FIXATION PROCESS OF LAMINATED BAMBOO COMPRESSION FROM CURVED CROSS-SECTION SLATS

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FIXATION PROCESS OF LAMINATED BAMBOO COMPRESSION FROM CURVED CROSS-SECTION SLATS. Removing the outer part of bamboo for manufacturing flat bamboo lamination has disadvantage on the density of the product. The purpose of this experiment was to investigate the fixation of compressed bamboo from curved cross-section slats. The compression of bamboo slats using densification technique was aimed for uniform density. Furthermore, steam treatments were conducted to fix the deformation. The compressed bamboo slats revealed that the density of the samples at the bottom parts increased from 0.4–0.56 g/cm^3 to 0.89–1.05 g/cm^3 after pressing with a compression level between 46.98–63.97%, while the samples in the middle parts increased from 0.7–0.83 g/cm^3 to 1.02–1.18 g/cm^3 with the compression level of 32.92–41.5%. These results were slightly higher than that of the upper parts, which was between 0.91–0.98 g/cm^3. The recovery of set decreased and the weight loss increased with increasing temperature and steam treatment time. Fixation of compressive deformation could be achieved at 160°C within 60 minutes. The bottom parts of samples experienced a slightly greater weight loss compared to the middle parts, i.e. 8.38% and 7.49%, respectively. The anatomical structure of bamboo tended to deform during densification process. Furthermore, the steam treatments affected the colour of densified bamboo which became darker. From this experiment, it can be concluded that the manufacture of laminated bamboo from bamboo slats can be uniformed in strength by equalizing the density at the bottom and middle with the upper parts through the densification technique. However, further research should be conducted to know the delamination and shear strength of the bamboo lamination.

Keywords: Laminated bamboo, curved cross-section slats, fixation process, steam treatment

PROSES FIKSASI KOMPRESI BAMBU LAMINASI DARI BILAH BERPENAMPANG LENGKUNG. Penghilangan bagian luar dari bambu pada pembuatan laminasi berbentuk datar mempunyai kelemahan pada kerapatan produknya. Tujuan penelitian ini adalah untuk meneliti fiksasi bambu kompresi dari bilah berpenampang lengkung. Pengepresan bilah bambu dengan teknik densifikasi ditujukan untuk menyeragamkan kerapatannya. Selanjutnya, perlakuan uap panas dilakukan untuk mempertahankan deformasinya. Bilah bambu yang dikompresi tersebut menunjukkan bahwa kerapatan contoh uji di bagian bawah meningkat dari 0,4–0,56 g/cm^3 menjadi 0,89–1,05 g/cm^3 setelah dipres dengan tingkat kompresi antara 46,98–63,97%, sedangkan contoh uji di bagian tengah meningkat dari 0,7–0,83 g/cm^3 hingga 1,02–1,18 g/cm^3 dengan tingkat kompresi antara 32,92–41,5%. Hasil ini sedikit lebih tinggi dari pada di bagian ujung, yaitu antara 0,91–0,98 g/cm^3. Pemulihan ketebalan menurun dan kehilangan berat meningkat dengan meningkatnya suhu dan waktu perlakuan uap panas. Fiksasi dari deformasi tersebut dapat dicapai pada 160°C dalam waktu 60 menit. Contoh uji bagian bawah mengalami kehilangan yang sedikit lebih besar dibandingkan dengan bagian tengah, yaitu masing-masing 8,38% dan 7,49%. Struktur anatomi bambu cenderung berubah bentuk selama proses densifikasi. Selanjutnya, perlakuan uap panas berpengaruh pada warna bambu kompresi yang menjadi lebih gelap. Dari penelitian ini dapat disimpulkan bahwa pembuatan bambu laminasi dari bilah bambu dapat diseragamkan kekuatannya dengan menyamakan kerapatan di bagian bawah dan tengah dengan bagian ujungnya melalui teknik densifikasi. Namun, penelitian selanjutnya perlu dilakukan untuk mengetahui delaminasi dan keteguhan geser dari bambu laminasi tersebut.

Kata kunci: Bambu laminasi, bilah berpenampang lengkung, proses fiksasi, perlakuan uap panas

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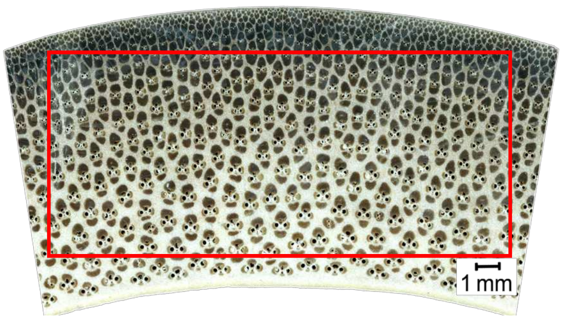
I. INTRODUCTION

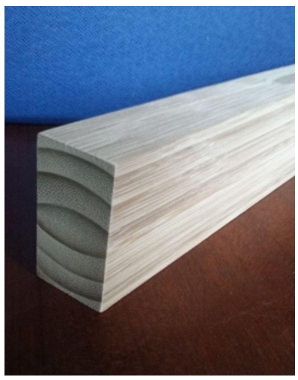
The high rate of population growth in Indonesia undoubtedly leads to increasing housing demand. With the expected high demand for housing, it is necessary to provide adequate raw material. Bamboo can be an alternative raw material to diversify non-timber building materials to substitute wood-based building materials which availability decreases. Bamboo material is abundant and can be obtained easily in almost areas in Indonesia with a total production of more than 20.3 million culms in 2018 (Statistics Indonesia, 2019). It has a short harvesting age of 3–5 years (Hastuti, Primairyani, & Ansori, 2018; Rahmawati, Baharuddin, & Putranto, 2019), and prices are relatively cheaper compared to wood. The strength value of bamboo is equivalent to strength class III of wood, even the strength of the board from processed bamboo products can reach strength class I–II (Li, Zhang, Huang, & Deeks, 2013; Mahdavi, Clouston, & Arwade, 2012; Nugroho & Ando, 2000, 2001; Sulastiningsih & Nurwati, 2009). Based on these considerations, bamboo products' development has strategic value, and it is important to continue to be pursued. However, bamboo morphology is not as solid as wood because it has a cavity in the centre of the bamboo stem. Therefore, the bamboo utilisation needs further treatment, especially for the structural application, for instance, using the lamination technique.

