cross-sectional area. On the other hand, research on the box-section beam made of laminated bamboo is limited. For this reason, the study was conducted. **Objective:** The purpose of this study was to characterize the mechanical properties of the box-section beam made of sliced-laminated dendrocalamus asper (Asian bamboo) under bending. **Results:** The results showed that all the beams failure on shear mode with the maximum shear stress occurs in the range 2.86 MPa to 4.85 MPa with an average of 4.06 MPa. Bending stress at proportional limits was 28.60 MPa to 41.32 MPa with a mean 33.42 MPa. MOE of the beams occurs in the range 11,537 MPa to 15,739 MPa with a mean 13,522 MPa. **Conclusion:** Based on average of maximum shear stress and MOE, the box-section beams made of sliced-laminated Dendrocalamus asper had comparable to C35 or D40 strength class as structural timber regulation in Europe.

To Cite This Article: Karyadi, Sri Murni Dewi, Agoes Soehardjono MD., Characteristics of mechanics of box-section beam made of sliced-laminated dendrocalamus asper under bending. ***Aust. J. Basic & Appl. Sci.,*** *8(16): 428-433, 2014*

INTRODUCTION

Wood consumed for building materials in the world reached 1.8 billion m^3 per year. The fulfillment of this requirement causes a pressure on the forestry sector. This situation is one of the causes the forest loss reached 0.71% per year in the range 2000-2010 (FAO, 2010). To reduce the wood usage as a building material, it is necessary to find a substitute material having similar physical, mechanical, and appearance properties. Dendrocalamus asper (Asian bamboo) is a material having specific gravity, MOR, MOE, and compressive strength are 0.55 to 0.90 grams/cm^3 (on 12% moisture content), 198.52 MPa, 15,363 MPa, and 14.39 MPa respectively (Malanit, 2009). Thus, Dendrocalamus asper can be promoted as a building material.

The properties of bamboo-laminated beams have been carried out by previous researchers (Karyadi dan Suwarno (2006); Shan, *et al*. (2008); Xiao, *et al*. (2010); Corel, *et al*. (2010)). These studies only investigated the behavior of solid beam due to bending loads and not yet examine the behavior of the box-section beam.

The box-section beam more efficient than a solid cross section due to placing all materials along the periphery. Thus, the box-section beam will provide a greater moment of inertia than the solid cross-section for the same cross-sectional area (Gere and Timoshenko, 1994). On the other hand, research on the box-section beam made of laminated bamboo is limited. For this reason, the study was conducted.

Bending stress and shear stress in the box-section beam was calculated by following formulas:

Bending stress : $$\sigma = \frac{M}{S}, \quad (1)$$

Shear stress : $$\tau = \frac{VQ}{Ib} \quad (2)$$

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Flexural modulus of elasticity (MOE) for the four-point bending test, as shown in Figure 3, was calculated by a formula,

$$\Delta C = \frac{Pa}{24EI}(3L^2 - 4a^2) \tag{3}$$

In the formulas (1), (2), and (3), M: bending moment, S: modulus of cross-section, V: shear forces, Q: first moment of area, I: moment of inertia, b: appropriated width of cross sections, and E: flexural modulus of elasticity.

MATERIALS AND METHODS

Dendrocalamus asper for this study was taken from Malang, East Java, Indonesia. The culm (3-4 years old) then formed into a rectangular cross-section sliced with 5 mm thickness, 20 mm width, and 3000 mm length. Given the culm wall thickness varied from bottom to top, a sliced with 5 mm of thickness was taken from the part that is closest to the skin. It is expected that the sliced have nearly uniform physical and mechanical properties. The sliced were preserved by soaking it in a mixed solution of tetra sodium borax (Na2B4O2) and boric acid (H3BO3) with a concentration of 1% of each for 24 hours.

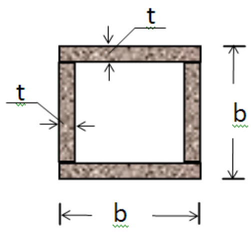

Fig. 1: Box-section beam

Specimens (Figure 1) were made in three variations of cross-sectional width (b), i.e. 80 mm, 120 mm, and 160 mm. The wall thickness of the beam (t) was made in three variations of sizes, i.e. 15 mm, 20 mm, and 25 mm. The spans of beams were set approximately 15 times the width of the cross section (b), with the expectation, the beams to be failure in bending. In order to support beams during testing, 2 x 100 mm of length was added. The dimensions for all beams were shown in Table 1.

