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Research Article

The Strength of Axially Loaded Square Hollow-Section Column Made of Laminated Asian Bamboo (*Dendrocalamus asper* Becker)

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Abstract: An experimental study on square hollow-section columns with central axial load has been conducted to find the strength of the columns. There were thirty test columns, each of them was formed by laminated Asian bamboo glued by urea formaldehyde of 2.68 N/m^2 and cool compressed for 4 h at 2 MPa. The nominal size of the sectioned column was 80, 120 and 160 mm with the wall's thickness were 15, 20 and 25 mm, respectively. The thirty columns were categorized into 3 groups, namely 9 specimens of short columns, 12 specimens of intermediate columns and 9 specimens of long columns. The results of the study show that all of the short columns experienced failure due to material crushing when the pressure reached 59.08 MPa. The intermediate columns experienced three failures, namely material crushing or inelastic buckling or splitting wall of the columns, while all specimens of long columns experience failure due to elastic buckling. The ratio of the critical load of the test results and the predicted critical load by using Ylinen formula reach 0.76 to 1.45. Such results show that the Ylinen Formula can be used to design the square hollow-section column of laminated Asian bamboo.

Keywords: Asian bamboo, axial, column, lamination, square hollow-section

INTRODUCTION

Bamboo is a kind of plant which has wood-like physical and mechanical characteristics. One type of bamboo is Asian bamboo (*Dendrocalamus asper*) which density, MOR, MOE and compression strength perpendicular to the grain are 0.55 until 0.90 g/cm^3, 198.52, 15.363 and 14.39 MPa, respectively (Malanit, 2009). With such physical and mechanical characteristics, Asian bamboo can be used for building construction.

Various attempts have been performed in order to utilize bamboo as an element for building construction. Xiao *et al.* (2010a), Correal *et al.* (2010) and Sinha *et al.* (2014) have utilized laminated bamboo as beams, while Xiao *et al.* (2010b) and Li *et al.* (2015) have utilized laminated bamboo for columns. Such various studies were performed on the elements of building structures with solid sections.

In order to reduce the amount of the material used, then the element of square hollow-section structure can be a choice since square hollow-section provides a bigger moment of inertia than the solid section for sections with similar size (Gere and Timoshenko, 1994). Research on hollow-section wooden columns has been conducted (Neubauer, 1972; Dyer, 1992; Harries *et al*., 2000). The results of such research show that hollow-section wooden columns are stronger than solid wood columns for sections with similar size. Additionally, Harries *et al.* (2000) also state that the strength of hollow-section wooden column can be predicted by using the formula proposed by Ylinen (1956) as Eq. (1):

$$f_{cr} = \frac{F_c + f_c}{2c} - \sqrt{\left(\frac{F_c + f_c}{2c}\right)^2 - \frac{F_c \cdot f_c}{c}} \tag{1}$$

where,

f_{cr} : The critical stress of the columns
f_c : The critical stress which is determined by using Euler Formula
F_c : The absolute stress
c : Ylinen parameter

Research on hollow-sectioned columns as stated above was performed for wooden materials and there is not a research yet which is performed on bamboo

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Table 1: The length of columns for testing (cm)

Section width (b) (cm)		8.0			12.0			16.0		
Wall thickness (t) (cm)		1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
1	2	3	4	5	6	7	8	9	10	11
Slenderness ratio (λ)	10	27	26	25	43	42	40	60	58	56
	30	82	77	74	130	125	120	179	173	168
	50	136	129	123						
	70	191	181	173						
	90	245	232	222						
	110	300	284	271						

materials. Research on hollow-section element made of laminated bamboo was only performed to the element of the beam (Karyadi *et al*., 2013; Karyadi *et al*., 2014). By referring to the above explanation, this study aimed to identify the strength of square hollow-section columns of laminated Asian bamboo.