In the laminated bamboo manufacture, bamboo slats are generally made in a flat square shape on each side. However, it has several disadvantages because the bamboo slats' cross-sectional size depends on the bamboo stem's thickness. Cutting into a square shape will be effective only for bamboo species with thick walls (Sulastiningsih & Nurwati, 2009; Sutiyono, 2010). Generally flat cross-section lamination is made by removing the outer part of the bamboo (Figure 1a), which has a higher density than the inner part. However, this method is low in recovery and it is considered as unefficient. The weaknesses in the manufacture of the laminated bamboo can be reduced by utilizing the bamboo slats that still maintain their curved shape. Curved slats will increase the yield of laminated bamboo, usually 7–13% higher than those with square cross-sections (Budiana, Kusmawan, & Rusli, 2014). Besides, the curved cross-section has a better mechanical advantage than the square one due to the cross-section's larger modulus, more resistant to loading and more rigid as reported by Mujiman et al. (2014).

The manufacture of laminated bamboo from curved cross-section bamboo slats has been carried out in preliminary research (Figure 1b). However, the bamboo lamination was not considered among the factors which affected the manufacturing, such as density. This is a major problem because it will result in non-uniform density and strength of laminated bamboo.



(a)



(b)

Figure 1. Bamboo slats with square (a) and curved (b) cross-sections

On the other hand, the density of bamboo increases from the bottom to the upper parts of the stem and from the inner to the outer parts (Rosalita, Nugroho, Subiyanto, & Kusumah, 2009; Yu, Jiang, Hse, & Shupe, 2008). Dwianto et al. (2020) reported the density of 3 years old andong bamboo (*Gigantochloa pseudoarundinacea* (Steud.) Widjaja), which was taken from the 1st to 20th internodes, increased from 0.48 g/cm^3 at the bottom to 0.74 g/cm^3 at the upper parts. These are influenced by the portion between the vascular bundles and its parenchyma cells. The strength characteristics also have the same pattern because the strength of a material is greatly influenced by its density (Dwianto et al., 2020).

Therefore, an effort should be conducted to uniform the density by using densification technique. The bottom parts of the bamboo slats with lower densities can be compressed to match the upper parts' density. The densification process in the radial direction of the bamboo slats is possible because the inner parts of the bamboo consist of parenchyma cells that have thin cell walls. This phenomena is similar with the wood densification process, where the deformation starts from the thin cell walls in the early wood (Laine, Segerholm, Rautkari, Wa, & Hughes, 2016). In general, the bigger diameter of the bamboo is preferable for this utilization. The diameter of the bamboo decreases from the bottom to the upper parts. It is believed that the bigger the diameter, the higher the proportion of parenchyma cell. Therefore, densification of the big diameter of bamboos is required to optimize the application. However, the recovery to the initial shape becomes one of the issues of the compression techniques.

In order to prevent recovery of the deformation from the densification process due to the influence of moisture, a permanent fixation treatment is required. There have been many permanent fixation treatments for wood densification (Amin & Dwianto, 2006; Bao, Huang, Jiang, Yu, & Yu, 2017; Darwis, Wahyudi, Dwianto, & Cahyono, 2017; W Dwianto, Morooka, Norimoto, & Kitajima, 1999; Inoue, Norimoto, Tanahashi, & Rowell, 1993; Kariz et al., 2017; Zhan & Avramidis, 2015), while bamboo was less of a concern (Subiyanto, Dwianto, & Higashihara, 2011). Inoue et al. (1993) stated that permanent fixation of wood densification could be achieved by saturated steaming at a temperature of 180°C for 8 minutes or 200°C for 1 minute. These results were not much different from the research of Navi and Heger (2004) who reported that fixation could be achieved by saturated steam treatment at 165°C for 30 minutes, 190°C for 8 minutes, or 200°C for 2 minutes. Dwianto et al. (1999) investigated that the permanent fixation was caused by stress relaxation of the internal stress. The development of a method through post-treatment of compressed wood was able to produce permanent fixation (Antikainen et al., 2014; Laine, Rautkari, & Hughes, 2013; Zhan & Avramidis, 2015). Wood and bamboo are lignocellulosic materials; therefore bamboo fixation treatment may not be much different from wood. Therefore, this study was conducted to investigate the fixation process of compressed laminated bamboo from curved cross-section slats.

II. MATERIAL AND METHODS

A. Materials and Morphological Characterization of Bamboo Stem

This experiment used 3 stems of 3 years-old sembilang (*Dendrocalamus giganteus* Munro) bamboo which is usually utilized as a structural material in Indonesia. The samples were taken from a bamboo collection garden at the Research Center for Biomaterials LIPI, Cibinong. The morphological characterizations of bamboo stems included the measurements outer diameter and stem thickness.

B. Densification Technique and Fixation Treatment of Bamboo Slats

The bottom parts of the bamboo slats were taken from internode number 1 to 3 with an average thickness of 15 mm, the middle parts were taken from internode number 10 to 13 with an average thickness of 7.5 mm, and the upper parts were taken from internode number 31 to 40 with an average thickness of 4.5 mm. The target of each compression of bamboo was uniform density. To get the same target density, the bottom parts of the bamboo slats were arranged in 4 layers, the middle parts were arranged in 6 layers, while the upper parts were arranged in 6 layers, also. Therefore, the compression target of 50% was conducted for the bottom and 30% for the middle parts, and was expecting attaining the same density with the upper parts. The bamboo slats were prepared in wet condition; they were arranged in a moulding equipped with a lock/clamp and pressed until reached an approximate thickness of 3 cm (Figure 2).

It was also reported that the higher the temperature, the lower the time required to reach the fixation. However, it has a negative effect on the weight loss, which has linear relationship with the time. Therefore, this experiment was conducted with lower temperature, to reduce the weight loss during the fixation process. The compressed bamboo slats were then put into a chamber in clamped condition and subjected to steam treatment at temperatures of 120°C, 140°C and 160°C for 30 and 60 minutes. After that, they were oven-dried at 100°C for 24 hours. At this stage, the measurement of changes in the test samples' weight before and after the steam treatment was carried out.