Table 1: Dimension of the box-section beam

Designation	Dimension (mm)		Span length (mm)	Total length (mm)	Weight (N/m')
	b	t			
1	2	3	4	5	6
L.8.15	80	15	1180	1380	31.09
L.8.20	80	20	1180	1380	40.66
L.8.25	80	25	1180	1380	44.17
L.12.15	120	15	1800	2000	48.33
L.12.20	120	20	1800	2000	60.94
L.12.25	120	25	1800	2000	80.56
L.16.15	160	15	2480	2680	70.42
L.16.20	160	20	2480	2680	91.25
L.16.25	160	25	2480	2680	114.58

The walls of the beam were made of sliced bamboo that glued to each other as shown on figure 2. Bonding was done with urea formaldehyde adhesives at the application rate 268grams/m^2 and cold-pressed by 2 MPa for 4 hours (Masdar, et al. 2011). The amount of the sliced bamboo glued was adjusted to the size of the beam wall thickness (t) and the width of the beam cross section (b).

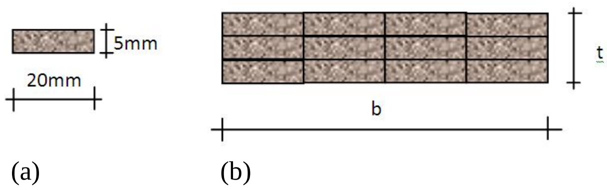

Fig. 2: (a) Sliced bamboo, (b) Laminated bamboo

Four-point bending test was done by referring to the Annual Book of ASTM Standards Volume 4:10: D 198-02: Standard Test Method of Test Statics of Lumber in Structural Sizes, Section 4-11 (ASTM, 2003). Two types of support were needed in this experiment, a pinned and a roller support. The load was generated from a hydraulic jack with a 50 KN capacity, and was read by a load cell 50 KN capacity on a 50 N accuracy. In order to measure the mid span deflection (ΔC) and at the supports (ΔA and ΔB), LVDT with an accuracy of 0.001 mm were used (figure 3).

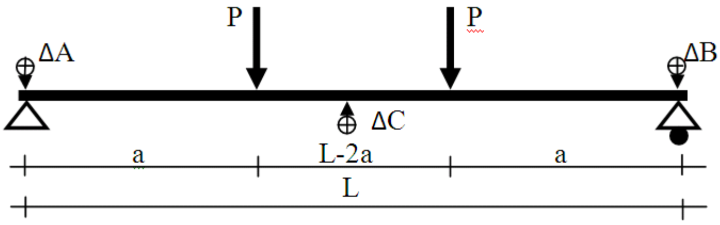

Fig. 3: Four-point bending test setup

The maximum capacity of the box-section beam is defined as the maximum load that causes the beam failure, and characterized by the loss of the ability to receive the load. The maximum stress of a beam was taken as either shear or bending strength depending upon the type of failure mode. Furthermore, bending stress was calculated by the formula (1), the shear stress was calculated by the formula (2), and the flexure modulus of elasticity was calculated by the formula (3).

RESULTS AND DISCUSSION

The main data in this study was the relationship between load and mid span deflection. Loading procedure was performed from zero and was gradually increased until the beam failure. By using the load data can be calculated magnitude of the shear stress and bending stress occur on the beams. While by using the load and mid span deflection data, the analysis was performed to obtain flexure modulus of elasticity.

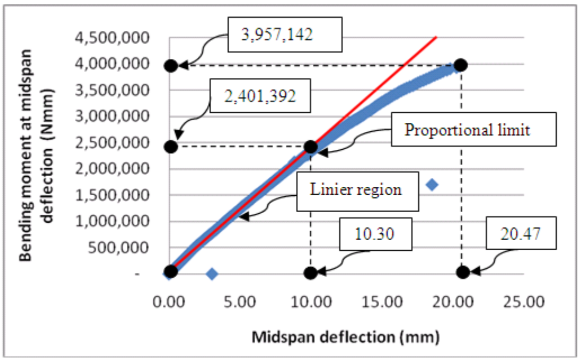

Fig. 4: Relationship between bending moment and mid span deflection for L.8.15 designation

Load and Deflection Relationship:

The results of nine box-section beam testing showed that the relationship between load or bending moment and mid span deflection have similar trends. The trends are linear at small loads and nonlinear at large loads. A point between linear and non-linear region is called the proportional limit. Figure 4 presents a relationship between bending moment and mid span deflection for L.8.15 designation beam.

