VOLUME 8

Production, Design and Industrial Aspects

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Preface

Juergen Hierold
UNIDO

The development of industries to provide employment and income for people in developing countries is one of UNIDO's highest priorities. These have to be in line with strategies to ensure environmental sustainability with the specific targets to integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources. UNIDO has, since 1999, appreciated the enormous potential of bamboo to satisfy industrial processing raw material needs and has made a point of compiling databases on processes, specialized equipment and machinery and on investigating economic feasibility of industrial enterprises.

Bamboo technologies are a feasible way to achieve these sometimes conflicting goals, industrialization and environmental preservation. The tremendous potential of bamboo technologies in terms of

- wood substitution to fight deforestation,
- employment generation,
- locally added value to raw materials or
- environmentally sound development

is the reason for UNIDO's ongoing support for bamboo projects and the World Bamboo Conference.

This panel's contributions focus mainly on the vital advantages bamboo usage can have on the development and production of building materials and pulp & paper. The potential of bamboo for UNIDO's overarching goal of poverty reduction through productive activities is clearly reflected in the contributions to this session.

UNIDO has been recognized as one of the leading International Agencies worldwide in bamboo processing technologies and industrialization with very specific know-how in the sector and is promoting bamboo industrialization process worldwide with great success during the last 10 years. UNIDO is also very much aware of the importance of Research & Development efforts to improve the effectiveness of bamboo technologies. We therefore look forward to the fruitful discussions and the inspiring input stemming from the World Bamboo Conference 2009.

The Gluability and Bonding Strength of *Dendrocalamus asper* Backer for Exterior Structural Applications

Pannipa Malanit[1, 2], Marius C. Barbu[1, 3], Arno Frühwald[1]
[1]Department of Wood Science, University of Hamburg, Germany
[2] School of Engineering and Resources, Walailak University, Thailand
[3]Faculty for Wood Industry, "Transilvania" University Brasov, Romania

Abstract

This study evaluated the effect of culm location in an Asian bamboo, *Dendrocalamus asper* Backer, on the pH and acid-buffer capacity and glueline bonding strength of strands using different types of adhesive. These properties were analyzed in order to prove its suitability to be promoted as a raw material for the manufacture of structural composite products like Oriented Strand Board (OSB), Oriented Strand Lumber (OSL) etc.

The pH and acid-buffering capacity were investigated in three locations, which composed of bottom, middle and top parts, along the culm length. The obtained results from this study indicate that the average pH value and acid-buffer capacity of *Dendrocalamus asper* is 5.4 and 0.53 milliequivalents, respectively The different culm location of a 3 years old has no effect on this value. The bonding strength development of bamboo strands bonded with some exterior used type adhesives was investigated by using a special testing device called an Automated Bonding Evaluation System (ABES). This experiment proposed three parameters, i.e., three types of glues; Melamine Formaldehyde (MF), Melamine Urea Phenol Formaldehyde (MUPF), and Phenol Formaldehyde (PF), and four pressing temperatures (130, 150, 170 and 190°C) and different pressing time (20 to 200 seconds). It was found that bonding strength was improved by increasing the hot pressing time and temperature. All adhesives showed satisfactory bond quality for the gluelines in the bonding of the bamboo strands. The best adhesive to bond bamboo strands following the ABES was found to be MF.

Introduction

The available high quality wood from natural forest in the world has declined. Then, structural composite products (e.g., Waferboard, Oriented Strand Board and Structural Composite Lumber) for construction building has been taken placed of massive wood lumber and increase their global market share every year. In the past few decades, wood composite industry has used the forest plantation and saw mill residues as the raw material for engineered product manufacturing. At the same time, the strength harvesting regulation and pressure from environmental policy have created decreasing high quality wood supply and an increasing cost. Consequently, the search for alternative resources of fiber instead of the traditional use of wood has been focused. Non-wood or agricultural-material has been received considerable attention as an alternative raw material for structural composite products.

Bamboo is a non-wood lignocellulosic material which has been widely used since thousands of years in tropical countries as a material for construction, furniture manufacture and daily household. Recently, it has been widely used as a raw material for wood composite manufactures, such as for Medium Density Fiberboard (MDF), Particleboard (PB) and Oriented Strand Board (OSB), owing to its high strength and properties. It is known that the chemical composition of bamboo culms is similar to that of wood with cellulose, hemicellulose and lignin accounting for over 90% of the total mass. From the study of Kamthai (2003), the average chemical composition of a three-year old *Dendrocalamus asper* consists of α-cellulose (68%) and lignin (29%). It contains about 1.5% of ash, 6% of alcohol-benzene soluble, 8% of hot-water soluble, 7% of cold-water soluble and 25% of 1% NaOH soluble materials. However, a change in raw material may affect on product properties and requires additional adjustment of some processing manufacture, such as the adhesive system. Since the adhesive is a significant cost factor in board production (about 20% of total production cost), future development of bamboo-based composites will require an analysis of bamboo gluability and the bonding strength of its strands.

The cross-linking rate of most thermosetting adhesives used in wood composite manufacturing depends on the pH levels. Thence, the acidity of raw material and the catalyst which is added into the adhesive play a very important role in providing the optimum condition during resin curing. The buffer capacity is the resistance of wood to change in its pH level by acid additional. Maloney (1993) suggested that the wood which requires a larger amount of acid catalyst to decrease its pH to a level required for optimum adhesive cure is considered as a high buffering capacity species. Many previous researchers (Freeman 1959; Johns and Niazi 1980; Van Niekerk and Pizzi 1994; Zanetti and Pizzi 2003) studied the influence of pH and buffer capacity of wood on curing time of some resins and product properties. According of these studies, the adhesive curing time and its bond strength decreased with the wood increasing pH and buffer capacity. Moreover, catalyst buffering action has strong effects on curing time and the degree of networks formed of MUF, PF and tannin based adhesives. Thus, the pH and buffering capacity measurement of raw materials is fundamental to determine the optimum of pressing parameters (i.e., time and temperature) for wood-based composite manufacturing. Understanding these properties is important when discussing the suitability of bamboo as a potential raw material for structural composite products.

Therefore, the objectives of this paper are to measure and compare the mean pH value and buffer capacity in each culm location of *Dendrocalamus asper* and investigate application by using the ABES equipment the strength development characteristics and bonding quality between bamboo strands using different adhesives for exterior.

Materials and Methods

Materials

In this study, the 3 years old of *Dendrocalamus asper* culms were collected from plantations located in Nakorn Sri Thammarat, South of Thailand. The three culms were harvested and immediately transported to Wood Science and Engineering Research Unit, Walailak University in Thailand. These bamboos had an average culm length of 18 m. The culm diameter at the bottom was about 11.5 cm, while the top culm was about 2 cm. The average culm wall thickness was 1.6 cm. The average specific gravity at 12% MC was 0.75. Each culm was divided into three parts each of 6 m lengths. Specimens were obtained from three locations which were related to the height position in the culm following the scheme in Figure 1.

Bamboo chips from each part were cut into fine particles by a Wiley machine. The samples were then put into a shaken screener to pass through a $40^{\#}$ mesh screen and retained on a $60^{\#}$ mesh screen. The particle remaining on the mesh screen was used for the measurement of pH value and buffer capacity.

The bamboo strands with a size of 120 mm by 20 mm and a thickness of 0.7 mm were used to prepare the two-layer lap-shear specimens for the ABES bond quality testing. All strands had been dried a final MC of 12% before gluing.

Three commercial exterior adhesives were used in this research: Melamine formaldehyde (MF), Melamine urea phenol formaldehyde (MUPF) and Phenol formaldehyde (PF). The MF resin (Prefere13H560) was supplied by Dynea. The MUPF resin (KML 534) was supplied from BASF. The PF resin (Bakelite 1279 HW) was supplied by Hexion. All adhesive mixtures were prepared following the supplier's suggestion. Their properties are presented in Table 1.

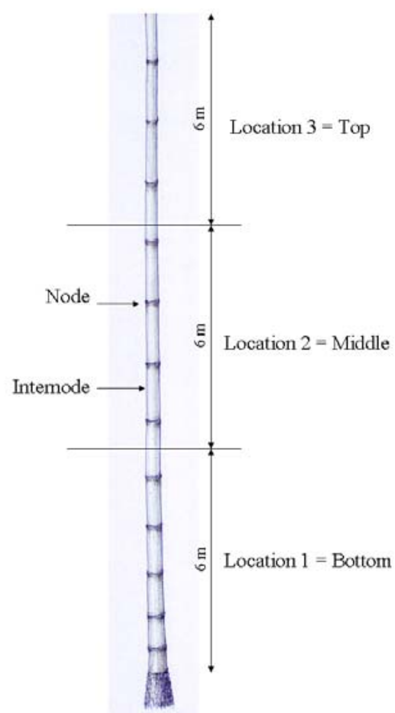


Figure 1 Sampling technique from *Dendrocalamus asper* culm for pH and buffer capacity analysis

Table 1 Characteristic property of the used glues

Properties	Glue types		
	MF	MUPF	PF
Appearance	Pale liquid	Pale brown liquid	Red brown liquid
Solids content (%)	62.5	64±1	48
pH at 20^0C	9.73	9.3-9.8	8.5-10.5
Viscosity at 20^0C (mPa∗s)	100-150	150-400	650-700

pH Value and Buffer Capacity Measurement

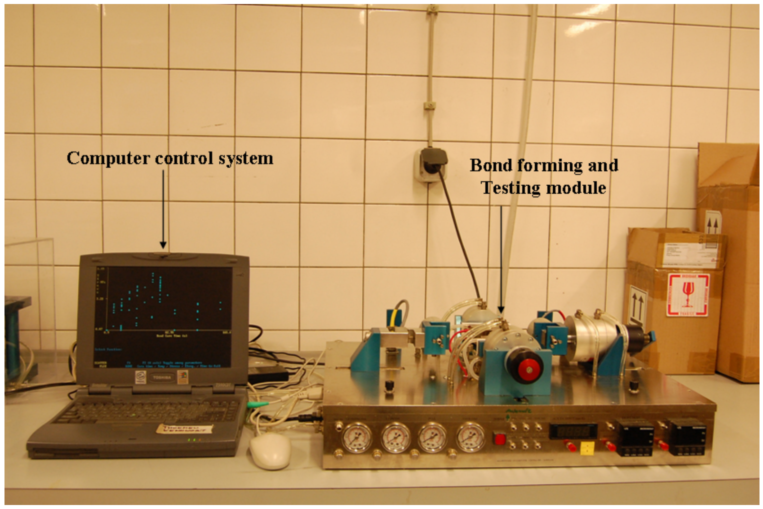
Most of pH value reports have been analyze by hot water extracts, obtained by refluxing for short periods (Johns and Niazi 1980; Xing et al. 2004). However, cold water extracts for a longer period is also presented and accepted in laboratory scale (Hague et al. 1998). The cold extract pH was measured according to TAPPI T 509 om-83. 1 g of specimen was put into a 100 ml beaker and distilled water was added to bring the total volume to 70 ml. The mixture was stirred and allowed to soak for one hour at room temperature (20^0C). A pH meter (Type WTW pH 330i) was used for the measurement.

The buffer capacity measurement procedure was adapted from the method suggested by Maloney (1993). 30 g of dry specimen were soaked and stirred in 400 g of distilled water at 20 ± 1^0C for 30 minutes. The liquid was then poured into a Buchner (Coors) filter no.2 containing a Whatman filter paper no.4. The liquid was drawn through the filter paper with the aid of a vacuum and 150 g of the liquid was transferred in a 400 ml beaker. The same pH meter was used for determining the pH value. The solution was then titrated to a pH of 3.5 with nominal 0.01N Sulfuric acid solution. The liquid was mixed by a magnetic stirrer. The pH and milliequivalents (N×ml) of acid needed to change the pH to 3.5 were calculated as the buffer capacity

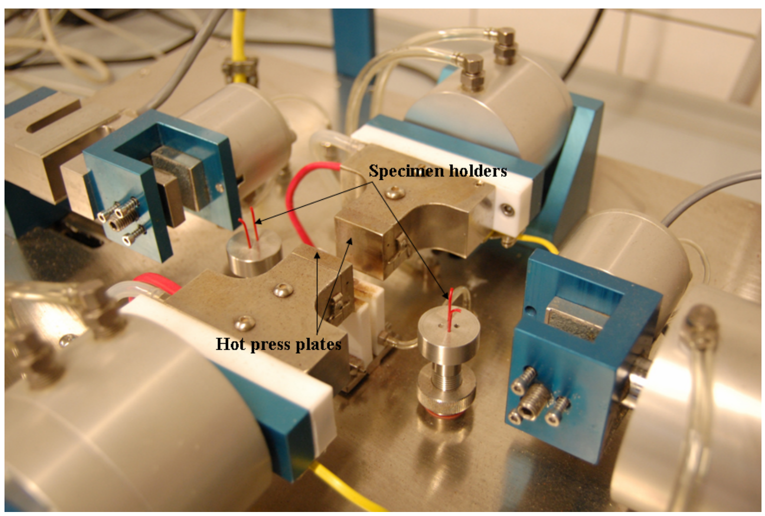
Each specimen was conducted using three replications. Analysis of the variance was performed and Duncan's Multiple Range Test was used for the comparison procedure.