Figure 2. Laminated bamboo moulding for steam treatment

C. Analysis of Physical Properties

The testing of physical properties of bamboo slat samples included density, recovery of set, and weight loss. The density measurement referred to the ISO 22157-1 (2004) standard. The test samples were initially weighed (W_1) and their volumes were measured (V_1), then oven-dried at 100-105°C for 24 hours or until their weight was constant (W_2). The determination of density was calculated by equation 1.

$$Density = \frac{W_2}{V_1} \quad \text{...(1)}$$

The thickness recovery measurement method referred to Amin and Dwianto (2006) to determine the fixation of compressed bamboo slats. Before compressed, all the bamboo slats were dried in the oven for 3 days at 60ºC, and the thickness (To) and initial weight (Wo) was measured. The bamboo slats were arranged on the moulding, then compressed and subjected to steam treatment. Furthermore, all the samples were oven-dried and the thickness (Tc) was measured. The recovery test was carried out with soaking in room temperature water for 24 hours and boiling for 30 minutes. The boiled bamboo slats were dried again in the oven, then the thickness (Tr) and the final weight slats (Wr) were measured. The recovery of set (RS) and weight loss (WL) were measured by Formula 2 and 3.

$$RS\% = \left[\frac{(Tr - Tc)}{(To - Tc)}\right] x100 \quad \text{...............................(2)}$$

$$WL\% = \left[\frac{(Wo - Wr)}{(Wo)}\right] x100 \quad \text{...............................(3)}$$

D. Observation of Anatomical Structures

The anatomical observation was conducted on three different parts, i.e. bottom, middle and upper. The samples were 1 cm (length) x 1 cm (width), while the thicknesses were based on their original stem thickness. The analysis was on the cross section of the samples before and after compression and steam treatment by stereo microscope Keyence VHX 6000.

III. RESULT AND DISCUSSION

A. Morphological Characterization of Bamboo Stem

The stem of bamboo is straight and cylinder-formed with nodes, and the parts between nodes are called internodes (Zhang, Jiang, & Tang, 2002). Every node has two closely positioned rings. The part between the rings is the node itself. There is a wooden partition between two neighboring internodes, which strengthens the stem. The length of internodes, the number and form of nodes depend on the species of bamboo. The internodes are hollow inside, which forms bamboo cavities. The thickness of stem wall varies greatly following different bamboo species.

Morphological characteristics of the outer diameter, stem thickness and density of each internode of sembilang bamboo were analysed to determine the causes of differences in their density distribution pattern. Figure 3 shows the average outer diameter (a), stem thickness (b), density (c), and the relationship between stem thickness and density (d) of sembilang bamboo. The outer diameter of sembilang bamboo decreased from an average of 16 cm at the bottom to about 7 cm at the upper parts of the stem following the polynomial equation of $y = -0.0039x2 - 0.0628x + 15.787$; $R^2 = 0.9995$ (Figure 3a). It shows that laminated bamboo

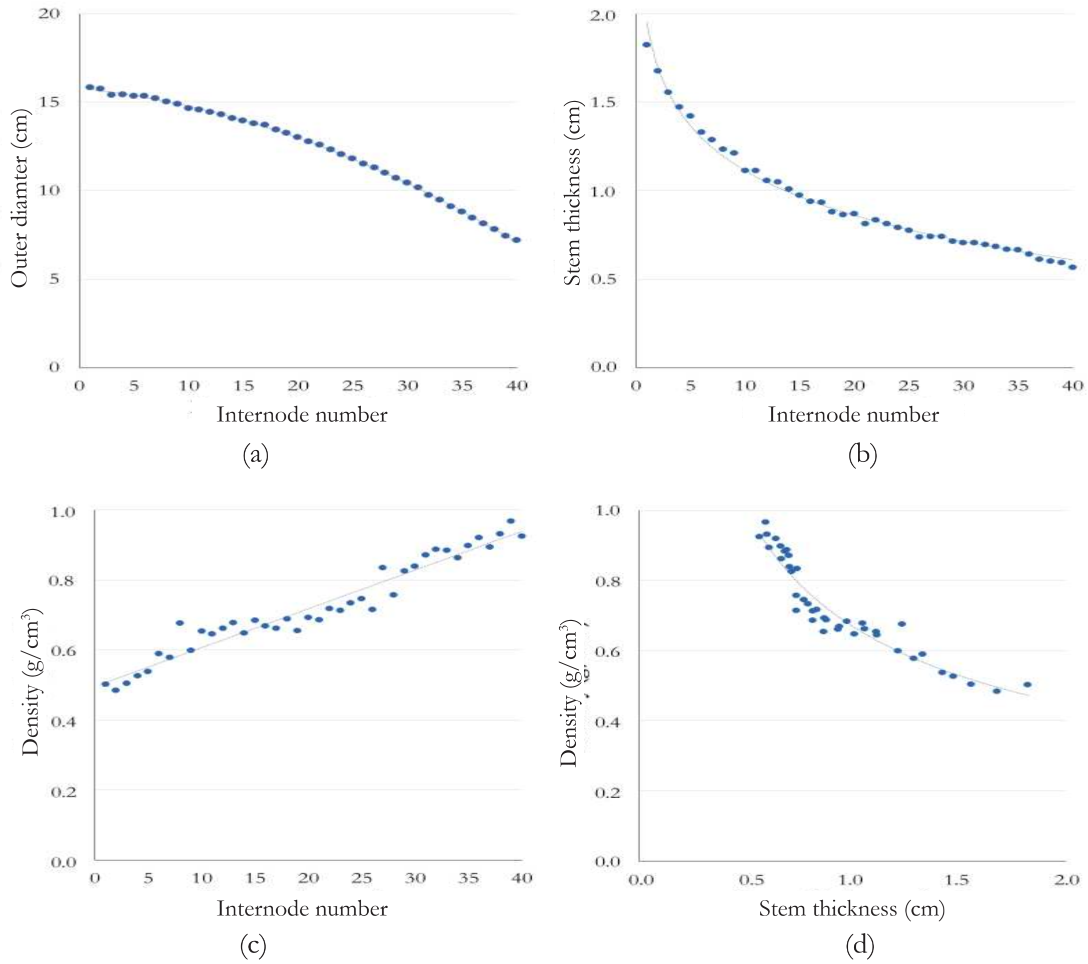


Figure 3. Outer diameter (a), stem thickness (b), density (c), and the relationship between stem thickness and density (d) of sembilang bamboo

with a curved cross-section width of 5 cm can be made using sembilang bamboo up to the 40th internode.

The stem thickness of sembilang bamboo decreased drastically from an average of 1.8 cm at the bottom to the 20th internode to about 0.6 cm at the upper parts of the stem following the logarithmic equation of y = -0.364ln (x) + 1.9523; R^2 = 0.9902 (Figure 3b). The difference in the stem thickness in each internode from bottom to the upper parts greatly affected the density. It can be seen that the density of sembilang bamboo increased from an average of 0.4 g/cm^3 at the bottom to almost 1.0 g/cm^3 at the upper parts of the stem following the polynomial equation of $y = 5e\text{-}05x^2 + 0.0091x + 0.5102$; R^2 = 0.943 (Figure 3c). The average density decreased with stem thickness following the equation of y = 0.6697x–0.582; R^2 = 0.9218 (Figure 3d).