Table 2: Results

Designation	Max. bending Moment (Nmm)	Mid span deflection at Proportional limit (mm)	Max. mid span deflection (mm)	Bending stress at proportional limit (MPa)	Max. bending stress (MPa)	Shear stress at proportional limit (MPa)	Max. shear stress (MPa)	MOE (MPa)
1	2	3	4	5	6	7	8	9
L.8.15	3,957,142	10.30	20.47	32.84	54.12	2.73	4.50	11,537
L.8.20	5,371,763	10.44	23.98	39.26	67.15	2.83	4.85	12,564
L.8.25	5,638,513	11.11	23.51	41.32	67.41	2.58	4.21	12,410

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L.12.15	8,896,080	12.67	28.80	28.73	45.39	2.49	3.94	11,906
L.12.20	8,337,120	10.65	13.70	30.19	36.08	2.39	2.86	14,586
L.12.25	14,256,080	12.72	24.63	35.41	55.98	2.55	4.04	14,301
L.16.15	18,241,596	14.75	25.51	30.58	47.36	2.65	4.11	13,665
L.16.20	25,634,496	15.55	29.13	33.81	54.93	2.74	4.46	14,986
L.16.25	25,320,996	12.52	22.92	28.60	47.76	2.17	3.62	15,739
Mean				33.42	52.91	2.57	4.06	13,522
Minimum				28.60	36.07	2.17	2.86	11,537
Maximum				41.32	67.41	2.83	4.85	15,739
Standard deviation				4.54	10.16	0.20	0.58	1,480

Shear strength:

All specimens were failed in the shear mode. Thus, the maximum shear stress can be calculated, but not the modulus of rupture (MOR). However, there are important parameters of flexure can be found, these are the bending stress at the proportional limit, mid span deflection at proportional limit, and flexure modulus of elasticity. All these quantities are listed in Table 2.

The maximum shear stress of nine box-section beams have range 2.86 MPa to 4.85 MPa with a mean 4.06 MPa and 0.58 MPa standard deviation. The mean is 38.05**%** lower than the average shear stress for identical beams under torsion (i.e. 6.56 MPa) (Karyadi, *et al*. 2013). Results of research conducted by Riyanto and Gupta (1998) on Douglas-fir wood gives a similar result to this study. The shear stress of Douglas-fir obtained from the four-point bending test was 49.07% lower than the shear stress from torsion test. The mean shear stress of this study is also lower than the results of laminated bamboo shear-block conducted by Manuhua and Loiwatu (2010), i.e. 7.32 MPa. Furthermore, the average of shear stress at the box-section beams made of sliced-laminated Dendrocalamus asper (i.e. 4.06MPa) is equivalent to softwood species C24 to C50 strength classes or hardwood species D24 to D50 strength classes (EN 338, 2009).

Flexure Strength:

Modulus of rupture (MOR) cannot be found from this study because the beams collapse in shear mode. So the calculated maximum bending stress was bending stress at the time of beams failure. But the MOR can be estimated from the bending stress at the proportional limit.

Ahmad and Kamke (2005) examined the parallel strand lumber from Calcutta bamboo (Dendrocalamus strictus) and found that MOR (i.e. 126 MPa) is 188% higher than the bending stress at proportional limit (i.e. 66.9 MPa). Zhou and Bian (2014) examined the parallel strand bamboo and found that MOR is 200% to 300% higher than the bending stress at proportional limit. So, based on 200% to 300% range, the MOR of box-section beams in this study can be estimated at 66.83 MPa to 100.245 MPa.

These are comparison with previous studies. Sulastiningsih and Nurwati (2009) found that the MOR of five layers laminated bamboo board made of Gigantocloa Apus was 46.24 MPa. Manuhua and Loiwatu (2010) examined laminated board made of dendrocalamus asper and obtained the average of MOR was 92.830 MPa. Furthermore, Corel and Ramirez (2010) who tested the glue laminated Guadua Bamboo found the average of MOR was 113 MPa.