Bonding Quality

The development of bonding strength was investigated with the Automated Bonding Evaluation System (ABES). The ABES is designed to determine the development of adhesive bonding strength between two pieces of strands. The bonding is affected by temperature, curing time or the pressure that is applied to lab-shear samples (Humphrey 1993). This device is composed of a bond-forming and test module, which are present in Figure 2, and a computer control system with testing-software program.



(a)



(b)

Figure 2 Details of Automated Bonding Evaluation System device, (a) ABES overview, which is composed of the bond-forming with testing module and computer control system (b) A close-up of the bond forming zone, which is composed of the hot press plates and specimen holders.

The adhesive was spread onto one side (5x10 mm^2 of overlapping area) of the bamboo strand with a hand brush at an application rate of 200 g/m^2. As suggested by hypothesis and literature review (Lee et al. 1996), the outer layer of bamboo culm is difficult to glue than the inner layer, because of the specific gravity variation. Hence, two strands were placed in the bond pressing zone of ABES with both grains parallel to each other in an outer-layer-to-inner-layer configuration.

After lay up, the strands were then hot-pressed under controlled parameters of temperature, time and pressure which are given in Table 2. After each bond was cured to the required time and temperature, the pressure was released from the specimen, which was then immediately pulled in a shear mode according to the ASTM D-3165-07. Tensile load and gripping head movement (sample elongation) were PC-monitored during strands pulling, and load at failure was recorded by a computer like for the determining the shear strength of the adhesive bond. At least three replications were performed for each of the condition. The operation manner of equipment experiment is described in Figure 3.

Table 2 Design parameters for the experiments

Sample parameters	Data
Resin types	• MF (Prefere 13H560) + 3% NH_4NO_3 • MUPF (KML 534) + 3% NH_4NO_3 • PF (Bakelite 1279 HW) + 6% K_2CO_3
Resin spread rate	200 g/m^2
Sample moisture content	12%
Pressing parameters	
Pressing temperatures	130, 150, 170 and 190^{0}C
Pressing times	20 to 200 seconds
Pressure	4 N/mm^2 (constant)

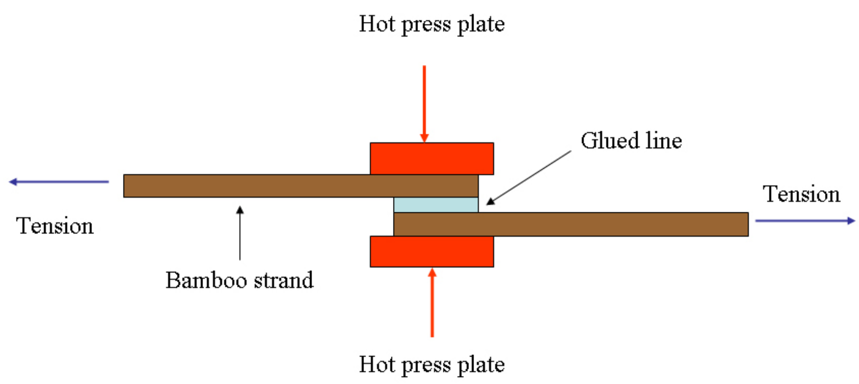


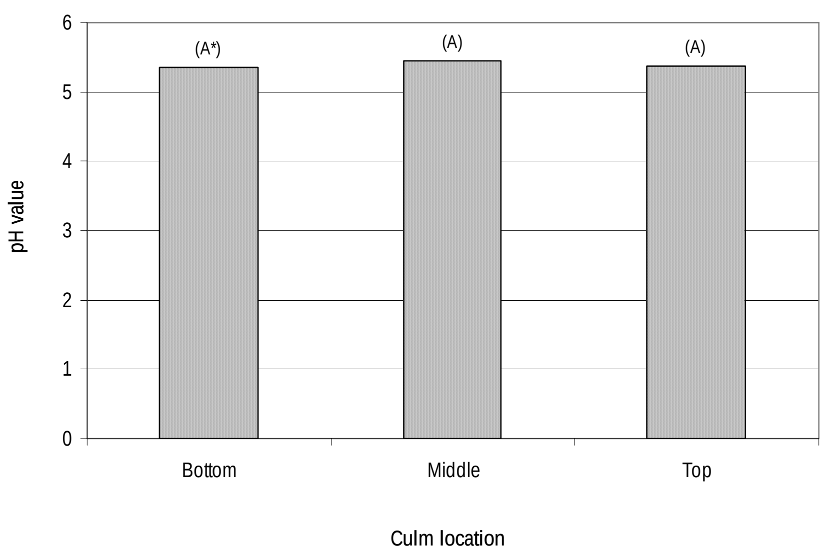
Figure 3 Schematic description of shear test by Automated Bonding Evaluation System (ABES)

Results and Discussion

pH and Effect of Culm Location on Value

Figure 4 presents the pH value data, obtained for the measurement from three locations of three bamboo culms. The pH value of *Dendrocalamus asper* ranges in the acid region from 5.36 – 5.45. The highest value occurs in bottom part, while the lowest value occurs in top part of the culm. The differences of pH value between each location is not significant (F-value = 0.23). Compared to wood species, the pH value of *Dendrocalamus asper* is quite similar to some softwood and hardwood species, which have value in the range of 4-6 (Fengel and Wegener 1984).

It is desirable that the pH value of *Dendrocalamus asper* is quite similar to common wood species. Moreover, the different culm location has no sever effect on pH value. The same technology and practices might be applied to this bamboo specie when being used as raw material in wood composites manufacturing.



Note: * Means with the same letter for the location are not significantly different at p<0.05 by Duncan's Multiple Range Test

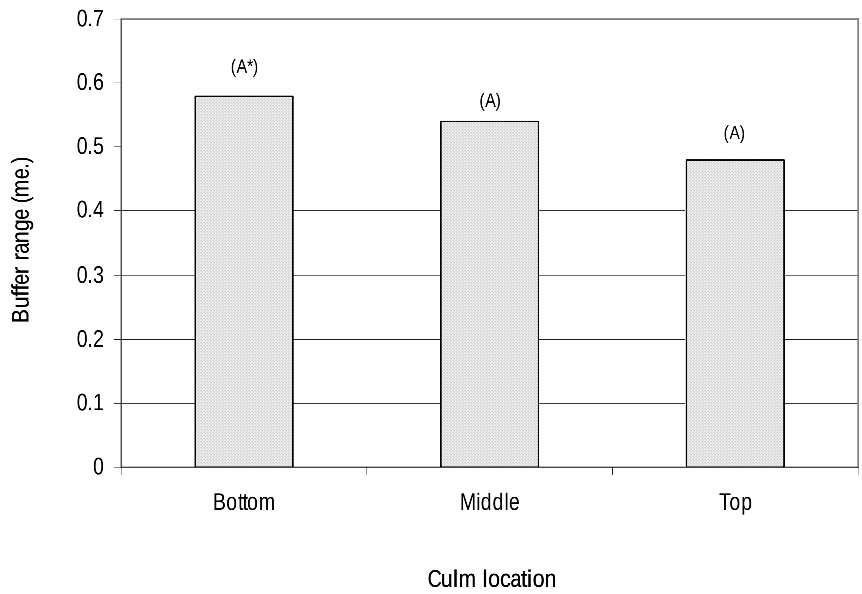
Figure 4 pH value of *Dendrocalamus asper* at different locations

Buffer Capacity and the Effect of Culm Location on Value

The acid-buffering capacity of *Dendrocalamus asper* at three different locations in the culm is illustrated in Figure 5. The average value of bottom, middle and top parts of the culm are 0.58, 0.54 and 0.48 milliequivalents, respectively. Although there are not significant differences between the location (F-value = 0.27), the value gradually decrease from bottom to the top of the culm. The bottom part of culm shows highest acid-buffering capacity compared to the top. It is known that bamboo extractives have some variation in their vertical location. The bottom part of the culm has significantly higher extractive contents, particularly with hot-water extracts, alcohol-benzene extracts, 1%NaOH extracts and ash, than the other parts (Kamthai 2003). It is reasonable to hypothesize that the chemical composition of bamboo, especially water extracts and inorganic matters, has effect on its buffer capacity. This hypothesis can be confirmed by study of Passialis et al (2008). They found out that hot-water extracts and inorganic elements, which evidently present in bark of wood, have significantly effect on buffer capacity of raw material.

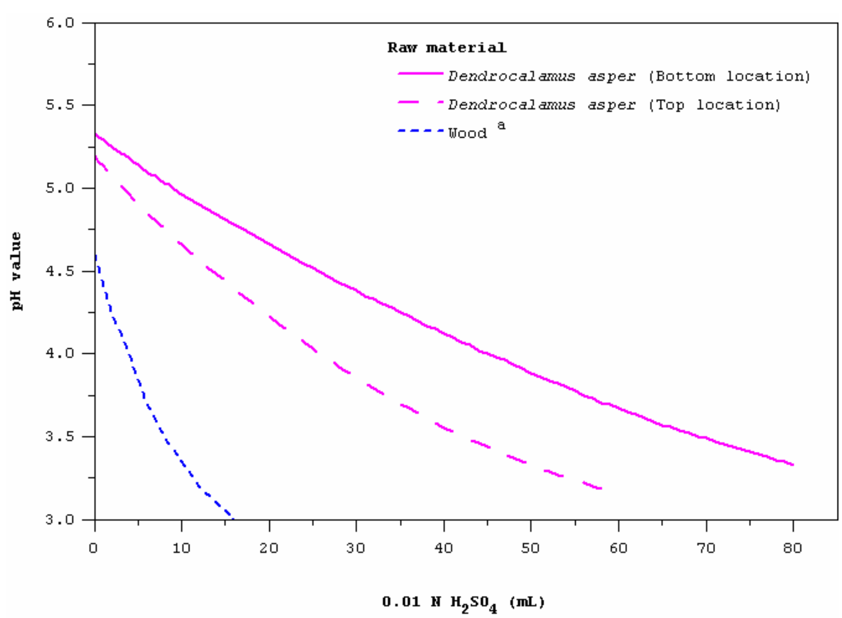
The pH value changes for bottom and top parts of *Dendrocalamus asper* on the acid addition is presented in Figure 6. It is clear that *Dendrocalamus asper* has extremely high resistance to pH changes and weakly responds to the acid addition when compared to normal wood, as also shown in Figure 6. *Dendrocalamus asper* needs 5 to 6 times the amount of acid which is required for wood to achieve a pH of 3.5. It would be considered that *Dendrocalamus asper* is a high buffer capacity specie. It requires a huge amount of acid catalyst to reduce the pH to the optimum level which is required for a resin cure. This may cause problems to use it as raw material in wood composite with conventional gluing technology. Some strategies, such as the use of special glue to produce boards or adjusted hot-pressing parameters, might be applied to improve resin curing and therefore improve product properties too.

As the result of this research, the buffer capacity would be mentioned as a key factor for consideration *Dendrocalamus asper* as the raw material in all wood composite manufacturing processes. It is also a noteworthy issue that its buffer capacity varies along the culm location, although the differences seem small until the statistical analysis cannot find. Thus, it should require some special consideration in regard to catalyst addition and resin cure.



Note: * Means with the same letter for the location are not significantly different at $p<0.05$ by Duncan's Multiple Range Test

Figure 5 Buffer capacity of *Dendrocalamus asper* at different culm locations



Source: [a] Sauter (1996)

Figure 6 Effect of raw material type on pH changes during the acid addition.

Bonding Strength Development of MF, MUPF and PF adhesives

The development of bond strength was observed in terms of the shear strength of each adhesive as a function of pressing time and temperature. A typical bond strength development of MF, MUPF and PF adhesive is shown in Figure 7, 8 and 9, respectively.

The results of ABES test indicate that bonding strength of glue-line vary significantly with different adhesive type, pressing temperatures and time. The maximum value of shear strength is 8.90 N/mm^2 for MF resin at 170°C and 200 seconds (as shown in Figure 7), while the minimum value of shear strength is 0.15 N/mm^2 for MUPF resin at 130°C and 20 seconds (as shown in Figure 8).