The density of bamboo depended on their anatomical structures. Zhang et al. (2002) reported that bamboo's basic density was in the range of 0.4–0.8 g/cm^3. They argued that bamboo's basic density mainly depended on the density of vascular bundles and their composition. As a rule, the bamboo stem density increased from inner to the outer parts and from the lower to the upper parts. Kabir, Bhattacharjee, and Sattar (1993); Patel et al. (2013); Sattar, Kabir, and Bhattacharjee (1990) reported that the density of bamboo

Table 1. Density increment, weight loss and recovery of set of compressed sembilang bamboo slats by steam treatment

Treatment		Position	Stem thickness	Compression		Density		Weight loss	Recovery of Set
Temp (°C)	Time (min)		(mm)	Target (%)	Actual (%)	Before (g/cm³)	After (g/cm³)	(%)	(%)
120	30	Bottom	14.46 (0.54)	50.00	57.68 (1.14)	0.42 (0.02)	0.89 (0.01)	6.20 (0.28)	89.15 (2.06)
		Middle	7.79 (0.46)	30.00	35.96 (2.45)	0.73 (0.11)	1.07 (0.01)	4.51 (0.25)	87.77 (7.20)
		Upper	4.60 (0.11)	0.00	0.00 (0.00)	0.87 (0.01)	0.91 (0.01)	4.44 (0.02)	-
140	30	Bottom	14.44 (1.10)	50.00	53.69 (10.3)	0.45 (0.07)	0.94 (0.03)	6.24 (0.84)	54.79 (3.82)
		Middle	7.22 (0.13)	30.00	36.54 (4.19)	0.72 (0.06)	1.07 (0.03)	5.93 (0.61)	48.02 (2.29)
		Upper	4.87 (0.56)	0.00	0.00 (0.00)	0.85 (0.06)	0.92 (0.07)	4.16 (0.34)	-
160	30	Bottom	15.66 (1.41)	50.00	58.84 (0.19)	0.53 (0.05)	1.02 (0.01)	7.31 (0.22)	7.32 (0.65)
		Middle	8.05 (0.47)	30.00	36.17 (3.71)	0.75 (0.04)	1.18 (0.01)	6.31 (0.47)	7.93 (0.79)
		Upper	4.18 (0.16)	0.00	0.00 (0.00)	0.83 (0.01)	0.95 (0.01)	5.85 (0.15)	-
120	60	Bottom	13.81 (0.79)	50.00	46.98 (6.62)	0.56 (0.03)	1.00 (0.01)	6.66 (0.38)	72.06 (3.12)
		Middle	7.62 (0.07)	30.00	32.92 (3.28)	0.70 (0.01)	1.02 (0.01)	5.77 (0.61)	65.48 (3.16)
		Upper	4.17 (0.14)	0.00	0.00 (0.00)	0.89 (0.02)	0.94 (0.01)	4.50 (0.16)	
140	60	Bottom	16.19 (1.14)	50.00	55.92 (3.54)	0.44 (0.04)	0.95 (0.03)	6.71 (0.07)	37.79 (2.15)
		Middle	6.96 (0.49)	30.00	37.63 (2.44)	0.72 (0.01)	1.11 (0.02)	5.87 (0.64)	27.54 (1.26)
		Upper	4.26 (0.29)	0.00	0.00 (0.00)	0.90 (0.01)	0.95 (0.01)	4.59 (0.17)	-
160	60	Bottom	15.59 (0.55)	50.00	63.97 (3.95)	0.40 (0.01)	1.05 (0.01)	8.38 (0.09)	0.00 (0.18)
		Middle	8.26 (0.78)	30.00	41.50 (5.32)	0.83 (0.01)	1.17 (0.01)	7.49 (0.30)	-0.17 (0.15)
		Upper	4.29 (0.66)	0.00	0.00 (0.00)	0.96 (0.01)	0.98 (0.00)	5.69 (0.65)	-

Note: The value of the numbers in parentheses is the standard deviation varied from 0.50 to 0.80 g/cm^3 depending on anatomical structures such as quantity and distribution of fibres around vascular bundles, with its maximum density usually obtained from 3 years old mature culms.

B. Equalization of Density and Fixation of Compressed Bamboo Slats

Table 1 shows the average results of bamboo slats' physical properties before and after compression and steam treatment. The stem thickness of the sembilang bamboo was very different between bottom, middle, and upper parts, which were 13.81–16.19 mm, 6.96–8.26 mm, and 4.17–4.87 mm, respectively. This trend was similar with the densities which were 0.40–0.56 g/cm^3, 0.7–0.83 g/cm^3, and 0.83–0.96 g/cm^3, respectively. Therefore, the compression target in this experiment corresponded to their thicknesses which were 50% for the bottom and 30% for the middle. The compression targets were intended to equalize the density between the bamboo slats at the bottom and middle with the upper parts. The upper parts did not determine the compression target but undergoes compression when equalizing the curved lines so that the density increased slightly. The steam treatment was conducted at temperatures of 120°, 140°, and 160°C for 30 and 60 minutes to determine the recovery of set or level of fixation. Furthermore, the increase in density and weight loss due to the steam treatment was measured.

Figure 4 shows relationship between density and compression level (a) and steam treatment (b). Compression target was 50% for the bottom and 30% for the middle parts; however, the compression levels were mostly higher. This was probably due to shrinkage of the samples in radial direction. The results showed that the density of the bottom parts increased from 0.40–0.56 g/cm^3 to 0.89–1.05 g/cm^3 at the compression level of 46.98–63.97%. On the other hand, the middle parts increased from 0.70–0.83 g/cm^3 to 1.02–1.18 g/cm^3 at the compression level of 32.92–41.50% (Figure 4a). The increase in density at the bottom and middle parts was slightly higher than that of the upper parts, which was between 0.91–0.98 g/cm^3 (Figure 4b). Meanwhile, the increase in steaming temperature and time did not significantly affect the increase in density.