MATERIALS AND METHODS

The Asian bamboo for this study was gathered from Malang, East Java, Indonesia and the 3-4 year-old bamboo was selected. The bamboo which had been cut was then formed into rectangular sectioned bamboo laths which were 5 mm thick, 20 mm wide and 100-300 cm length. Because of various thicknesses of the inner part of bamboo walls, then the bamboo laths were made from the outer part of the bamboo walls. Therefore, bamboo laths with uniform physical and mechanical characteristics could be obtained.

Preservation was performed in order to protect the bamboo from powder post beetles and fungi. The preservative used was the combination of tetrasodium borax ($Na_2B_4O_2$) and boric acid (H_3BO_3). Such two materials were dissolved in water with the comparison of 10 N of tetrasodium borax: 10 N of boric acid: 1000 N of drinking water. The bamboo laths were then soaked in such solution for 24 h.

The adhesion process of bamboo laths to be laminated bamboo column was performed after the bamboo laths had less than 12% moisture content. The type of adhesion used was urea formaldehyde with the amount of adhesive spread of 2.68 N/m^2 and was cool compressed of 2 MPa for 4 h.

The specimen of square hollow-section columns (Fig. 1) was made into three variations of section sizes (b) namely 80, 120 and 160 mm, respectively which are likely to be used for building construction. The thickness of beam section wall (t) was made into three variations of sizes, namely 15, 20 and 25 mm, respectively. The slenderness ratio of columns (λ) was made into 6 variations, namely 10, 30, 50, 70, 90 and 110, respectively. The slenderness ratio and the section size would determine the length of the columns as shown in Table 1. The column testing was guided by the Annual Book of ASTM Standards Volume 04.10: D198-02 section 20-27 (ASTM, 2003). Figure 2 shows the setting up of laminated column testing.

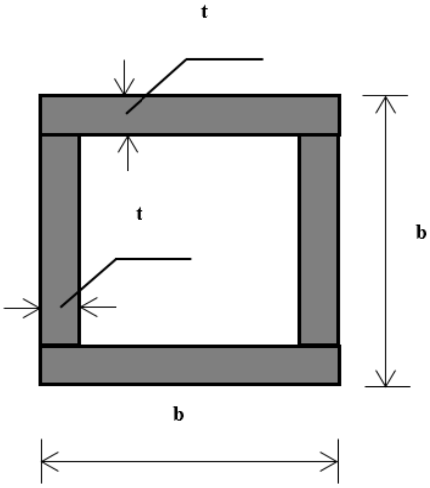


Fig. 1: Section of column of laminated asian bamboo

RESULTS AND DISCUSSION

In general, this study aimed to identify the capability of square hollow-section columns of laminated Asian bamboo in receiving the axial load. Such capability is stated in critical load, i.e., the load which caused the failure of the columns. A test towards 30 column specimens was performed in order to reach such purpose. From such specimens, there are 9 short columns, 12 intermediate columns and 9 long columns.

Tested critical load: Based on slenderness ratio, columns are categorized into 3 types, namely short column, intermediate column and long column. Table 2 represents the compression test results on such three types of columns.

The short columns with the slenderness ratio of 10 were the columns which experienced failure due to the exceeded ultimate stress of the columns which was characterized by material crushing. From the test, it can be identified that columns with the slenderness ratio of 10 reached their ultimate stress in the range of 50.13-66.88 MPa with the average of 59.08 MPa and standard deviation of 5.08 MPa. The average ultimate stress on these short columns is close to the ultimate stress of laminated Asian bamboo resulted from research conducted by Setyo *et al*. (2013) namely of 53.40 Mpa with the standard deviation of 3.39 Mpa. Furthermore, such ultimate stress of short columns was used as a

Table 2: Test results of critical load of columns (kN)

Section width (b) (cm)		8.0			12.0			16.0		
Wall thickness (t) (cm)		1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
1	2	3	4	5	6	7	8	9	10	11
Slenderness (λ)	10	195.50	286.00	316.75	380.00	535.00	640.00	479.00	668.00	884.00
	30	169.50	213.00	271.50	379.00	518.00	542.00	392.00	678.00	837.00
	50	175.00	220.00	265.00						
	70	140.40	163.80	193.05						
	90	131.04	138.06	142.85						
	110	100.62	120.51	122.85						