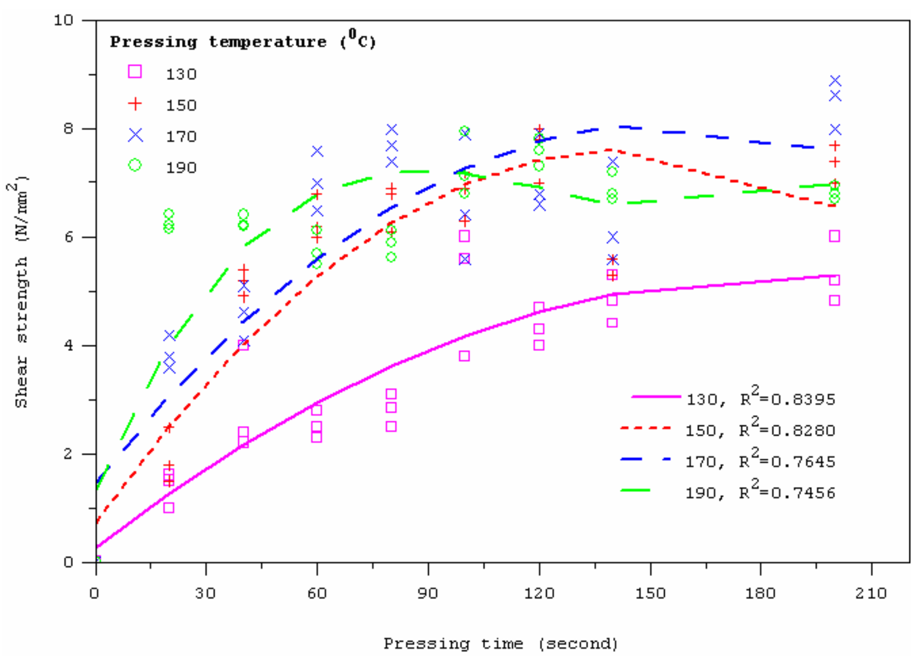


Figure 7 Development of shear strength of MF glued bamboo strands tested by ABES method as a function of pressing times and temperatures.

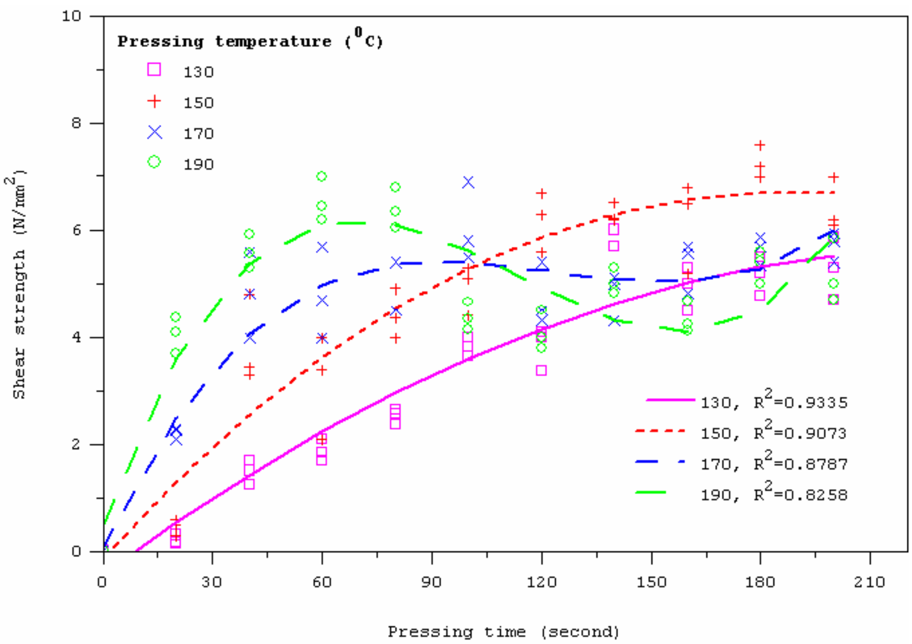


Figure 8 Development of shear strength of MUPF glued bamboo strands tested by ABES method as a function of pressing times and temperatures.

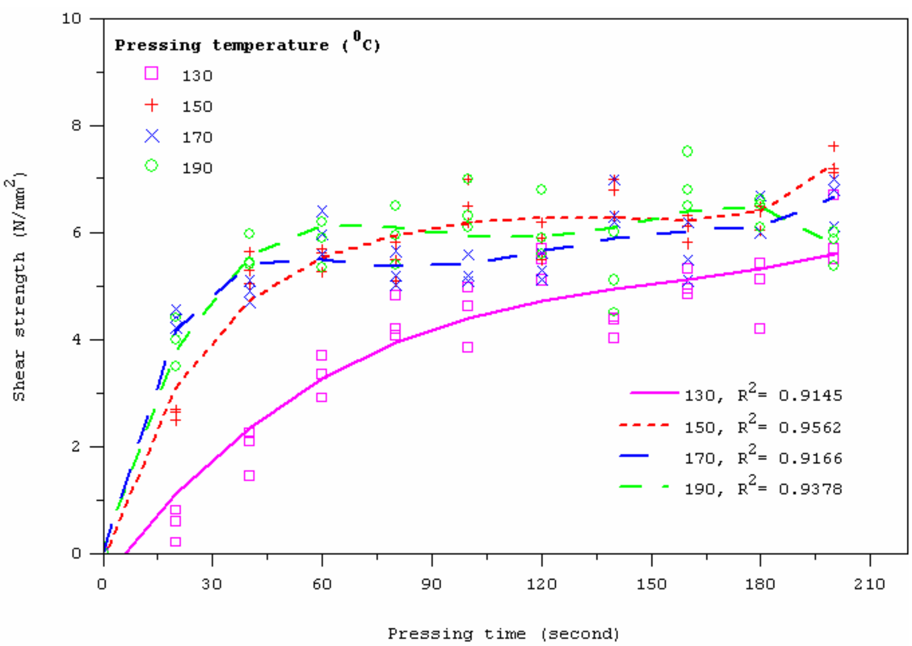


Figure 9 Development of shear strength of PF glued bamboo strands tested by ABES method as a function of pressing times and temperatures.

Influence of Pressing Temperature and Time

The results also indicate that bonding quality vary significantly with different pressing times. The effect of the higher pressing temperature is mainly related to an increase in shear strength in the glueline. The temperature increase influences the rate at which adhesive bonds develop which can be suggested by the rapidly increasing of initial strength. As usual, heat is used during the pressing for faster bonding development. The resin can cure fast when the pressing temperature increases. At low temperatures, the bonding strength is limited because the resin can not completely cure, but an excess temperature can reduce or eliminate the bonding strength in glueline as illustrates at 190°C for MF and MUPF resin (as shown in Figure 7 and 8, respectively).

Notably, most of curves for shear strength development related to pressing time could be separated into two distinct phases, where each phase can be explained the observed relation. In the first phase, which can be denoted as an initial, the shear strength is low at the beginning of the hot pressing for each temperature level since the tiny bond line occurs. After 20 seconds of pressing, strong adhesion between the adhesive and bamboo start to build up, resulting in a rapid increasing of bonding strength which causes the growth as a linear fraction of the shear strength graph. The results suggest that the higher pressing temperature, the shorter the first phase, as distinctly illustrated in Figure 9. At 150°C, the end of first phase is reached at 80 seconds pressing time, while the end of first phase for 170°C is reached in 40 seconds pressing time.

In the second phase, the bonding strength further increase with the increasing pressing time until the maximum value of each graph is reached, where the bonding strength value is highest. With the further pressing time, the strength is slightly constant. During the end of this phase, the shear strength slightly decreases with the longer pressing time at higher pressing temperature, as distinctly illustrated in 170°C for MF and 170, 190°C for MUPF resin (as presented in Figure 7 and 8, respectively). It can be observed that longer pressing time would deteriorate the completed bond which already occurs in the glueline.

Noteworthy, the bonding strength development, which were taken place at the excess temperatures (in the case of 190°C for MF and MUPF resin) behave differently. They are slightly constant and show small shear strength values. In accordance with Blomquist et al. (1983), PF resin requires high press temperatures for condensation reaction. Actually, this is the basic results on the laboratory scale. Further study is requested in order to explore this in an optimal parameter on an industrial scale.

Furthermore, the pressing temperature has a greater influence than the pressing time. At lower temperature, a longer pressing time is needed to reach the maximum bonding strength, whereas the shorter pressing time is used at a higher temperature, as distinctly illustrated in Figure 8. At 150°C, the maximum shear strength is 7.60 N/mm^2 at 180 seconds pressing time, while the maximum shear strength for 170 and 190°C is 6.90 and 7.00 N/mm^2 at 100 and 60 seconds pressing time, respectively.

Influence of Resin Types

The three adhesives, which were evaluated in this study, show different maximum shear strength. It can be seen that MF resin shows the highest shear strength value (8.90 N/mm^2) as shown in Figure 7, while the maximum shear strength value for MUPF (7.60 N/mm^2) is quite similar to that of PF (7.90 N/mm^2) as shown in Figure 8 and 9, respectively. The results suggest that all of them appear to have a similar pattern for the bond strength development, although the times, when particular phases occurred, vary with the different adhesives. Furthermore, all of them are thermosetting resins. Their cross linking reactions take place in the bond under applied pressure and heat, but their network bonding can be effect by excess temperature. It is important to note that the adhesive types vary significantly in the bonding conditions for which they are require in use, especially with regard to pressing temperature and time. MF and MUPF can harden and bond properly at lower temperature (150-170°C), while PF requires higher temperature (190°C).

Conclusions

The pH value, buffer capacity of *Dendrocalamus asper* and its bonding strength development have been analyzed. The following conclusions can be drawn from this part of the study:

1. *Dendrocalamus asper* has pH value on acid side (an average value is 5.40) which is compared to other wood species, particularly softwood. The pH value does not vary along the location of the culm.
2. Buffering capacity of the *Dendrocalamus asper* strands is shown to be 5 times higher than those of other wood species. The value slightly varies along the culm location.
3. The bond strength between bamboo strands and adhesive is improved according to ABES tests by increasing the hot pressing time and temperature. Several adhesives exhibited satisfactory bond strength. The best glueline strength between bamboo strands was found by the ABES method to be MF.

Acknowledgements

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Experimental Study of Glued Laminated Guadua as Building Material: Adhesive Calibration

Juan F. Correal, Director of Integrated Lab and Assistant Professor
Fernando Ramirez, Associate Professor
Luis E. Yamin, Associate Professor
Civil and Environmental Engineering Dept., Universidad de Los Andes, Bogotá, Colombia

Abstract

Round G*uadua angustifolia Kunt* bamboo has been used as a structural material in Colombia for the construction of traditional houses mainly in the coffee growing region. Nonetheless, its use in large structural applications has been limited mainly because of the variation of bamboo geometrical and mechanical properties. As a consequence, and taking into account the current standardization of the construction industry, Glued Laminated Guadua (GLG) has emerged as an excellent alternative for the construction of large structural elements. Only exploratory studies have been done on the potential use of GLG as a construction material. The Universidad de Los Andes in Bogotá-Colombia is performing for the first time in Colombia a comprehensive study on the structural behavior of the GLG. The best type of adhesive as well as its optimum spread rate, based on an experimental adhesive calibration program, was determined in the first stage on this study. Static bending and glued line shear tests were performed on GLG specimens assembled with four types of adhesives and using the manufacturer recommended spread rate. Urea-Formaldehyde (UF), Melamine-Formaldehyde (MF), Melamine-Urea-Formaldehyde (MUF), and mixture of 50% of UF and 50% MF were the adhesive selected for this study. Bond shear strength of specimens manufactured with MUF was slightly higher than those using the other type of adhesives. However, the differences in shear bond strength, bending strength, and modulus of elasticity among all the adhesives were not significant, indicating that the recommended adhesive spread rate is excessive. In addition, tests were performed using six different adhesive spread rates of the mixture of 50% of UF and 50% MF, and optimum adhesive spread rate was proposed.

Introduction

Based on the Department of National Planning of Colombia, there is a lack of housing of about 2.3 million in the country. In addition, the offer to demand ratio of houses is about 0.53 showing that the housing construction is not enough to cover the demand of the growing of the population. There is also a need of new construction materials and systems in order to solve this problem. Bamboo is an interesting material to use since it has high strength to weight ratio, relative low cost, fast growing rate and reproduction capabilities (sustainability), and it helps with oxygenation of the environment and captures carbon dioxide (eco-friendly). A giant specie of bamboo called G*uadua angustifolia Kunt* grows naturally in Colombia, Venezuela and Ecuador and it has been introduced in other Andean and Central American Countries. In Colombia, there exists about 35.000 hectares of *Guadua angustifolia kunt* and only 40 % of these Guadua is used in construction mainly as a material for falsework of concrete floors. Although, Guadua has been used in construction of structures with relative success, it has been done following experiences from previous generations called non-codified standard. In order to define the potential applications of Guadua as a construction material and its possible implementation in buildings codes extensive research need to be done to evaluate its structural behavior.

Studies have shown that round Guadua has excellent mechanical properties (Durán et al. 2002; Lopez et al. 2002; Prieto et al. 2002; Pantoja et al. 2005). Nevertheless, one of the problems with round Guadua is the variability of its geometry, mechanical properties and anatomical composition that makes this material difficult to characterize (Gritsch et al. 2004) and affecting its use in large structures. Glued laminated Guadua (GLG) has emerged as an excellent alternative, since preliminary studies (Barreto 2003; Duran 2003, Correal et al. 2008) indicated that GLG has mechanical properties as good as the best structural wood in Colombia. However, more studies are required in order to determine the actual potential use of Guadua as a construction material. The Universidad de Los Andes in Bogotá is conducting in Colombia a detailed research program on round Guadua and Glued Laminated Guadua (GLG) in order to understand the structural behavior not only under static loads but also under dynamic loads like earthquakes. This research consists of physical and mechanical characterization, strength verification of structural elements, behavior of typical connections, and seismic validations of construction systems. As a part of the mechanical characterization of the GLG an adhesive calibration experimental program has been developed. This paper reports the effect of different adhesive types and adhesive spread rate on the GLG flexural properties and internal shear bond strength. Finally, an optimum amount of adhesive is proposed based on the experimental program results.