The recovery of set decreased with increasing steam temperature and time (Figure 5a). The bottom part samples underwent a slightly higher thickness recovery than the

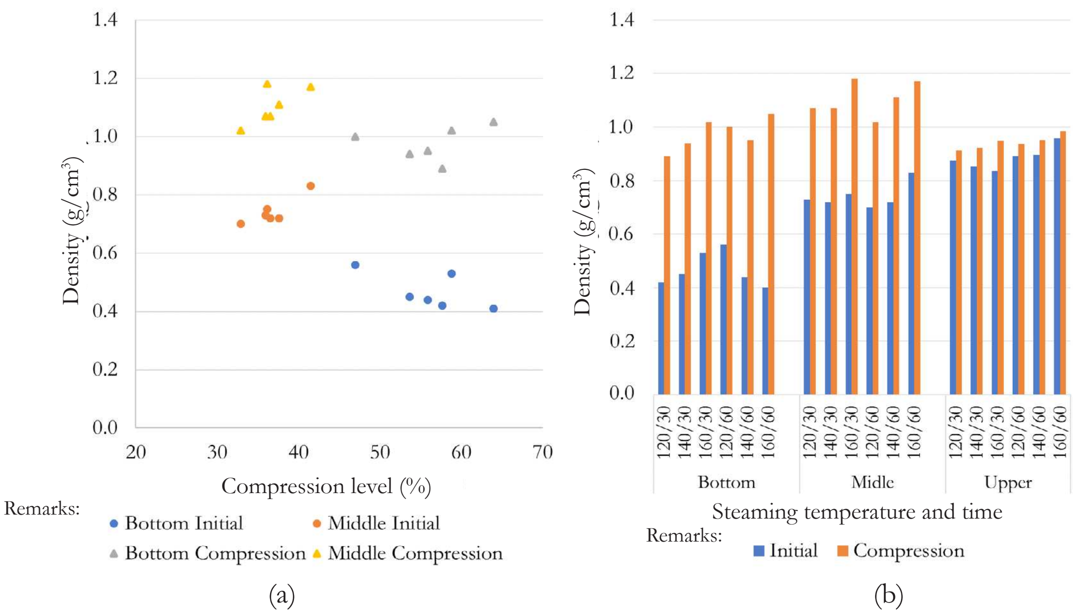
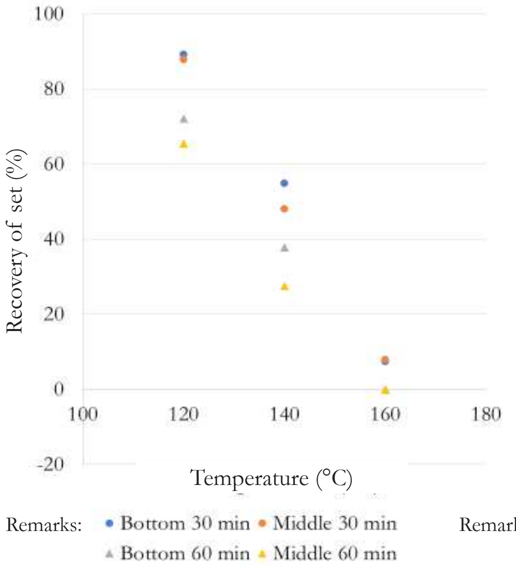
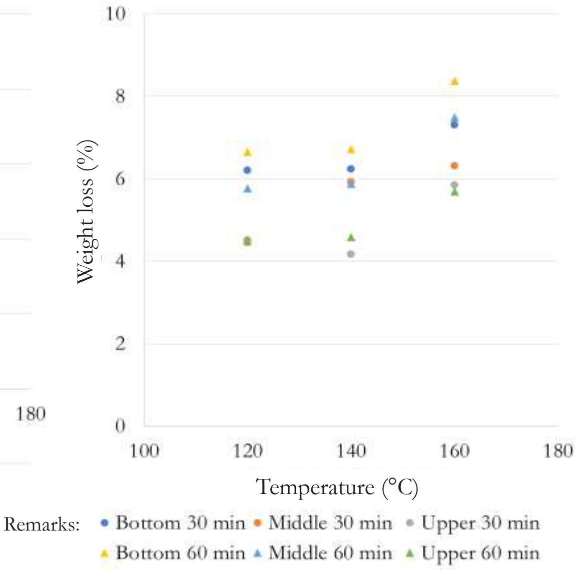


Figure 4. The relationships between density and compression level (a) and steam treatment (b).



(a)



(b)

Figure 5. Relationship between recovery of set (a) and weight loss (b) with temperature and time of steam treatment

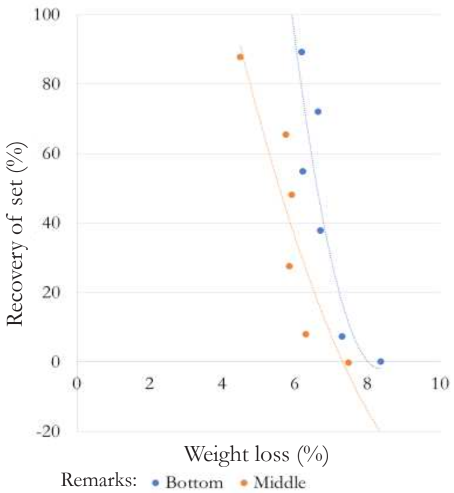


Figure 6. Relationship between recovery of set and weight loss

middle part samples. However, fixation could be achieved by both parts of samples at the same steam temperature and time, i.e. 160°C within 60 minutes. The weight loss increased with increasing steam temperature and time (Figure 5b), especially at 160°C. Although it was not too different, it appeared that the samples at the bottom lost more weight than the middle and upper parts; then the samples at the upper parts lost least weight.

Figure 6 shows the relationship between recovery of set and weight loss; the lower the fixation, the greater the weight loss was. Therefore, it was assumed that the fixation was influenced by the magnitude of the weight loss. Besides, it can be seen that the bottom part samples experienced greater recovery of set and weight loss than the middle part samples. This was indicated by separate equation between the bottom, i.e. $y = 17.174x^2 - 287.08x + 1197.9$; $R^2 = 0.7957$ and the middle part samples, i.e.

$y = 3.3206x^2 - 71.57x + 346.12$; $R^2 = 0.809$. However based on this experiment, the fixation level would be achieved when the weight loss were 8.38% and 7.49% at the bottom and middle parts, respectively.

The anatomical structure of bamboo is different in each position. Generally, the bottom parts of bamboo have a greater proportion of vessel cell, higher lumen diameter, and thicker cell wall than those of middle and upper parts. As a lignocellulosic material, bamboo consists of cellulose (±55%), hemicellulose (pentosan ±20%), and lignin (±25%) in the complex structure (Chen, 2015; Dotan, 2014; Khalil et al., 2012; Li., Wang, Wang, Cheng, & Han, 2010). However, the minor chemical compound on the bamboo species, such as pigment, tannins, protein, fat, was higher than those of wood (Fazita et al., 2016). Since the anatomical structural were different on the axial direction, the chemical components, such as holocellulose and extractive contents are also different in these third parts. Holocellulose is a total fraction of the carbohydrate, which consist of cellulose and hemicellulose. Besides, hemicellulose is a low molecular polymer sensitive to temperature (Murda et al., 2018).