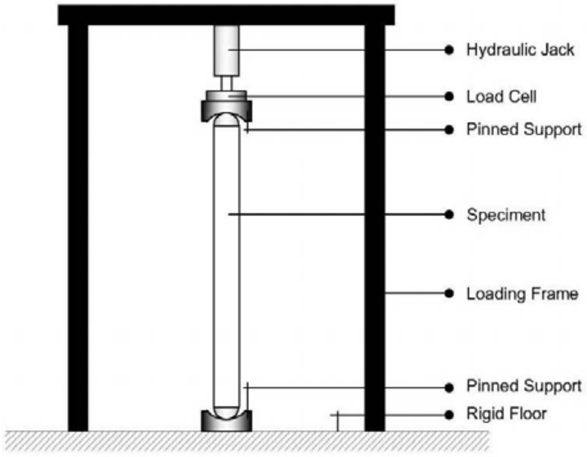


Fig. 2: Setting up of column testing

basis for predicting the critical stresses of the intermediates and long columns.

Predicted critical load: The average of the tested ultimate stress of short columns in this study is 59.08 MPa and the average elastic modulus of the columns gathered from a flexural test conducted by Karyadi *et al.* (2014) is 13,522 MPa, was used as a basis for predicting the critical load of the long and intermediate columns. Moreover, the Yilnen parameter value (c) for these laminated columns was determined to be 0.90. This value is in accordance with the recommendation of American Forest and Paper Association for columns which use glue lamination timber (glulam) (ASCE, 1996). The level of homogeneity of laminated bamboo is similar to the glue-laminated timber (glulam). Therefore their c parameter values are considered as similar.

The prediction of the theoretical load of the columns was made by using Ylinen formula (formula 1). The prediction was made with an assumption that the ends of the columns have non-sway support which was in accordance with the condition during the test. The column length coefficient of such tips of support (K_e) = 1. However, considering the imperfect condition of the support, such K_e value is deviating from such requirement. The K_e value could be determined by using the least square method which creates determination coefficient (R^2). By calculating the R^2 for the K_e value of 0.70 up to 1, the highest R^2 value which was obtained was 0.961481 when the K_e = 0.77. Such K_e value was used as a basis for predicting the strength of the columns' critical load. The prediction results of the theoretical load of columns are presented in Table 3.

In order to identify the deviation value between the critical loads generated from the column test and the prediction results, then the ratio between the tested and predicted critical loads (R_{pp}) was determined. The R_{pp} value = 1 shows that the tested critical load is equal to the predicted critical load. For $R_{pp}>1$ shows that the tested critical load is higher than the predicted critical value and vice versa. Table 4 shows the ratio between the tested critical value and the predicted critical value. From such Table, the ratio was obtained in the range of 0.76-1.45.

The difference between the prediction results and the test results is caused by the variation of the compression strength and elastic modulus of laminated bamboo beams. It has been explained in the previous section that the prediction of critical load performed by using Ylinen formula was made in the average critical stress of 59.08 MPa and the standard deviation of 5.08 Mpa and the elastic modulus of 13,521 MPa and the standard deviation of 1,480 MPa. By assuming that it has normally distributed for both critical stress and elastic modulus, then the critical stress and the elastic modulus would deviate from the average value of fewer than three times of its standard deviation (Burr, 1974). Furthermore, if the lowest compression stress and elastic modulus were used as a basis for predicting the columns' critical load, then the prediction of lowest columns' critical load can be obtained, the same goes for predicting the highest compression stress. The test results on the critical load of the columns are in the area between the lowest prediction and the highest prediction. The graphic of the relationship between the slenderness and critical load (Fig. 3) represents such situation. From the above explanation, it can be concluded that the Ylinen formula can be utilized to predict the critical load of square hollow-section columns of laminated Asian bamboo.