Material

Four-year-old *Guadua angustifolia kunt* bamboo culms with an average base diameter of 7 to 14 cm and 30 m height were obtained from the city of Caidedonia-Colombia located at 1400 meters in elevation. The average thickness of the culm wall varies from 2.0 to 0.8 cm. The culms are cut into 2 to 3 meters long pieces and they were taken into the warehouse of the Colguadua Ltda factory. The fabrication process of the GLG is summarized in Figure 1(a). The 2 to 3 m long culm pieces are cut again into 1 to 1.5 m long in order to have straight pieces. Each piece is split in the radial direction into proper number of slices, and the nodes are removed from the culms. The quasi-flattened Guadua slices are passed through a grinding machine to remove the inner and outer layers. These slices are then immersed in a chemical solution to protect bamboo against insects attack, and then dried in an oven at 80 ^{o}C to reach an average moisture content of 5%. Once the slices are dried, their four faces are polished with a machine to flatten their surfaces obtaining Guadua laminae. Each Guadua lamina is about 7 to 10 mm thick, and 1 to 1.5 m long. All laminas are impregnated with adhesive resin along the narrow face (Figures 1(a) and 1(b)) and stacked to form Guadua sheeting. A hot press at 100 ^{o}C with a lateral pressure of 1.2 MPa is applied to the laminae. Once the adhesive is cured, the Guadua sheets are glued together by the wide faces in order to form boards in a hot press at a pressure of 2 MPa for 15 minutes at 100 ^{o}C.

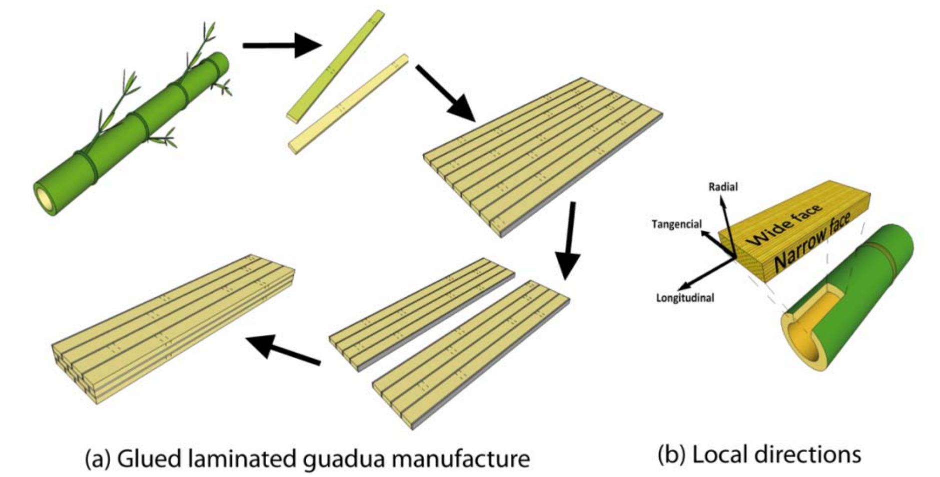
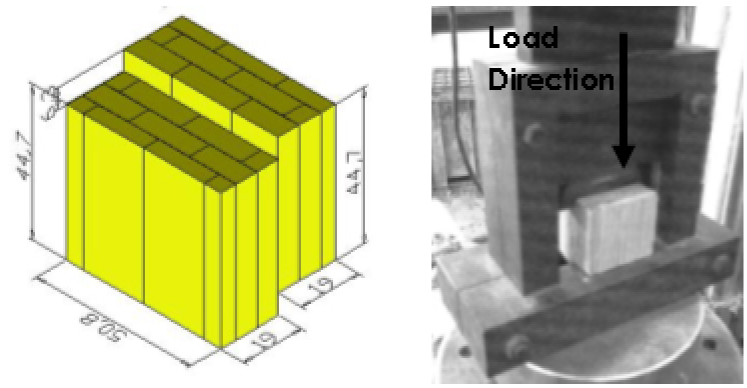


Figure 1. Manufacturing process of glued laminated Guadua

Experimental Program

The adhesive calibration program consisted of two phases. The objective of phase I was to determine the best adhesive from the point of view of its strength. For this stage four types of adhesive and two adhesive spread rate applied to the narrow and wide faces of the laminae (Figure 1b) were selected. The adhesives used were Urea-Formaldehyde (UF), Melamine-Formaldehyde (MF), Melamine-Urea-Formaldehyde (MUF), and mixture of 50% of UF and 50% MF. The adhesive spread rate used over the wide faces was 400 g/m^2 and 450 g/m^2 while adhesive spread rate used along the narrow faces was 200 g/m^2 and 250 g/m^2. This amount of adhesive was based on the adhesive manufacturer specifications and recommendations. Once the best type of adhesive is selected based on phase I results, phase II began to estimate the optimal spread rate. The spread rate used along the narrow faces was half of that used on the wide faces. The amount of adhesive on wide faces in g/m^2 selected was 260, 280, 300, 400 and 450. Five samples for each adhesive type and adhesive spread rate were tested.

Test procedures selected for the adhesive calibration program were static bending and glued line shear. Samples were tested on a MTS Universal Testing Machine in the Structural Model Lab of the Universidad de Los Andes in Bogotá, Colombia. Specimens followed the specifications given by the Colombian Institute of Standards Techniques (ICONTEC) for woody materials which are based on the ASTM standards D1037 (2006) and D143 (2007) for glued line shear and the static bending tests, respectively. The specimens used for the static bending tests were 50 x 50 mm in section, and 760 mm in length. The load was applied at the center of the 380 mm span with a load rate of 2.5mm/min. The failure load and displacement at the middle of the span were recorded, and the modulus of elasticity (MOE) and rupture (MOR) were calculated. Figure 2 presents the dimensions of the test specimen and setup for the glued line shear test. The load was applied through a self aligning seat with a continuous motion of the movable head of the testing machine with a rate of 0.6mm/min. Shear strength at failure based on maximum load was determined.



(a) Specimen Dimension in (mm) (b) Test setup

Figure 2. Glued line shear test

Results and Discussion

A total of two hundred samples were tested during the adhesive calibration program. A summary of the average stresses for glued line shear and bending tests, along with the corresponding coefficients of variation (CV) for both phases are presented in Table 1. A comparison of the bond shear strength for different types of adhesives using the spread rate specified by the manufacturer (phase I) is shown in Figure 3. Although the specimens with MUF adhesive exhibited slightly higher values of bond shear strength, there were no significant differences in this value among the four adhesives used. Moreover, the amount of the adhesive applied on the wide and narrow faces did not affect the value of bond shear strength. Similar behavior was observed for the MOE and MOR obtained from the bending tests with different type of adhesives and spread rates. Failure of the substrate (Guadua) was observed in all the specimens of glued line shear and bending tests. It seems that spread rate specified by the adhesive manufacturer was on the conservative side producing failure of the substrate.

Table 1. Summary of the average stresses for glued line shear and bending test.

PHASE I							
Adhesive		Bond Shear Stress		Bending Stresses			
				MOE		MOR	
Type	Spread Rate [g/m^2] Wide/Narrow Faces	Average Stress [MPa]	CV [%]	Average Stress [MPa]	VC [%]	Average Stress [MPa]	CV [%]
UF	400/200	12.3	3.3	13821	5.8	112	8.6
	450/200	12.9	4.0	13645	4.5	116	7.7
	400/250	12.3	6.0	14125	4.1	117	6.8
	450/250	12.7	7.7	13676	4.8	114	3.4
MF	400/200	12.9	7.1	13190	3.0	113	9.0
	450/200	13.0	2.8	14163	6.6	118	9.0
	400/250	12.0	2.9	14077	5.2	116	7.2
	450/250	13.0	6.4	13778	4.3	117	8.7

Table 1. Summary of the average stresses for glued line shear and bending test. (continuation)

PHASE I							
Adhesive		Bond Shear Stress		Bending Stresses			
				MOE		MOR	
Type	Spread Rate [g/m^2] Wide/Narrow Faces	Average Stress [MPa]	CV [%]	Average Stress [MPa]	VC [%]	Average Stress [MPa]	CV [%]
MUF	400/200	12.9	4.9	13373	2.9	110	5.2
	450/200	13.1	3.3	13301	4.8	116	3.2
	400/250	13.0	6.4	13599	4.6	113	7.2
	450/250	13.1	2.3	13451	4.0	117	6.9
50% UF + 50% MF	400/200	12.7	4.8	13737	4.2	113	6.9
	450/200	12.8	4.2	13974	7.6	116	7.7
	400/250	12.8	5.2	14022	7.8	115	6.1
	450/250	12.9	5.6	14095	4.7	117	6.4
PHASE II							
50% UF + 50% MF	260/130	9.6	12.9	13220	4.9	103	7.4
	280/140	9.5	12.3	13058	7.0	104	8.7
	300/150	13.1	7.7	13732	6.2	113	6.8
	350/175	12.9	7.5	13658	6.4	113	6.5

Durability is one of the most important properties in a structural element. Thus, it is necessary to have weather and water resistance adhesive for exterior or semiexterior structural applications in GLG. UF adhesives have low water resistance and it can be used for interior applications. In the other hand, MUF adhesives have higher resistance to water attack compare to UF adhesives but they are usually more expensive. Therefore, a combination of UF and MF might be a practical and economical solution having an adequate performance for exterior applications. Based on phase I results, it seems that all the adhesives behave well from the strength point of view. Taking into account strength, durability and cost, the 50% UF +50% MF was the adhesive selected for the phase II of the calibration program. Figure 4 shows the average bond shear strength ± standard deviation of the specimens with 50% UF+50% MF adhesive and different spread rate. Bond shear strength remained practically constant with an average value of 13 MPa for an adhesive spread rate at wide/narrow faces of 300/150 g/m^2 and higher. For lower adhesive spread rate, 280/140 and 260/130 g/m^2, the bond shear strength was 9.5 MPa, which is 27% lower than that obtained for higher adhesive spread rates. Failure of the substrate was observed in the glued line shear specimens with adhesive spread rate at wide/narrow faces of 300/150 g/m^2 and higher. Whereas, combined failure of the adhesive and substrate was observed in the specimens with adhesive spread rate at wide/narrow faces of 280/140 g/m^2 and lower. This combine failure was achieved because the value of shear bond stress is almost the same as the value of strength parallel to the grain of GLG reported by Correal et al. (2008). In general, these results indicate that adhesive spread rate at wide/narrow faces of 300/150 g/m^2 seems to be the optimal amount of adhesive

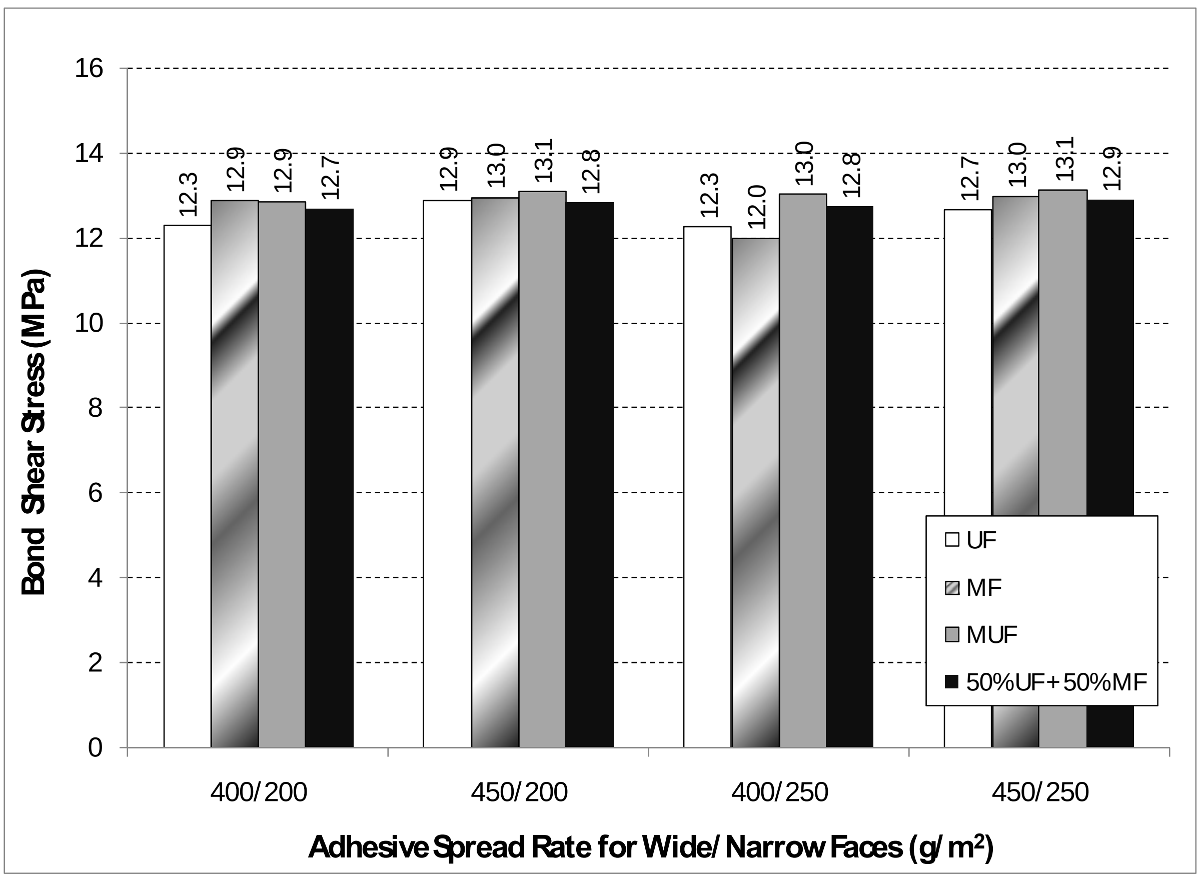


Figure 3. Bond shear strength for different types of adhesives and spread rate.