Moreover, Esteves and Pereira (2009) reported that hemicellulose was the first degraded wood component when subjected to heat treatment. Loiwatu and Manuhuwa (2008) reported that extractive contents on the bottom, middle, and upper parts were 6.52%, 5.44%, and 5.43%, respectively. Extractive contents were dominant in the cell lumen, and also in the cell wall. Extractive contents, such as tannin, resin, and volatile compound, were also degraded by heat or steam treatment. Therefore, densification process on the bottom parts at 160ºC steam treatment for 60 minutes has higher weight loss than that of the middle parts.

Subiyanto et al. (2011) conducted research on the permanent fixation of radially compressed Tali and Gombong bamboos in dry condition by heat treatment. The results showed that the recovery of the set at 160°C was around 35–40% even when they were heated for more than 12 hours. In addition, the fixation was achieved at 180°C for 8 hours and 200°C for 4 hours; the weight loss was around 6–8% of both treatments. This weight loss was similar with our study by using steam treatment at 160°C for 60 minutes (1 hour) as the optimal treatment.

The densification of bamboo with steam treatments below 160ºC has not occurred yet due to the existence of internal stress stored in the bamboo structure during the deformation. Fang, Mariotti, Cloutier, Koubaa, and Blanchet (2012) stated that internal stress was stored in the semi-crystalline cellulose, hemicellulose, and lignin. This stress can be reduced or released by applying the heat or steam treatment (Dwianto et al., 1999; Dwianto, Morooka, & Norimoto, 1998). They reported that the permanent fixation of wood compression by heat or steam treatments was caused by the release of stress stored in microfibrils and hemi-lignin matrix due to the degradation of polymers in wood cell walls as the decomposition of hemicellulose and lignin. The relaxation of internal stress by steam treatment caused the changes in the composition of wood and created cross-links on lignin to reduce wood hygroscopicity (Guo, Yin, Zhang, Salmén, & Yin, 2017; Obataya & Chen, 2018).

C. Observation of Anatomical Structures

The tissues of bamboo stem include surface system (epidermis, subcutis, cortex), entire system (fundamental tissues, pith rings, piths) and vascular system (Zhang et al., 2002). The surface system is bamboo skin, located in the outermost part, pith rings and piths located in innermost part. They form the stem wall's outer and inner surface layers, protecting closely the fundamental tissues and vascular system. Vascular bundles are distributed among the stem wall's fundamental tissues, and their density decreases from the outer part of the stem wall to the inner part. Fundamental tissue is parenchyma cells, mainly distributed within the vascular system as a stuffing material. These

Table 2. Number and frequency of vascular bundles and percentage of fiber bundles in sembilang bamboo

Observation	Sample position		
	Bottom	Middle	Upper
Sampling area (mm^2)	14.409 (0.94)	10.876 (0.54)	5.294 (0.17)
Number of vascular bundles (unit)	28 (2.64)	27 (1.50)	25 (0.58)
Frequency of vascular bundles (unit/mm^2)	2 (0.06)	3 (0.10)	5 (0.15)
Percentage of fiber bundles (%)	39.78 (1.50)	43.25 (1.91)	43.35 (2.35)

Note: The value of the numbers in parentheses is the standard deviation

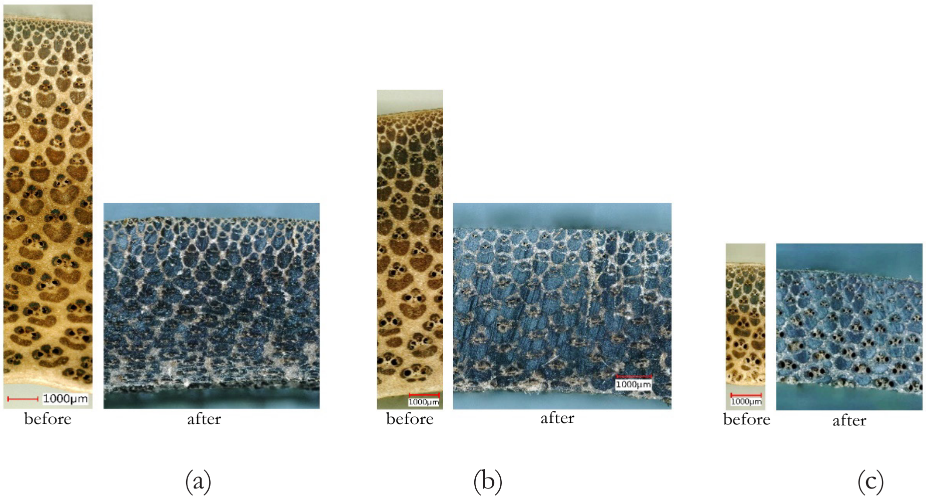


Figure 7. Anatomical structures of cross-section uncompressed and compressed bamboo at the bottom (a), middle (b), and upper parts (c)

are the fundamental part of bamboo material. Most of the cells are larger, with a thinner wall. The thickness of bamboo skin (outermost part) and pith (innermost part) as surface layers seemed unchangeable from bottom to the upper part of bamboo culms. Therefore, the stem wall thickness changes were mostly due to the portion changes of parenchyma cells and vascular bundles, which were distributed along the stem wall. The density of vascular bundles decreased from the outer part of the stem wall to the cross-section's inner part.

Table 2 shows the number and frequency of vascular bundles and percentage of fibre bundles in the bottom, middle and upper parts of sembilang bamboo. The frequency of vascular bundles and percentage of fibre bundles increased by increasing height of the bamboo. These unique characteristics of the cell compositions of the bamboo were assumed to affect the difference of density in the axial direction.

Figure 7 shows anatomical structures of cross-section uncompressed and compressed bamboo at the bottom (a), middle (b), and upper parts (c). The anatomical structures of bamboo tended to deform during the densification process. This process caused deformation on the parenchyma and vessel cells in the bottom and middle parts of bamboo, then, the vascular bundles appeared denser. The deformation occurred on the weakest structures, such as parenchyma cells, because having thinner cell walls than the other cells (Darwis et al., 2017; Laine et al., 2016). Vascular bundles of densified bamboo on the bottom-inner parts were flat. These shapes were not found in the other parts, especially in middle parts. In this region, the shapes of vascular bundles were remained unchanged from the original one, but those vessels were closer. Besides, the steam treatment affected the colour of the densified bamboo and became darker.