Modes of failed columns: The modes of failed columns referred to the changed shape of the column when it was not strong enough to withstand the load. There are five kinds of column failures in this study, i.e., material crushing, inelastic buckling, splitting, elastic buckling and the combination of splitting and inelastic buckling.

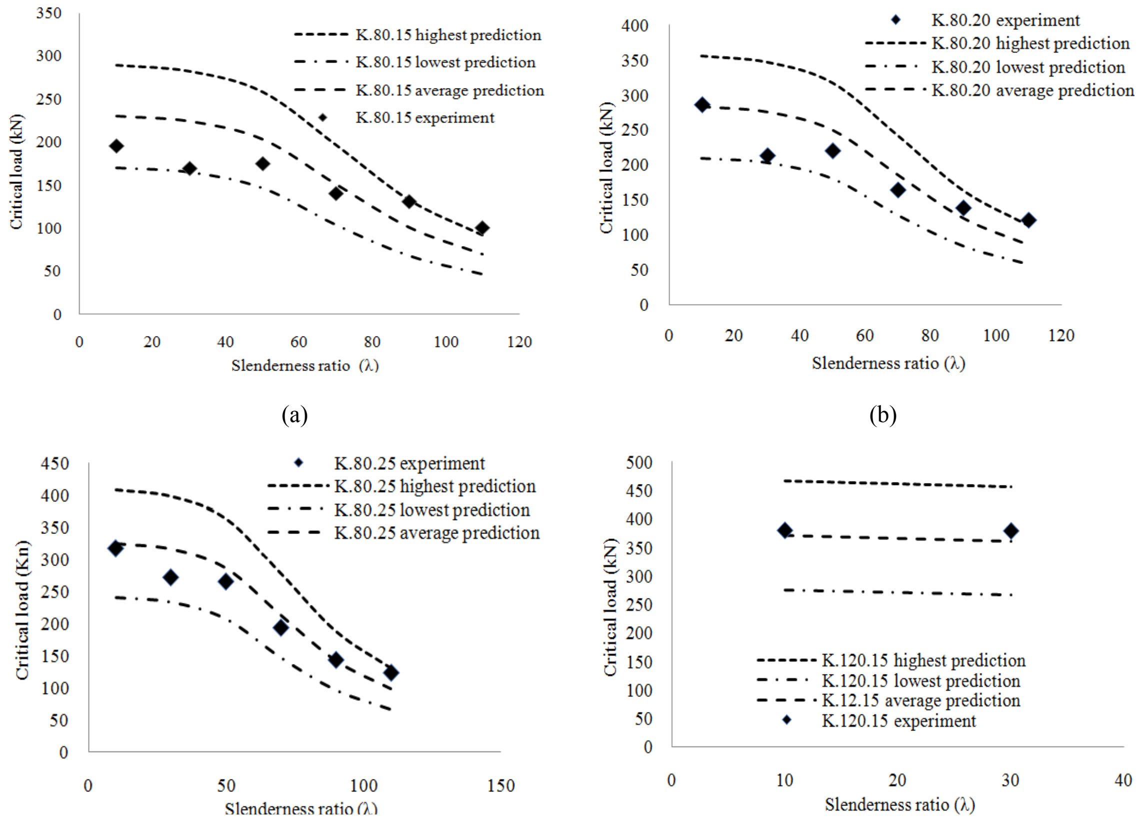
The failure mode of material crushing occurs when the pressure of all parts of the column has reached the ultimate stress. This failure mode is indicated by damages on the weak points of the column without buckling (Fig. 4a). The failure mode of inelastic buckling occurs with buckling and the stress on such parts of the column has exceeded the ultimate stress. This failure mode is indicated by the bends on the column and crushing in the middle area of column (Fig. 4b). The failure mode of splitting is a failure mode which occurs if the walls of the column split to the direction of its longitudinal axis. This failure mode occurs if the shearing stress to the direction of a column's longitudinal axis exceeds the shearing stress which can be endured by the laminated bamboo (Fig. 4c). There are two kinds of splitting failure mode.