In contrast with bond shear stress, bending stresses were not drastically affected by the adhesive dosage as can be seen in Figure 5. Like bond shear strength, MOR did not change for adhesive dosages of 300/150 g/m^2 and higher. Difference of 4.5% and 7.7% were found between adhesive dosages at wide/narrow faces of 300/150 g/m^2 and 280/140 g/m^2 for MOR and MOE, respectively. MOE and MOR values are not affected by adhesive dosage because the maximum horizontal shear stress producing in the bending tests was about 4.0 MPa. This value is only 50% of the lowest bond shear strength obtained of 8.3 MPa. As a result, all of the bending specimens exhibited failure of the substrate without any delamination.

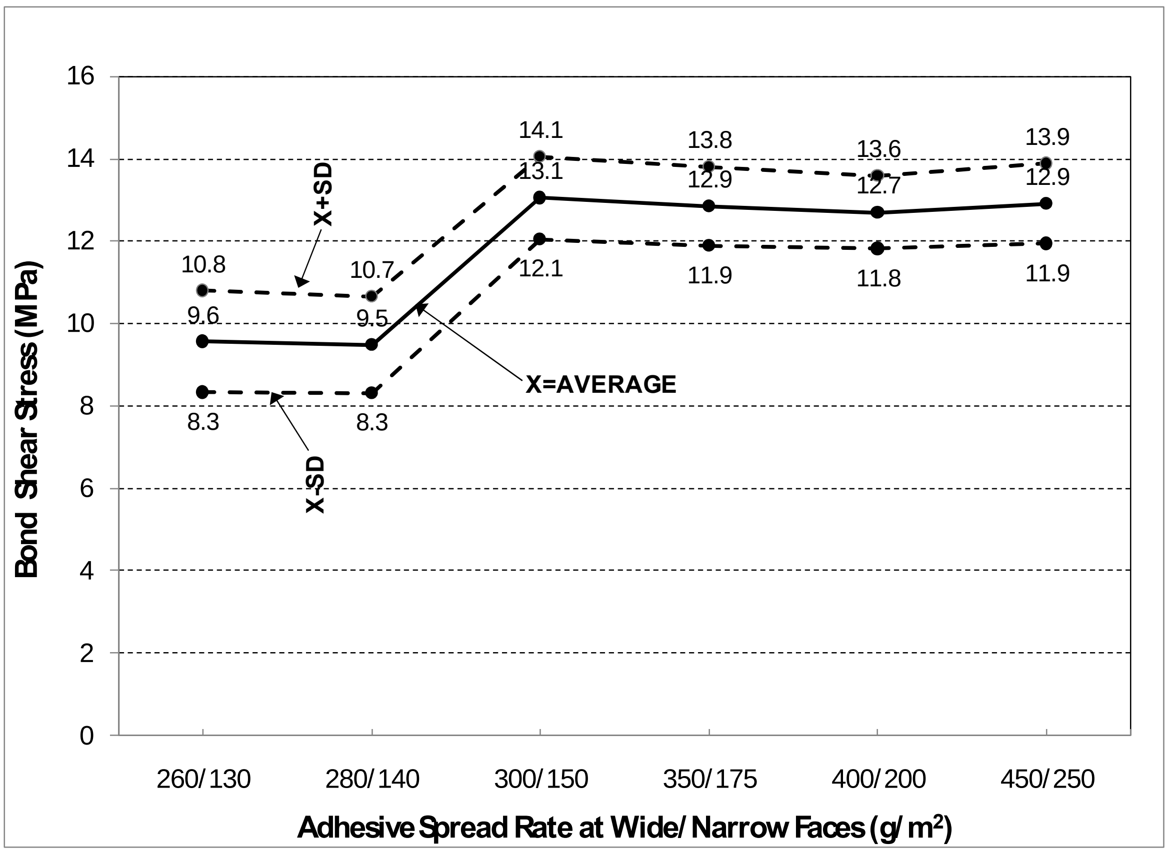


Figure 4. Bond shear strength for different adhesive spread rate of 50% UF +50% MF adhesive.

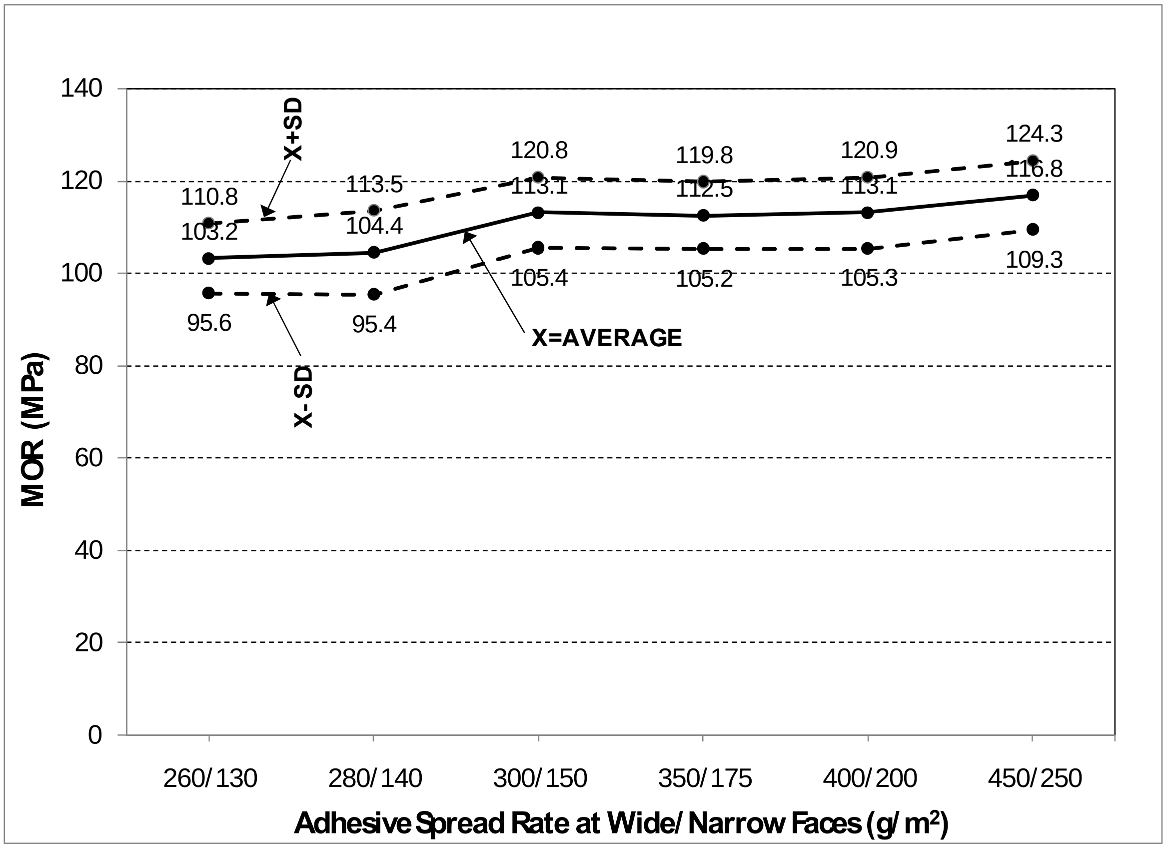


Figure 5. Modulus of rupture for different adhesive spread rate of 50% UF +50% MF adhesive.

Conclusions

Based on the results of this study, the following conclusions are drawn:

1. Bond shear strength is a good indicator of the optimal amount of adhesive to be used in any glued laminated material. The optimal amount of adhesive is reached when bond shear strength is close to the strength of the substrate, and failure of substrate is achieved. Adhesive failure need to be avoided since it is very difficult to predict.
2. Particularly for GLG, 300gr/m^2 of adhesive applied on the wide faces and 150gr/m^2 along the narrow faces is the right adhesive spread rate to use. Taking into account the adhesive spread rate recommended by the adhesive manufacturer and the optimal adhesive spread rate established in this study, substantial savings can be obtained since 66% of adhesive can be saved.
3. Bending properties (MOE and MOR) of GLG are not affected by the adhesive spread rate used in this study. This behavior is explained by the fact that the horizontal shear stresses induced by bending are lower than the bond shear strength and failure of the substrate will occur first than bond failure (delamination).

Acknowledgement

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Mechanical Properties and Failure Characteristic of Phenolic-Treated Plybamboo

Anwar, U.M.K[1]., Hamdan, H[1]., Paridah, M.T[2]., Mohamad Omar, M.K[1]., Mohd Jani, S[1] and Siti Rafidah, M[1]

[1] Forest Research Institute Malaysia (FRIM), Kepong, Selangor Darul Ehsan

[2] Universiti putra Malaysia, Serdang, Selangor Darul Ehsan

Abstract

The mechanical properties and failure characteristic of phenolic-treated (low-molecular-weight phenol formaldehyde) plybamboo made from *Gigantochloa scortechinii* were studied. The MOR, MOE and compression parallel to grain of the phenolic-treated plybamboo were significantly higher compared to those of untreated plybamboo. The failure in bending test occurred in compression and tension failure for 3 ply and rolling shear for 5-ply for phenolic-treated plybamboo. In compression parallel to grain, the crushing failure occurred. Generally, the treatment of bamboo strips with LMwPF resins was found to significantly improve the properties of plybamboo.

Keywords: impregnation, phenolic resin, plybamboo

Introduction

The improvements of lignocelluse material using impregnation method have been widely studied (Stamm and Beacheler, 1960; Hill, 2006). A significant improvement in mechanical and dimensional stability was reported when sliced birch (*Betula pendula*) was impregnated with polypropylene (Mahlberg *et al.,* 2001). Deka *et al.* (2003) noticed that when bamboo was impregnated with resin (phenol formaldehyde, urea formaldehyde or melamine formaldehyde) it caused significant increase in strength properties and exhibited higher dimensional stability.

Like many other modification systems, resin treatments are expected to influence the strength properties (Mahlberg *et al.,* 2001; Deka *et al.,* 2003; Shams *et al.,* 2004). Zaidon *et al.* (1990) found that the polyacralate influenced the mechanical properties of wood. The objective of this study was to evaluate the mechanical properties and failure characteristics of plybamboo manufactured from strips of 4-year-old *Gigantochloa scortechinii* that have been impregnated with low molecular weight (LMwPF) resin.

Material and methods

The bamboo (*Gigantochloa scortechinii*) was collected from the Forest Research Institute Malaysia (FRIM), Kepong, Selangor. The age of the bamboo was four years old. The bamboo strips were impregnated with low molecular weight phenol formaldehyde (LMwPF) resin and then the samples were dried in an oven for a few hours. The phenolic-treated bamboo strips were glued together edge-to-edge using phenol resorcinol formaldehyde (PRF) resin to produce a veneer. The veneers were then assembled perpendicular to each other to form a 3-ply (12 mm) and 5-ply (20 mm) plybamboo using phenol formaldehyde resin as a binder. The plybamboo were hot pressed at an optimum pressing condition of 140^{o}C.

Results and Discussions

Generally, the mechanical properties of phenolic-treated plybamboo meet the minimum requirement stipulated in the Forestry Trade Standard of the People's Republic of China: LY 1055-91 (Anon, 1992[a]). Table 1 shows the effects of the resin treatment on the mechanical properties (modulus of rupture, modulus of elasticity and compression parallel to grain) of the plybamboo. Clearly, phenolic treatment had significantly ($p \leq 0.05$) improved the mechanical properties of the plybamboo. The presence of LMwPF resin apparently had strengthened the weaker parenchymatous cells comparable to the vascular bundles. Similar observation using different materials has been reported by other researchers (Kajita and Imamura, 1991; Wang *et al*., 2000; Shams *et al.,* 2004; Paridah *et al.,* 2006).