IV. CONCLUSION

From the measurement of morphological characteristics, it can be concluded that sembilang bamboo has the advantage of a larger diameter. The density of bamboo slats at the bottom parts increased from 0.40–0.56 g/cm^3 to 0.89–1.05 g/cm^3 at the compression level of 46.98–63.97%. Furthermore, the middle parts increased from 0.70–0.83 g/cm^3 to 1.02–1.18 g/cm^3 at the compression level of 32.92–41.50%. The density of the middle parts was slightly higher than that of the upper parts, which was between 0.91–0.98 g/cm^3. The recovery of set decreased and the weight loss increased with the increasing temperature and steam treatment time. Fixation could be achieved at 160°C within 60 minutes. To achieve the fixation, the bottom parts of the samples experienced a slightly greater weight loss than the middle parts, i.e. 8.38% and 7.49%, respectively.

The anatomical structure of bamboo slats tended to deform during the densification process. This process caused by deformation on the parenchyma and vessel cells in the bottom and middle parts, then the vascular bundles appeared denser and closer than the initial structure. Furthermore, the steam treatment affected the colour of densified or compressed bamboo, which became darker.

From this experiment, it can be concluded that the manufacture of laminated bamboo from bamboo slats can be uniformed in strength by equalizing the density at the bottom and middle with the upper parts through the densification technique. However, further research should be conducted to know the delamination and shear strength of the bamboo lamination.

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REFERENCES

Amin, Y., & Dwianto, W. (2006). Pengaruh suhu dan tekanan uap air terhadap fiksasi kayu kompresidengan menggunakan close system compression. *Journal of Tropical Wood Science and Technology*, *4*(2), 55–60.

Antikainen, T., Paajanen, O., Rautkari, L., Kutnar, A., Kamke, F. A., & Hughes, M. (2014). Simultaneous drying and densification of silver birch (*Betula pendula* L.) veneers: Analysis of morphology, thickness swelling, and density profile. *Wood Science and Technology*, *48*(2), 325–336. doi://10.1007/s00226-013-0605-0.

Bao, M., Huang, X., Jiang, M., Yu, W., & Yu, Y. (2017). Effect of thermo-hydro-mechanical densification on microstructure and properties of poplar wood (*Populus tomentosa*). *Journal of Wood Science*, *63*(6),591–605. doi://10.1007/s10086-017-1661-0.

Budiana, I., Kusmawan, D., & Rusli. (2014). Sifat fisik dan mekanik bambu laminasi sistem bilah lengkung dan penambahan air suling sebagai optimasi polymer isocyanate. In W. Suwinarti, I. Kusuma, Erwin, & Ismail (Eds.), *Prosiding Seminar Nasional Masyarakat Peneliti Kayu (MAPEKI) XVI* (103–112). Indonesian Wood Research Society (MAPEKI), Bogor.

Chen, H. (2015). Lignocellulose biorefinery feedstock engineering. In *Lignocellulose Biorefinery Engineering Principles and Applications* (pp. 37–86). Elsevier Ltd. doi://10.1016/C2014-0-02702-5.

Darwis, A., Wahyudi, I., Dwianto, W., & Cahyono, T. D. (2017). Densified wood anatomical structure and the effect of heat treatment on the recovery of set. *Journal of the Indian Academy of Wood Science*, *14*, 24–31. doi://10.1007/s13196-017-0184-z.

Dotan, A. (2014). Biobased Thermosets. In H. Dodiuk & S. Goodman (Eds.), *Handbook of thermoset plastics book* (3rd ed., 577–622). doi://10.1016/C2011-0-09694-1.

Dwianto, W, Morooka, T., & Norimoto, M. (1998). The compressive stress relaxation of wood during heat treatment. *Journal of the Japan Wood Research Society*, *44*(6), 403–409.

Dwianto, W, Morooka, T., Norimoto, M., & Kitajima, T. (1999). Stress relaxation of sugi (*Cryptomeria japonica* D. Don) wood in radial compression under high temperature steam. *Holzforschung*, *53*(5), 541–546. doi://10.1515/HF.1999.089.

Dwianto, Wahyu, Damayanti, R., Darmawan, T., Sejati, P. S., Akbar, F., Adi, D. S., … Triwibowo, D. (2020). Bending strength of lignocellulosic materials in softening condition. *Indonesian Journal of Forestry Research*, *7*(1), 59–70. doi://10.20886/ijfr.2020.7.1.59-70.

Esteves, B. M., & Pereira, H. M. (2009). Wood modification by heat treatment: A review. *BioResources*, *4*(1), 370–404. doi://10.15376/biores.4.1.370-404.

Fang, C. H., Mariotti, N., Cloutier, A., Koubaa, A., & Blanchet, P. (2012). Densification of wood veneers by compression combined with heat and steam. *European Journal of Wood and Wood Products*, *70*, 155–163. doi://10.1007/s00107-011-0524-4.

Fazita, N., Jayaraman, K., Bhattacharyya, D., Haafiz, M., Saurabh, C., & Hussin, M. (2016). Green composites made of bamboo fabric and poly (lactic) acid for packaging applications-A review. *Materials*, *9*(6), 435.

Guo, J., Yin, J., Zhang, Y., Salmén, L., & Yin, Y. (2017). Effects of thermo-hygro-mechanical (THM) treatment on the viscoelasticity of in-situ lignin. *Holzforschung*, *71*(6), 455–460. doi://10.1515/hf-2016-0201.

Hastuti, R. W., Primairyani, A., & Ansori, I. (2018). Studi keanekaragaman jenis bambu di Desa Tanjung Terdana Bengkulu Tengah. Diklabio: *Jurnal Pendidikan dan Pembelajaran Biologi*, *2*(1), 96–102. doi://10.33369/diklabio.2.1.96-102.

Inoue, M., Norimoto, M., Tanahashi, M., & Rowell, R. (1993). Steam or heat fixation of compressed wood. *Wood and Fiber Science*, *25*(3), 224–235.

ISO. (2004). *International standard ISO 22157-1. Bamboo-determination of physical and mechanical properties-part 1: Requirements* (1st ed.). Geneva: International Organization for Standardization.

Kabir, M., Bhattacharjee, D., & Sattar, M. (1993). Effect of age and height on strength properties of *Dendrocalamus longispathus*. *Bamboo Information Centre India Bulletin*, *3*(1), 11–15.