Table 3: Predicted critical loads (kN)

Section width (b) (cm)		8.0			12.0			16.0		
Wall thickness (t) (cm)		1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
1	2	3	4	5	6	7	8	9	10	11
Slenderness	10	229.80	282.83	324.08	371.21	471.38	559.77	512.63	659.94	795.46
(λ)	30	223.76	275.40	315.56	361.46	459.00	545.07	499.17	642.60	774.57
	50	202.77	249.56	285.96						
	70	150.78	185.58	212.65						
	90	100.67	123.91	141.98						
	110	69.61	85.67	98.17						

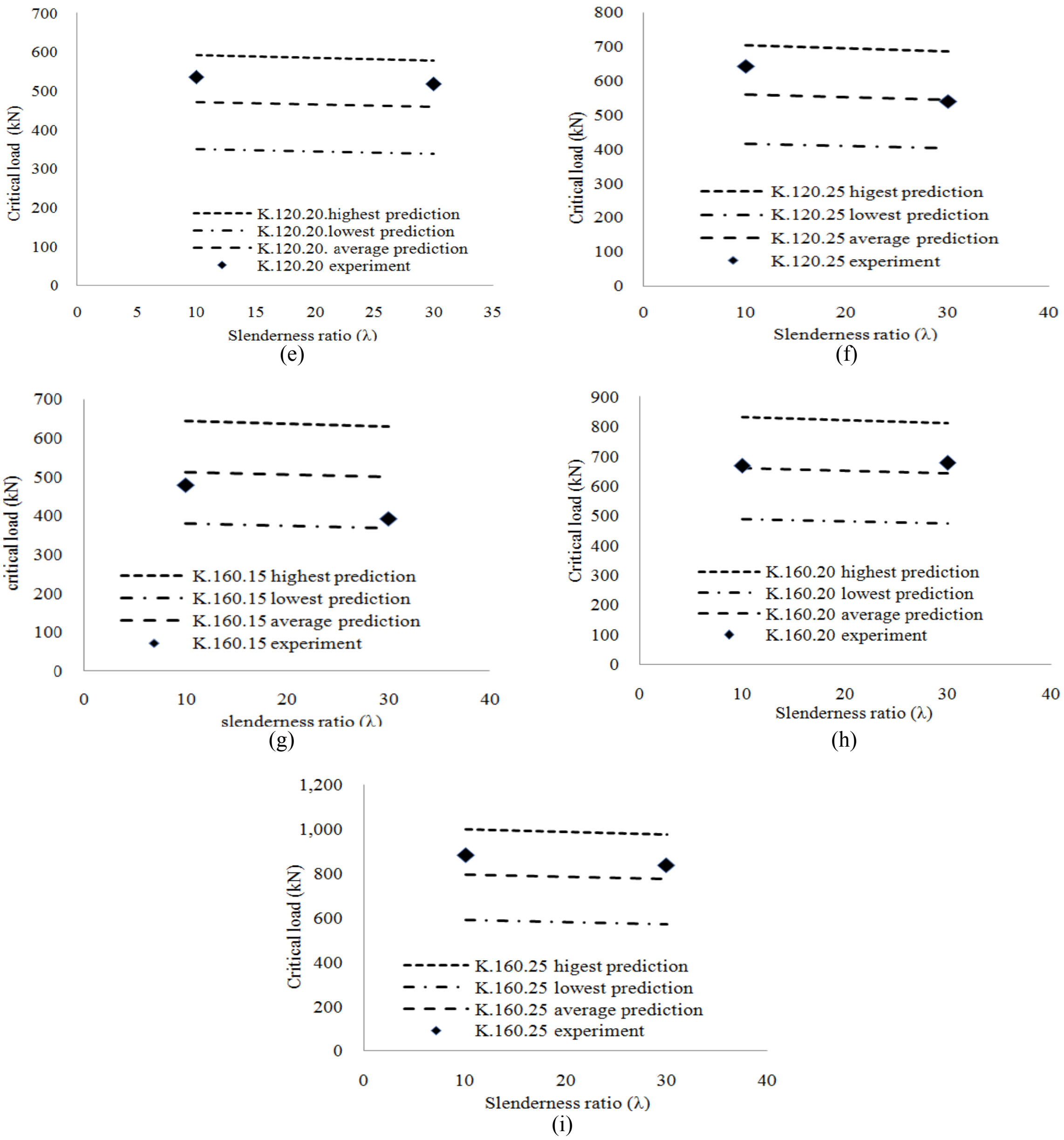
Table 4: Ratio between the tested critical load and predicted critical load