The mean value for modulus of rupture (MOR), modulus of elasticity (MOE) and compression parallel to grain of untreated and phenolic-treated plybamboo were shown in Table 1. The mechanical properties of untreated (3- and 5-ply) were lower than phenolic-treated plybamboo. For 5-ply, the values for MOR, MOE and compression parallel to grain values of phenolic-treated plybamboo were 38%, 30% and 33% higher than the untreated plybamboo (Table 1). The effect from the phenolic-treatment (LMwPF resin) was apparently more dominant in bending strength for 5-ply and in compression parallel to grain in 3-ply.

Table 2 shows the specific strength (SS, i.e., strength / density) of each sample for untreated and phenolic-treated plybamboo. The overall specific values of MOR, MOE and compression parallel to grain of untreated plybamboo, were significantly lower compared to those of phenolic-treated boards. The results suggest that, phenolic treatment did increase the mechanical strength of the plybamboo significantly ($p \leq 0.05$) as can be seen in the higher specific strength value.

The mechanical properties of phenolic-treated samples were increased due to the presence (through bulking process) of the LMwPF resin. The improvement due to: (1) the LMwPF resin increases the strength of the bamboo strips by filling the voids either fully or partially in the parenchyma cells and (2) the improvement of bonding properties due to crosslinking between LMwPF (in the strips) and PF resin (on the surface of the strips).

The failure characteristics of phenolic-treated plybamboo (3-ply) were observed to occur as compression and tension failure (Plate 1). The failure for compression originates from the area where stress is applied (from load head) and progresses vertically in both the phenolic-treated and untreated plybamboo. Tension failure was also observed at the bottom of the samples. Same trends were noted by Zaidon *et al.* (1990) in the failure of treated wood (sweetgum and southern pine) failed normally in compression and followed by tension.

However, the rolling shears influence the stress distribution in 5-ply phenolic-treated plybamboo. From the observation during static bending,, the rolling shear occurred at perpendicular direction at 4^{th} layer from the load head. The failure (5-ply) apparently started from compressive failures at first layer and followed by a rolling shear as shown in Plate 2. These indicate the layer (4^{th} layer) was the weakest point where the rolling shear occurred between the vascular bundles and parenchyma.

Conversely, in untreated plybamboo (5-ply), the failure mainly occurs at the glue line between 3^{rd} and 4^{th} layer due to shear stress between PF glueline and bamboo veneer. Indeed, this phenomenon (glue line shear) had been used earlier by Newlin and Trayer, (1956) to explain the failure between adhesive and adherend where the failure is countered at the interfacial due to excessive shear deformation.

In compression parallel to the grain test, when the stress were applied on axial on the plybamboo samples, the outer region (first and fifth layer of a 5-ply board) shows signs of collapsing first while the middle layer resists. However, as the first layer collapses, the stresses rapidly concentrate and spread at the perpendicular orientation and thus forming which perform crack across the thickness of the lamilae. The failure occurred mainly at the topside of the specimen either 3- or 5-ply (Plate 3) of untreated and phenolic-treated plybamboo, which was indirect contact under the loading head.

Hamdan (2004) noted the failure in axial compression is usually initiated by the formation of minute compression failures (“kinking” or slip planes) in the cell wall and when the maximum strength is attained, gross macroscopically visible crushing and shearing bands arise due to buckling of the cell wall. Hidalgo (1993) explained that the uneven distribution of stress in the bamboo culms induces relative tensions in the innermost ring resulting in stress-displacement difference leading to longitudinal crack formation.

Conclusions

The study has proven that treating the bamboo strips with LMwPF resin had improved the strength of plybamboo made from it. Based on the mean value and specific strength (i.e., strength/density) of phenolic-treated plybamboo, these improvements were significant even after excluding the board density factor. In terms of failure characteristics, there is similar failure behavior between untreated and phenolic-treated plybamboo for 3-ply in compression and tension. The modes of failure were different for 5-ply phenolic-treated and untreated plybamboo. Crushing failure at the top end of the sample occurred during compression parallel to the grain test.

Acknowledgement

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Table 1. Mechanical properties of untreated and phenolic-treated plybamboo

Plybamboo specimen	Mean value (Nmm^{-2})			Strength improvement (%)		
	MOR	MOE	$Comp._{//}$	MOR	MOE	$Comp._{//}$
	3-ply (12 mm)					
Untreated	127[a] (8)	16778[a] (1375)	41[a] (5)			
Phenolic-treated	164[b] (18)	19767[b] (2393)	60[b] (5)	29	18	46
	5-ply (20 mm)					
Untreated	115[a] (7)	13561[a] (1245)	45[a] (5)			
Phenolic-treated	159[b] (16)	17648[b] (1474)	60[b] (4)	38	30	33

Note: MOR= Modulus of Rupture; MOE: Modulus of Elasticity; $Comp._{//}$: Compression parallel to the grain.
Values are average of 240 specimens
Values in parentheses are standard deviations
Means followed with the same letters [a,b] in the same column are not significantly different ($p \leq 0.05$)

Table 2. Specific strength of untreated and phenolic-treated plybamboo

Plybamboo specimens	Specific strength (MNm kg^{-1})		
	SS MOR	SS MOE	SS Compression // to grain
		3-ply (12 mm)	
Untreated	0.16[a]	20.8[a]	0.05[a]
Phenolic-Treated	0.19[b]	23.4[b]	0.07[b]
		5-ply (20 mm)	
Untreated	0.14[a]	16.3[a]	0.05[a]
Phenolic-Treated	0.17[b]	19.2[b]	0.07[b]

Note: SS MOR = Specific strength MOR= MOR/Density
SS MOE = Specific strength MOE= MOE/Density
SS Compression$_{//}$ to grain = Specific strength Compression parallel to grain = Compression$_{//}$ to grain /Density
Means followed with the same letters [a,b] in the same column are not significantly different ($p \leq 0.05$)

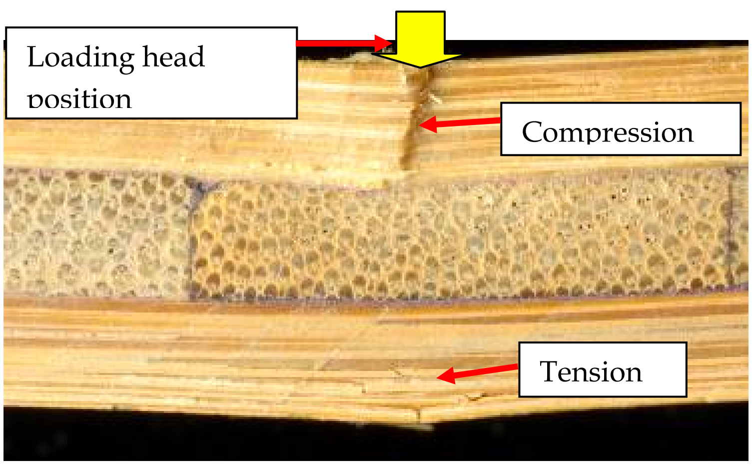

Plate 1. Failure of 3-ply phenolic-treated plybamboo in compression and tension after static bending test

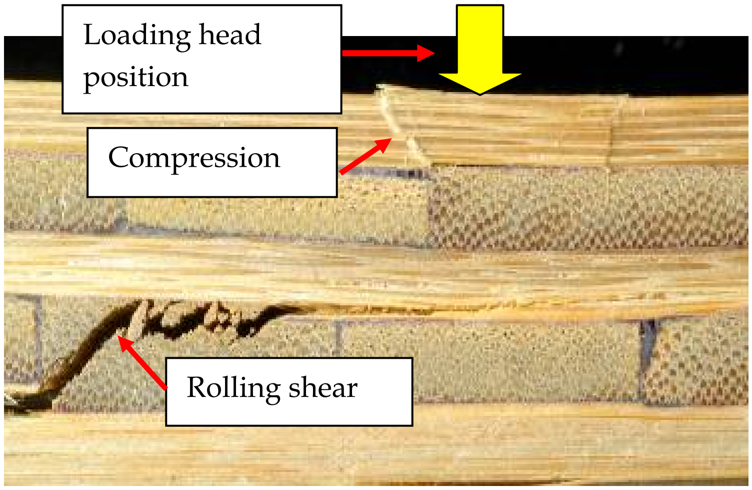

Plate 2. Failure of 5-ply phenolic-treated plybamboo in compression and rolling shear at 4th layer during static bending test

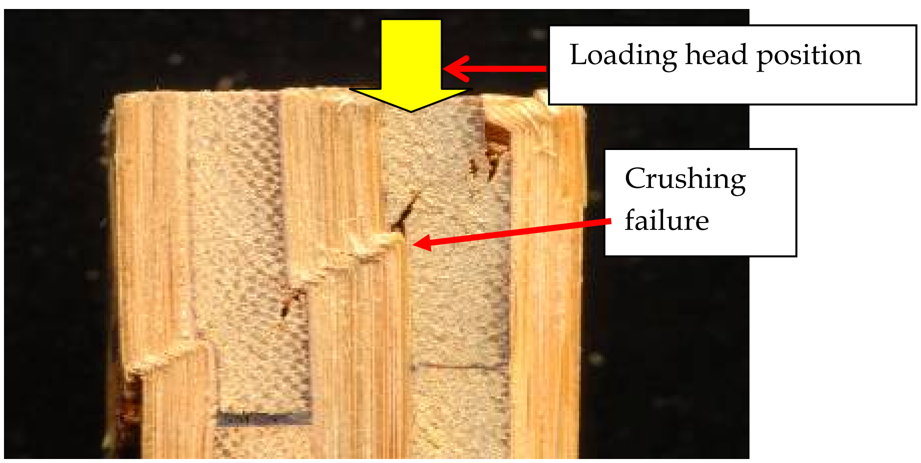

Plate 3. Failure at 5-ply phenolic-treated plybamboo in compression parallel to the grain test (edge view)

Alkali-oxygen Pulping on Steam-explosion Pretreated Bamboo Species

Wikhan Anapanurak[1], Nikhom Laemsak [2], Teera Veenin[3], and Pensri Atiwannapat[4]

[1] Pulp and Paper Technology Laboratory, KAPI, Kasetsart University, Bangkok, Thailand.
[2, 3] Wood Products Division, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.
[4] Forest Products and Economic Research Institute, Royal Forest Department, Bangkok,Thailand.

Abstract

A study was conducted on the morphology of the fibers and chemical composition of the 3-years-old bamboo-culm of *Thyrsostachys siamensis*, *Dendrocalamus latiflorus*, and *Bambusa arundinacea* for pulping them by alkali-oxygen process. This pulping conditions was pretreatment with steam pressure varied at 21 kg/cm^2 for 5 minutes follow by soaking with 1% NaOH, liquor to wood ratio 10:1 at 90 ^oC for 10 minutes and cooking with 15% NaOH, liquor to wood ratio 4:1 with oxygen pressure at 7 kg/cm^2 at 105 ^oC for 90 minutes. Pulps produced from different species of bamboo-culms were about 38.80-55.40% yield at the Kappa numbers ranged 9.74-15.91. Bleaching in different sequences both ECF and TCF, Z-P-Z-P bleaching sequence provided appropriate high brightness of all species and followed by D-P-D-P bleaching sequence and P-P bleaching sequence. Bleached Pulps manufactured from alkali-oxygen process and bleached with Z-P-Z-P sequence from 3 years-old *T. siamensis*, *D. latiflorus*, and *B. arundinacea* had high brightness of 80.00-90.70% and good strength properties in burst index, tear index, tensile index and folding endurance of 1.18-1.75 KPa.m^2/g, 5.84-9.11 mN.m^2/g, 15.49-29.21 N.m/g, and 1.36-4.74, respectively and also are classified as fitting for printing and writing paper.

Keywords: The 3-Years-old Bamboo Culms of *Thyrsostachys siamensis* , *Dendrocalamus latiflorus*, and *Bambusa arundinacea*, Alkali-oxygen Process, Product Quality from Bleached Pulp with ECF and TCF Bleaching, and Utilization.

Introduction

There are numerous species of edible bamboo in Thailand. Bamboos are planted widely in several provinces, most are in central Thailand such as Kanchanaburi, Nakornayok and Pachinburi etc. The most important purposes are for food, craft, industry, furniture, house structure in addition to raw material for pulping (11). Bamboo has been used as a raw material for pulping in Thailand for most 30 years. Bleached pulp produced from bamboo has good quality and is excellent for wrapping paper and printing and writing papers (3, 9, 12). In India bamboo is used as raw material for pulping about 66% of all pulp productions (10). Bamboo has long fiber and is a major raw material as a non-wood (9). Chemical pulping creates deplorable environmental pollution and appalling odor. Throughout the preceding few decades new pulping technology has been developed to resolve the environmental dilemma. New technologies are implemented in countless industries including pulp and paper industry. The purpose of this study is pulping from three species of bamboo-culms by a flawless technological process in implementing an alkali-oxygen process and this process condition is pretreatment with steam pressure at 21 kg/cm^2 for 5 minutes follows by soaking with 1% NaOH, liquor to wood ratio 10:1 at 90 ^{o}C for 10 minutes and cooking with 15% NaOH, liquor to wood ratio 4:1 with oxygen pressure at 7 kg/cm^2 at 105 ^{o}C for 90 minutes (1). Pulps produced are bleached by total chlorine-free (TCF) using Ozone (Z) – Hydrogen peroxide(P)-Ozone(Z)-hydrogen peroxide(P) sequence to compare the quality pulps, those bleached by total chlorine-free using P-P sequence and by elementary chlorine free (ECF) using Chlorine dioxide (D)-P-Chlorine dioxide, (D)-P sequence and also estimate to bleached pulp utilization of paper industry.