Kariz, M., Kuzman, M. K., Sernek, M., Hughes, M., Rautkari, L., Kamke, F. A., & Kutnar, A. (2017). Influence of temperature of thermal treatment on surface densification of spruce. *European Journal of Wood and Wood Products*, *75*, 113–123. doi://10.1007/s00107-016-1052-z.

Khalil, H., Bhat, I., Jawaid, M., Zaidon, A., Hermawan, D., & Hadi, Y. (2012). Bamboo fiber reinforced biocomposites-A review. *Materials and Design*, *42*, 353–368.

Laine, K., Rautkari, L., & Hughes, M. (2013). The effect of process parameters on the hardness of surface densified Scots pine solid wood. *European Journal of Wood and Wood Products*, *71*, 13–16. doi://10.1007/s00107-012-0649-0.

Laine, K., Segerholm, K., Rautkari, L., Wa, M., & Hughes, M. (2016). Wood densification and thermal modification : Hardness, set-recovery and micromorphology. *Wood Science and Technology*, *50*(5), 883–894. doi://10.1007/s00226-016-0835-z.

Li., L., Wang, Y., Wang, G., Cheng, H., & Han, X. (2010). Evaluation of properties of natural bamboo fiber for application in summer textiles. *Journal of Fiber Bioengineering and Informatics*, *3*(2), 94–99.

Li, H. T., Zhang, Q. S., Huang, D. S., & Deeks, A. J. (2013). Compressive performance of laminated bamboo. Composites part B: E*ngineering*, *54*(1), 319–328. doi://10.1016/j.compositesb.2013.05.035.

Loiwatu, M., & Manuhuwa, E. (2008). Chemical component and anatomical feature of three bamboo species from Seram, Maluku. *Agritech*, *28*(2), 76–83.

Mahdavi, M., Clouston, P. L., & Arwade, S. R. (2012). A low-technology approach toward fabrication of laminated bamboo lumber. *Construction and Building Materials*, *29*, 257–262. doi://10.1016/j.conbuildmat.2011.10.046.

Mujiman, Priyosulistyo, H., Sulistyo, D., & Prayitno, T. A. (2014). Influence of shape and dimensions of lamina on shear and bending strength of vertically glue laminated bamboo beam. *Procedia Engineering*, *95*(Scescm), 22–

30. doi://10.1016/j.proeng.2014.12.161.

Murda, R. A., Nawawi, D. S., Maulana, S., Maulana, M. I., Park, S. H., & Febrianto, F. (2018). Perubahan kadar komponen kimia pada tiga jenis bambu akibat proses steam dan pembilasan. *Jurnal Ilmu Teknologi Kayu Tropis*, *16*(2), 102–114.

Navi, P., & Heger, F. (2004). Combined densification and mechanical processing of wood. *Materials Research Society Bulletin*, *29*(5), 332–336.

Nugroho, N., & Ando, N. (2000). Development of structural composite products made from bamboo I: Fundamental properties of bamboo zephyr board. *Journal of Wood Science*, *46*, 68–74.

Nugroho, N., & Ando, N. (2001). Development of structural composite products made from bamboo II: Fundamental properties of laminated bamboo lumber. *Journal of Wood Science*, *47*(3), 237–242. doi://10.1007/BF01171228.

Obataya, E., & Chen, S. (2018). Shape recovery and anomalous swelling of steam-compressed wood by swimming ring-like expansion of cell lumina. *Wood Science and Technology*, *52*(4), 1009-1023. doi://10.1007/s00226-018-1018-x.

Patel, P., Maiwala, A., Gajera, V., Patel, J., & Magdallawala, S. (2013). Performance evaluation of bamboo as reinforcement in design of construction element. *International Refereed Journal of Engineering and Science*, *2*(4), 55–63. Retrieved from www.irjes.comwww.irjes.com at 16 April 2020.

Rahmawati, Baharuddin, & Putranto, B. (2019). Potensi dan pemanfaatan bambu tali (*Gigantochloa apus*) di Desa Leu Kecamatan Bolo Kabupaten Bima. *Jurnal Perennial*, *15*(1), 27-31.

Rosalita, Y., Nugroho, N., Subiyanto, B., & Kusumah, S. (2009). Pola distribusi kekuatan mekanik bambu betung (*Dendrocalamus asper*) dan bambu sembilang (*Dendrocalamus gigantochloa*). In S. Kusumah, Y. Massijaya, A. Firmanti, Subyakto, D. Nawawi, N. Wistara, … L. Risanto (Eds.), *Prosiding Seminar Nasional Masyarakat Peneliti Kayu (MAPEKI) XII* (pp. 78–85). Bogor: Indonesian Wood Research Society (MAPEKI).

Sattar, M., Kabir, M., & Bhattacharjee, D. (1990). Effect of age and height position of muli (*Melocanna baccifera*) and borak (*Bambusa balcooa*) bamboos on their physical and mechanical properties. *Bangladesh Journal of Forest Science*, *19*(1/2), 29–38.

Statistics Indonesia. (2019). *Statistics of Forestry Production 2018*. Jakarta: BPS-Statistics Indonesia.

Subiyanto, B., Dwianto, W., & Higashihara, T. (2011). Permanent fixation of radially compressed bamboo in dry condition by heating and its mechanism. *Journal of Tropical Wood Science and Technology*, *9*(1), 9–18.

Sulastiningsih, I. M., & Nurwati. (2009). Physical and mechanical properties of laminated bamboo board. *Journal of Tropical Forest Science*, *21*(3), 246–251.

Sutiyono. (2010). Penggunaan efektif batang enam jenis bamboo sebagai bahan baku bambu lamina. In D. Nawawi, M. Massijaya, N. Wistara, Suhasman, I. Rahayu, Arinana, & S. Kusumah (Eds.), *Prosiding Seminar Nasional Masyarakat Peneliti Kayu (MAPEKI) XIII* (pp. 555–560). Bogor: Indonesian Wood Research Society (MAPEKI).

Yu, H. Q., Jiang, Z. H., Hse, C. Y., & Shupe, T. F. (2008). Selected physical and mechanical properties of moso bamboo (*Phyllostachys pubescens*). *Journal of Tropical Forest Science*, *20*(4), 258–263.

Zhan, J., & Avramidis, A. (2015). Needle fir wood modified by surface densification and thermal post-treatment-hygroscopicity and swelling behavior. *European Journal of Wood and Wood Products*, *74*(1), 49–56. doi://10.1007/s00107-015-0969-y.

Zhang, Q., Jiang, S., & Tang, Y. (2002). INBAR. *Techical Report No 26. Industrial Utilization on Bamboo*. Beijing: Max Publishers Limited.