Modulus of Elasticity:

Modulus of elasticity (MOE) was occurring in the range of 11,537 MPa to 15,739 MPa with average 13,521 MPa and standard deviation of 1,480 MPa. The MOE was calculated from the linear part of the relationship between load and mid span deflection. It is comparable to the previous studies. Sulastiningsih and Nurwati (2009) examined the laminated bamboo boards and found MOE between 7,410 to 10,229 MPa. Xiao, et al (2010) found the MOE of 10,400 MPa for glue laminated bamboo veneer. Ahmad and Kamke (2005) examined the parallel strand lumber from Calcutta bamboo and found the MOE of 11,700 MPa. Zhou and Bian (2014) examined the sliced laminated bamboo and found the average of MOE is 12,656 MPa. Corel and Ramirez (2010) examined the glue laminated Guadua Bamboo and obtained the MOE is 13,732 MPa. It was compared to the EN 338 (2009), based on MOE, the box-section beams made of sliced-laminated Dendrocalamus asper had comparable to C35 or D40 strength class.

Beam Failure Mode:

The failure of the beams occurs suddenly with loud noise. At the same time, the beam loses the ability to resist the load. Cracks were occurring on the side of the beams in the direction of the longitudinal axis. The positions of the crack were approximately in the middle of beam height. The direction of the cracks was in parallel to bamboo grain which was the weakest part compared to the ability of bamboo to resist shear stress perpendicular to the grain.

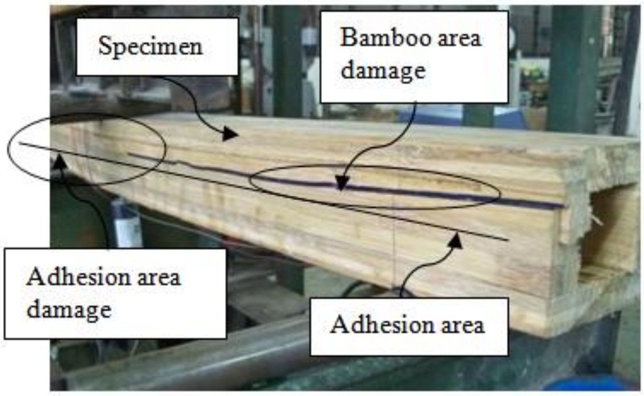

Fig. 5: Pattern of beam damage

Table 3: Percentage of beam damage

Designation	Damage (%)	
	Glue area	Bamboo substrate
L.8.15	0.00	100.00
L.8.20	9.76	90.24
L.8.25	31.70	68.30
L.12.15	17.85	82.15
L.12.20	0.00	100.00
L.12.25	0.00	100.00
L.16.15	40.79	59.21
L.16.20	24.81	75.19
L.16.25	48.76	51.24

Pattern of beam damage showed that the cracks occur in the area of adhesion or and in the bamboo sliced (Figure 5). Table 3 shows the percentage of the failure at both places. The greatest failure in the area of adhesion occurred on beam L.16.25 designation, i.e. 48.76% and the smallest failure on the beams L.8.15, L.12.20 and L.12.25 designation, i.e. 0%. The largest damage in the bamboo sliced occurred in the beams L.8.15, L.12.20, and L.12.25 designation i.e. 100% and the smallest damage occurred in the beam L.16.25 designation, i.e. 51.24%. The average of the beam damaged in the adhesion area was 19.30% and the mean of the beam damage in the bamboo sliced is 80.70%. These averages indicate that the adhesive used was stronger than the bamboo substrate to resist shear forces. Manuhua and Loiwatu (2010) examined the boards of laminated bamboo with a three-point bending and found that the damage in the substrate bamboo was 52.31% to 65.85% and the rest is damage in the gluing area.

Conclusions:

The conclusions below are drawn from this research:

1. The average of the maximum shear stress in the box-section beams made of Dendrocalamus asper was 4.06 MPa. This shear stress was equivalent to softwood species C24 to C50 strength classes or hardwood species D24 to D50 strength classes according to European regulation.
2. The mean of bending stress at proportional limit in the box-section beams made of Dendrocalamus asper was 33.42 MPa.
3. The mean of flexure modulus of elasticity (MOE) in the box-section beams made of Dendrocalamus asper was 13,521 MPa. The MOE had comparable to the wood of C35 or D40 strength classes according to European regulation.
4. Span of the box-section beams less than or equal to 15 times of the width causes failure in the shear mode.
5. The application of urea formaldehyde adhesives at a rate 268grams/m^2 and cold-pressed by 2 MPa for 4 hours gives higher shear strength than ability of the bamboo substrate to resist shear stress.

ACKNOWLEDGMENTS

This article is part of a dissertation of the first author who is studying doctoral program and receiving a scholarship from The Ministry of Education and Culture of The Republic of Indonesia.

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