Section width (b) (cm)		8.0			12.0			16.0		
Wall thickness (t) (cm)		1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
1	2	3	4	5	6	7	8	9	10	11
Slenderness	10	0.85	1.01	0.98	1.02	1.13	1.14	0.93	1.01	1.11
(λ)	30	0.76	0.92	0.86	1.05	1.13	0.99	0.79	1.06	1.08
	50	0.86	0.88	0.93						
	70	1.06	0.88	0.94						
	90	1.30	1.11	1.01						
	110	1.45	1.41	1.25						



(a) (b)

(c) (d)



(e) (f) (g) (h) (i)

Fig. 3: Graphic of relationship between columns' slenderness and critical load, K.80.15: Column with b = 8.0 cm and t = 1.5 cm (a) Column with code K.80.15, (b) Column with code K.80.20, (c) Column with code K.80.25, (d) Column with code K.120.15, (e) Column with code K.120.20, (f) Column with code K.120.25, (g) Column with code K.160.15, (h) Column with code K.160.20, (i) Column with code K.160.25

(a) (b) (c) (d)

Fig. 4: Pictures of columns failure modes (a) Material crushing (cr), (b) Inelastic buckling (ib), (c) Splitting (sp), (d) Elastic buckling (eb)

Table 5: Failure modes of columns

Section width (b) (cm)		8.0			12.0			16.0		
Wall thickness (t) (cm)		1.5	2.0	2.5	1.5	2.0	2.5	1.5	2.0	2.5
1	2	3	4	5	6	7	8	9	10	11
Slenderness (λ)	10	cr	cr	cr	cr	cr	cr	cr	cr	cr
	30	ib	cr	ib	cr	cr	sp/ib	sp	sp	sp
	50	sp	ib	ib						
	70	eb	eb	eb						
	90	eb	eb	eb						
	110	eb	eb	eb						

cr: Material cruching; ib: Inelastic buckling; sp: Splitting; eb: Elastic buckling

The first is pure split, which occurs when the parts of the splitting column show an elastic characteristic, namely returning to its straight shape after failure. The second is a combination of splitting and inelastic buckling, namely if the walls of the column does not return to its straight condition after failure. The last failure mode is elastic buckling, namely a failure when the column losses its strength and bent, but it will be immediately straightened up again after the load is removed (Fig. 4d).

The failure modes are closely related with the slenderness of the column. All of the columns with 10 slenderness ratio experienced failure due to material crushing. Columns with 30 and 50 slenderness ratio experienced failure due to material crushing, inelastic buckling, splitting, or a combination of such failure modes. Columns with 70 or more slenderness ratio experienced failure due to elastic buckling. Table 5 presents the tested failure modes of columns. On timber columns, the short columns have slenderness ratio around 0 up to 40, the intermediate columns have slenderness ratio around 40 up to 80 and the long columns have slenderness ratio of more than 80 (NBR 7190-97, 1997).