Experiment

Bamboo culms of species *Thyrsostachys siamensis* , *Dendrocalamus latiflorus*, and *Bambusa arundinacea* , 3 years old were supplied from project areas in Kanchannburi province and chipped in a laboratory by a chipper. Chips were screened to eliminate the undersize and oversize and to get the acceptable length of 5/8-1 inches and, subsequently seasoned to dry.

1. Morphological raw fiber was analysed for standard dimensions e.g. length, width, lumen diameter and cell wall thickness in according to the Franklin method (8). The calculations were made on Runkel ratio, flexibility coefficient, slenderness ratio and percentage of wall fraction for predicting fiber quality.

2. Chemical analyses of raw material made use of an average with respect to the Technical Association of the Pulp and Paper Industry (TAPPI) test method (5) such as solubility in alcohol, alcohol-benzene (T204-cm-97), hot water (T207-cm-97), 1%NaOH (T212-om-98), ash (T211-om-93), lignin(T222-om-88), alpha-cellulose (T203-om-88) and pentosan (T223-cm-01) with the exception of holocellulose by sodium chlorite method (6).

3. Pulping from the bamboo chips by alkali-oxygen process were prepared with steam pressure varied at 21 kg/cm^2 for 5 minutes follow by soaking with 1% NaOH, liquor to wood ratio of 10:1 at 90^o C for 10 minutes and cooking with 15% NaOH, liquor to wood ratio of 4:1 under oxygen pressure 7 kg/cm^2 at 105^o C for 90 minutes (1). Bamboo pulps from this process were analyzed by average the means of mutually screened and rejected yield and kappa number (T236-cm-99)

4. Bleaching pulps by D-P-D-P series for alkali-oxygen pulp. The conditions used are summarized in table 1.

Table 1: Condition for bleaching by D-P-D-P sequence

Items	Stage			
	D	P	D	P
Chemical charge,%	0.2xkappa no.	1	0.2	1
NaOH,%	-	1	-	1
Na_2SiO_3, %	-	1	-	1
$MgSO_4$,%	-	0.05	-	0.05
Consistency,%	10	12	10	12
Temperature, ^oC	80	90	80	90
Time, minute	120	120	120	120

Pulps produced were bleached by Z-P-Z-P sequence or P-P sequence for alkali-oxygen pulp. The conditions used are summarized in table 2.

Table 2: Condition for bleaching by Z-P-Z-P or P-P sequence

Items	Stage			
	Z	P	Z	P
Chemical charge,%	2.5	2	2.5	2
CH_3COOH, %	10	-	5	-
NaOH,%	-	1	-	1
Na_2SiO_3, %	-	1	-	1
$MgSO_4$,%	-	0.05	-	0.05
Consistency,%	4	12	4	12
Temperature, ^oC	25	90	25	90
Time, minutes	40	120	40	120

5. Physical properties analyzed by averaging those screened pulp yields used each species of bamboo-culms of the same pulping processes were disintegrated for 5 minutes, beating with appropriated revolutions and measured freeness of 300 ml (T227-om-99). The standard hand-sheets were tested for physical properties according to TAPPI Standards (T220-sp-01) on weight basis, burst strength, tear strength, tensile strength, stretch, folding endurance, brightness and opacity.

Results and Discussion

1. Morphological fiber

Mean average of fiber dimensions of 3 years-old *T. siamensis* , *D. latiflorus*, and *B. arundinacea* are shown in Table 3.

Table 3: Morphological fiber of three species of bamboo culms and anatomical properties

Items	*Thyrsostachys siamensis*	*Dendrocalamus latiflorus*	*Bambusa Arundinacea*
Length, mm	2.80	2.18	2.27
Width, µm	27.25	21.01	23.19
Lumen width, µm	10.51	11.35	3.45
Cell wall thickness, µm	8.37	4.83	9.87
Runkel ratio	1.59	0.85	5.72
Flexibility coefficient	0.39	0.54	0.15
Slenderness ratio	102.59	103.56	97.90
Wall fraction (%)	61.44	45.99	85.12

The table 3 showed that the lengths of fiber were respectively 2.80, 2.18 and 2.27 mm and defined them as long fibers(2). The highest length, width, lumen width and cell wall thickness were shown of *T. siamensis*, *T. siamensis*, *D. latiflorus*, and *B. arundinacea*, respectively. The lowest length, width, lumen width and cell wall thickness were for *D. latiflorus*, *D. latiflorus*, *B. arundinacea* and *D. latiflorus*, respectively. The range of Runkel ratio, flexibility coefficient, slenderness ratio, and percentages of wall fraction were respectively 0.85-5.72, 0.15-0.54, 97.90-103.56 and 45.99-85.12%. It is probable that pulp properties with Runkel ratio more than 1 would be harder in tension for fiber and less oriented fiber to make paper into fluffiness(7) except *D. latiflorus*, with flexibility coefficient less than 0.5. The paper had low tensile strength, burst strength and folding endurance apart from *D. latiflorus*, with slenderness ratio more than 75 were the paper of the best tear strength and with percent of wall thickness more than 40 percent would be thus poor paper while fibers completely oriented to get lower tensile and burst strength.

2. Chemical composition

The chemical compositions of 3 years-old *T. siamensis*, *D. latiflorus*, and *B. arundinacea* were showed in table 4.

Table 4: Chemical compositions of three species of bamboo-culms

Component (% by ODRM)	*Thyrsostachys siamensis*	*Dendrocalamus latiflorus*	*Bambusa arundinacea*
Alcohol-benzene solubility	6.19	3.53	3.96
Alcohol solubility	2.22	1.49	2.01
Hot water solubility	3.02	4.54	5.52
Total extractive	11.43	9.51	11.48
1%NaOH solubility	23.63	26.81	25.79
Ash	2.49	1.71	2.23
Lignin	23.79	23.31	23.02
Holocellulose	62.30	65.48	63.27
Alfa cellulose	36.22	41.02	38.20
Pentosan	11.94	14.35	12.12

The table 4 showed that *T. siamensis* had the highest solubility in alcohol and alcohol-benzene, and *B. arundinacea* was the highest in water solubility. *D. latiflorus* had the lowest solubility in alcohol and alcohol-benzene and *T. siamensis* had the lowest solubility in water and 1% NaOH. *B. arundinacea* had the highest extractive, and *T. siamensis* had the highest ash content while the lowest was shown *D. latiflorus*. Lignin content was highest for *T. siamensis* and lowest for *B. arundinacea*, and were in the range of 23.02-23.79% on the ovendried basis of raw material (percentage of ODRM). These values are on the side and showed that the pulps were somewhat easy to delignify. Holocellulose and alfa-cellulose content were highest for *D. latiflorus* and the lowest for *T. siamensis*, and in the range of 62.30-65.48, 36.22-41.02% of ODRM. It signified that the pulp yield was expected to be higher for *D. latiflorus* in relative to *B. arundinacea*, and *T. siamensis*. Pentosan content ranged from 14.35% of ODRM for *D. latiflorus* to 11.94% ODRW for *T. siamensis*. This implied the insufficient amount remained on pulp to increase physical properties of paper in burst strength and folding endurance.

3. Pulp yield production

Pulp yield and kappa number of three species of bamboo-culms by alkali-oxygen process are in tables 5.

Table 5: Yield and kappa numbers of three species of bamboo-culms by alkali-oxygen process

Species	Steam pressure (kg/cm2)	Yield (%)		Kappa no.
		Accepted	Reject	
Thyrsostachys siamensis	21	38.80	0.30	15.91
Dendrocalamus latiflorus	21	52.16	0.02	9.74
Bambusa arundinacea	21	55.40	0.35	13.29

Remark: Alkali-oxygen process was pretreatment with steam pressure at 21 kg/cm^2 for 5 minutes followed by soaking with 1% NaOH, liquor to wood ratio 10:1 at 90 ºC for 10 minutes and cooking with 15% NaOH, liquor to wood ratio 4:1 with oxygen pressure at 7 kg/cm^2 at 105 ºC for 90 minutes

Table 5 showed that pulping with steam explosion pre-treatment of 21 kg/cm^2, *B. arundinacea* pulp yield of 55.40% was higher than *D. latiflorus* and *T. siamensis* of 52.16, 38.80% of ODM respectively. *D. latiflorus* had lower Kappa number than *B. arundinacea* and *T. siamensis* (9.74, 13.29 and 15.91 respectively).

4. Physical properties of pulp

The pulps from *T. siamensis, D. latiflorus* and *B. arundinacea* by alkali-oxygen process was beaten until freeness of 300 ml obtained, then formed them to the standard hand-sheets. Physical properties were shown in table 6.

Table 6: Comparison of physical properties of three species of bamboo-culms pulp by alkali-oxygen process at 300 ml freeness

Items	*Thyrsostachys siamensis*	*Dendrocalamus latiflorus*	*Bambusa arundinacea*
PFI mill, rounds	2,536	544	2,692
Burst index, KPa. m^2/g	1.30	0.83	2.02
Tear index, mN. m^2/g	7.88	2.75	11.73
Tensile index, N.m/g	21.56	10.92	31.51
Breaking length, km	2.19	1.12	3.20
Stretch, %	1.26	0.62	1.87
Folding endurance,	16.60	0.00	7.75
Brightness, %	15.75	47.44	39.92
Opacity, %	99.26	95.63	96.15

Tables 6 showed that strength properties between the bamboo genus and species for alkali-oxygen process, *B. arundinacea* was highest in burst index, tear index and tensile index. *T. siamensis* had highest folding endurance, and *D. latiflorus* had the highest brightness. If strength properties were to be taken into account between species; it indicated that *D. latiflorus* pulp was weaker in burst index, tear index, tensile index, and folding endurance, but brighter than *B. arundinacea* and *T. siamensis*, respectively.

5. Physical properties of bleached pulp

The alkali-oxygen pulp of *T. siamensis, D. latiflorus* and *B. arundinacea* bleached by P-P, Z-P-Z-P and D-P-D-P sequence and were shown in tables 7, 8 and 9.

Table 7: Comparison of physical properties of three species of bamboo-culms bleached pulp with P-P by alkali-oxygen process at 300 ml freeness

Items	*Thyrsostachys siamensis*	*Dendrocalamus latiflorus*	*Bambusa arundinacea*
PFI mill, rounds	2,034	367	2,722
Burst index, KPa. m^2/g	1.38	0.80	1.52
Tear index, mN. m^2/g	8.76	2.12	5.65
Tensile index, N.m/g	24.19	7.41	20.60
Breaking length, km	2.45	0.75	2.11
Stretch, %	1.40	0.48	1.24
Folding endurance,	4.78	0.00	1.89
Brightness, %	29.45	72.74	59.08

Table 8: Comparison of physical properties of three species of bamboo-culms bleached pulp with Z-P-Z-P by alkali-oxygen process at 300 ml freeness

Items	*Thyrsostachys siamensis*	*Dendrocalamus latiflorus*	*Bambusa arundinacea*
PFI mill, rounds	2,000	1,100	1,900
Burst index, KPa. m^2/g	1.75	1.18	1.68
Tear index, mN. m^2/g	5.96	5.84	9.11
Tensile index, N.m/g	17.93	15.49	29.21
Breaking length, km	1.89	1.59	2.97
Stretch, %	0.34	0.27	0.41
Folding endurance,	1.75	1.36	4.74
Brightness, %	83.71	90.70	80.00

Table 9: Comparison of physical properties of three species of bamboo-culms bleached pulp with D-P-D-P by alkali-oxygen process at 300 ml freeness

Items	*Thyrsostachys siamensis*	*Dendrocalamus latiflorus*	*Bambusa arundinacea*
PFI mill, rounds	2,366	691	2,548
Burst index, KPa. m^2/g	1.50	0.82	2.02
Tear index, mN. m^2/g	8.64	2.52	8.52
Tensile index, N.m/g	25.68	8.35	25.56
Breaking length, km	2.61	0.86	2.50
Stretch, %	1.42	0.63	1.68
Folding endurance,	5.43	0.00	4.04
Brightness, %	54.05	90.05	88.91

Tables 7, 8 and 9 showed the strength properties of alkali-oxygen bleached pulps by P-P sequence, *D. latiflorus* was somewhat brighter (72.74%) than the others (29.45-59.08%), but *T. siamensis* had higher tear index, tensile index and folding endurance and *B. arundinacea* had higher burst index than others. With the Z-P-Z-P sequence , *D. latiflorus*, *T. siamensis*, and *B. arundinacea* were brightness of 90.70-80.00%, and they had burst index, tear index, tensile index and folding endurance of 1.18-1.75 KPa.m^2/g, 5.84-9.11 mN.m^2/g, 15.49-29.21 N.m/g, and 1.36-4.74, respectively. It is evident from this table 8, these three species of bamboo-culms pulped with the alkali-oxygen process and bleached with Z-P-Z-P sequence are probably appropriate for printing and writing paper in compliance with Thai Industrial Standards - TIS (4) as they have burst index of 1.18 -1.75 KPa.m^2/g, and brightness of 80.00-90.70%. And with the D-P-D-P sequence, *D. latiflorus*, and *B. arundinacea* were brighter (90.05-88.61%) than *T. siamensis* that only achieved 54.05%. *B. arundinacea* had higher bursting index, tear index, tensile index, and folding endurance than *D. latiflorus*. It is evident from this table 9, *B. arundinacea* pulped with the alkali-oxygen process and bleached with D-P-D-P sequence are probably appropriate for printing and writing paper in compliance with Thai Industrial Standards - TIS (4) as they have burst index of 2.02 KPa.m^2/g, and brightness of 88.91%. If the strength properties of alkali-oxygen bleached pulps were to taken into account between bleaching procedure to be found that Z-P-Z-D sequence and D-P-D-P sequence gave brighter pulps than P-P sequence.