CONCLUSION

- Based on their slenderness ratio, there are three failure modes of the column, i.e., material crushing occurred on the slenderness ratios of 10, material crushing, inelastic buckling, splitting, or a combination of such failure modes occurred on the slenderness ratios of 30 up to 50 and elastic buckling occurred on the slenderness ratios of 70 up to 110.
- The pressure on material crushing reached 59.08 MPa which are the ultimate stress of laminated Asian bamboo column.
- The ratio between the tested critical load and analyzed critical load gathered by using Ylinen Formula for square hollow-section columns of laminated bamboo is 0.76 up to 1.45.
- The Ylinen Formula can be used to predict the critical load of square hollow-sectioned columns of laminated Asian bamboo.

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REFERENCES

ASCE, 1996. Standards for Load and Resistance Factor Design (LRFD) for Engineering Wood Construction. American Forest and Paper Association, ASCE, New York.

ASTM, 2003. Annual Book of ASTM Standards Volume 04.10: D 198-02 Standard Test Method of Statics Test of Lumber in Structural Sizes. West Conshohocken, PA, USA.

Burr, I.W., 1974. Applied Statistical Method. Academic Press, New York.

Correal, J.F., F. Ramirez, S. Gonzalez and J. Camacho, 2010. Structural behavior of glued laminated guadua bamboo as a construction material. Proceeding of WCTE, Trentino, Italy.

Dyer, V., 1992. Strength and efficiency of wood box columns. J. Struct. Eng-ASCE, 118(3): 716-722.

Gere, J.M. and S.P. Timoshenko, 1994. Mechanic of Material. 3rd Edn., Chapman and Hall, London.

Harries, K.A., M.F. Petrou and G. Brooks, 2000. Structural characterization of built-up timber columns. J. Architect. Eng., 6(2): 58-65.

Karyadi, S.M. Dewi and A. Soehardjono, 2013. Experimental investigation on characteristics of mechanics of box-section beam made of sliced-laminated Dendrocalamus asper under torsion. Int. J. Eng. Res. Appl., 3(4): 1-5.

Karyadi, S.M. Dewi and A. Soehardjono, 2014. A comparison of shear strength of box-section beam made of sliced-laminated Dendrocalamus asper under torsion and transversal load. Proc. Eng., 95: 38-42.

Li, H.T., J.W. Su, Q.S. Zhang, A.J. Deeks and D. Hui, 2015. Mechanical performance of laminated bamboo column under axial compression. Compos. Part B-Eng., 79: 374-382.

Malanit, P., 2009. The suitability of Dendrocalamus asper becker for oriented strand lumber. Ph.D. Thesis for The Degree of Doctor of Natural Science in Department of Biology, Faculty of Mathematics, Information and Natural Science, University of Hamburg.

NBR 7190-97, 1997. Projeto de estruturas de madeira. Associacao Brasileira de Normas Tecnicas. Rio de Janeiro, Brazil.

Neubauer, 1972. Strength of wooden box-column. T. Am. Soc. Civ. Eng., 50(4): 710-713.

Setyo, H.N.I., I. Satyarno, D. Sulistyo and T.A. dan Prayitno, 2013. Kuat Tekan dan Angka Poisson Bambu Petung Laminasi. Prosiding Konferensi Nasional Teknik Sipil 7 (KoNTekS 7) Universitas Sebelas Maret. Surakarta. Indonesia, pp: M97-M103.

Sinha, A., D. Way and S. Mlasko, 2014. Structural performance of glued laminated bamboo beams. J. Struct. Eng., 140(1): 1-8.

Xiao, Y., Q. Zhou and B. Shan, 2010a. Design and construction of modern bamboo bridge. J. Bridge Eng., 15(5): 533-541.

Xiao, Y., G. Chen, B. Shan and L. She, 2010b. Two-by-four house construction using laminated bamboos. Proceeding of WCTE, Trentino, Italy.

Ylinen, A., 1956. A new method of determining the buckling stress and the required cross-sectional area for centrally loaded straight columns in elastic and inelastic range. Int. Assoc, Bridge Struct. Engrg., Zurich, Switzerland, 16(1956): 529-550.