Conclusions

Bamboo culms are a viable alternative for paper makers in quest of an ideal quality, an inexpensive source of non-wood fiber. It is obvious that all of bamboo culms yield anatomically long fiber. They have diverse morphological fiber and chemical composition affect of pulp yield and pulp quality. The different species of bamboo-culms were produced pulp about 38.80-55.40% yield at the Kappa numbers ranged 9.74-15.91. by alkali-oxygen process with steam explosion pretreatment at 21 kg/cm^2 for 5 minutes, followed by soaking with 1% NaOH, liquor to wood ratio 10:1 at 90 ^oC for 10 minutes, and cooking with 15% NaOH, liquor to wood ratio 4:1 with oxygen pressure at 7 kg/cm^2 at 105 ^oC for 90 minutes. Bleaching in different sequences both ECF and TCF, Z-P-Z-P bleaching sequence provided appropriate high brightness of all species and followed by D-P-D-P bleaching sequence only two(*D. latiflorus*, and *B. arundinacea*) and P-P bleaching sequence only one(*D.*

latiflorus). Bleached Pulps manufactured from alkali-oxygen process and bleached with Z-P-Z-P sequence from 3 years-old *T. siamensis*, *D. latiflorus*, and *B. arundinacea* had high brightness of 80.00-90.70% and good strength properties in burst index, tear index, tensile index and folding endurance of 1.18-1.75 KPa.m^2/g, 5.84-9.11 mN.m^2/g, 15.49-29.21 N.m/g, and 1.36-4.74, respectively and also are classified as suitable for printing and writing paper.

Acknowledgments

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Study of the Behaviour of Guadua Angustifolia Kunth Frames

Eng. Caori Takeuchi
Professor Universidad Nacional de Colombia

Eng. Fabian Lamus
Msc in Structures. Universidad Nacional de Colombia

Eng. Diego Malaver
Specialization in Structures. Universidad Nacional de Colombia

Eng. Juan Carlos Herrera
Msc in Structures. Universidad Nacional de Colombia

Eng. Jhon Fredy River
Msc in Structures. Universidad Nacional de Colombia

Abstract

As the Colombian code for earthquake resistant design and construction of buildings NSR-98 does not include provisions for the design of bamboo frames and the use of frames is an alternative to the load-bearing walls systems, The National University of Colombia has carried out an extensive research project about the behaviour of bamboo frames, aimed at the application of this sort of structures to house construction. In a first part of the research was investigated the behaviour of four different types of beam-column connections, as well as the performance of the best connection as part of a planar frame. For this, a real scale frame was build, with its beam-column joints easily to build and all the elements cut straight. In a second stage, planar frames with diagonal cables to restrict the lateral movement were tested. In a third stage, the behaviour of two different kinds of wall boards was investigated, in addition to the performance of the frame built with the panels. For this stage, numerical simulations were carried out for all the structural elements tested. Finally, in the last stage were tested tridimentional frames with diagonal bamboo elements and with the results was suggested the best structural configuration for a two-story house.

Keywords: Bamboo frames, Guadua Angustifolia Kunth, beam-column connections.

Introduction

Since many years ago, it has been common in Colombia build traditional houses using bahareque wall systems (the main constructing material is the local bamboo, combined with chicken steel meshes and plastered with cement mortar), however, the first construction recommendations were made just after the Quindio earthquake in 1999. The title E of the Standard Building "Bahareque houses of one and two stories" was proposed by the Colombian National Association of Earthquake Engineering (AIS) after an investigation about this construction system. Despite the fact that many investigations have been carried out, there are still some questions about the design of bamboo structures; especially with bamboo frame systems.

As structural systems of seismic resistance can be classified the moment-resistant frames, the concentric or eccentric frames with diagonals, or the load-bearing walls. In the first and second systems the frames are responsible for resisting both vertical and horizontal loads, while in the load-bearing walls system the walls are responsible for that function. It is possible as well to have combined systems, where the vertical loads are not necessarily supported by moment-resistant frames and the horizontal loads are supported by frames with diagonals or structural walls.

The bahareque structures work similar to the load-bearing wall systems, resisting the vertical and horizontal loads. However, the use of frames gives more architectonic flexibility because there is no necessity of some geometrical restrictions. Taking into account the benefits of using bamboo frames and considering that the Colombian code for earthquake resistant design and construction of buildings, NSR-98, does not include provisions for the design of bamboo frames, in the National University of Colombia has carried out an extensive research project that include several topics about the behaviour of bamboo frames.

In a first part of the research was investigated the behaviour of four different types of beam-column connections and the performance of the best connection as part of a planar frame. For this, a real scale frame was build, with its beam-column joints easily to build and all the elements cut straight. In a second stage, planar frames with diagonal cables to restrict the lateral movement were tested. In a third stage, the behaviour of two different kinds of boards was investigated, in addition to the performance of the frame built with the panels. For this stage, numerical simulations were carried out for all the structural elements tested. Finally, in the last stage were tested special frames with diagonal bamboo elements and with the results was suggested the best structural configuration for a two-story house.

Standard Frame

The same planar frame with standard dimensions was used throughout the entire project. The process of design and construction are summarised below.

Design

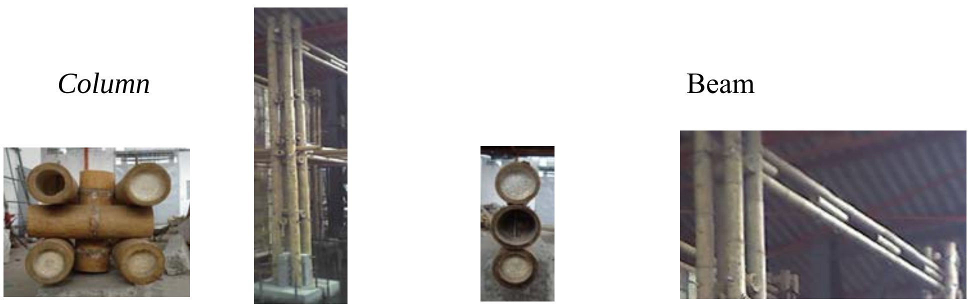
The construction of the guadua frames was planned to be quick and inexpensive, with an industrialized process carried out mechanically and in a short time.

Elements

The structures built in this research had two stories and one or two spans in each direction. The length of the spans depended on the internal architectonical distribution. Defined the dimensions of the structure, the bamboo elements were revised in order to have enough section to resist the external loads, and the culms were properly assembled.

Because of its natural conditions, the geometry of bamboo is a prismatic tube of hollow circular section. In order to form a structural section, each culm had its axis parallel to the longitudinal axis of the element, either a column or a beam, so the cross section of the structural element is made up of circular hollow sections.

In order to increase the inertia of the assembled structures and to make the construction of the connections easy, each culm was separated of each other using additional elements. The columns were formed by four culms and had additional elements forming cross sections. The beams were formed by two culms along its length, separated by short elements of bamboo (figure 1). All the bamboo elements were connected together by threaded bolts.



Column Beam

Cross section *General view* *Cross section* *General view*

Figure 1. Cross section and general views of the column and the beam of the standard frame

Design of connections

Easy and speed connections were selected and built, so complex cuttings and anchorages were eliminated because of the delay in the execution and the increase of the costs. All the element cuttings were straight and simple. On the other hand, in the connection design was included the geometry of beams and columns, so the beams fitted within the four column culms. The connection between those elements was made with threaded rods.

Construction

Materials

The structures were made up with Guadua Angustifolia Kunth, Macana variety not immunized. With an age ranged between 4 and 5 years, obtained from Armenia (Quindío, Colombia). For the beams the diameter of the elements ranged between 8 and 13 cm, and for the columns it ranged between 10 and 13 cm. After an exhaustive selection were not included elements with twists or cracks, and was not observed the presence of fungi or insects.

Construction

Figure 2 shows the selection of the elements to form beams and columns.

Figure 2. Elements selected and cut for construction of the standard frame

Figure 3 shows the construction of the frames after the prefabrication of beams and columns

Figure 3. Frame assemble

Investigation of the behaviour of a guadua angustifolia beam–column connection

In this first stage of the project was investigated the mechanical behaviour of a beam-column connection. A total of fifteen experimental tests of four different kinds of beam–column joints and three tests of planar frames were carried out. In addition, the best connection was analyzed using the finite element method, while the frames were studied theoretically using standard matrix analysis. (Lamus 2008).

Experimental methods

The mechanical properties of the bamboo were determined following the ISO 22157 recommendations. 40 tests of shear strength parallel to the fibre, 40 tests of compressive strength parallel to the fibre, and 20 tests of tensile strength parallel to the fibre were carried out. In addition to the standard tests, several non-standardized tests were done, such as 20 tests of radial compressive strength, 20 tests of tensile strength perpendicular to the fibre, and two torsion tests (Figure 4).

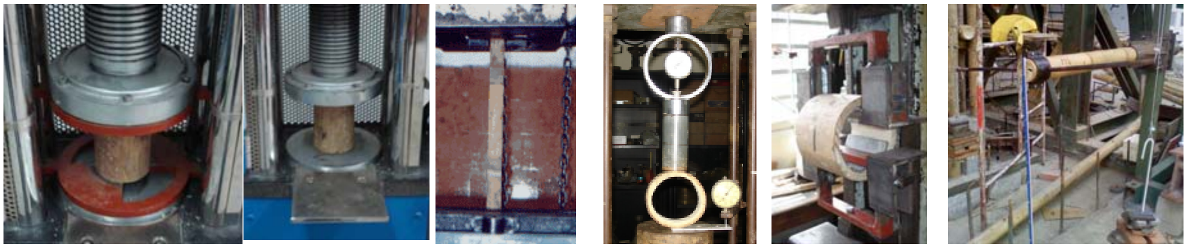


Figure 4. Laboratory tests: Shear parallel to the fibre, compression parallel to the fibre, tension parallel to the fibre, radial compression, tension perpendicular to the fiber, torsion.

With the results of the initial tests, the characteristic properties and values were calculated, including the longitudinal elastic modulus, the circumferential elastic modulus, and the shear modulus of rigidity.

The configuration of the connections used during the tests was determined assuming that these corresponded to the intermediate node of a two-story planar frame (2.9 m height and 4m of span). As a result, a T-shaped union was evaluated. In each test the column was supported horizontally at two points separated 2.9 m and the beam was in vertical position attached to the column at one end, and the other at cantilever. The load was applied horizontally in the same plane than the connection to the beam. Displacement measurements were taken at the top of the beam, at the support where the load was applied and at the connection. (Figure 5)

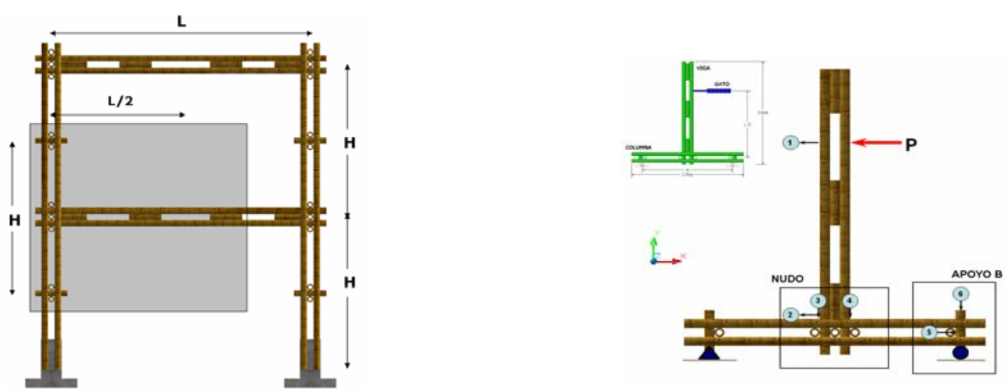


Figure 5. Beam-column connection: Localization in the frame, drawing of the connection

To the connections two kinds of tests were applied: monotonic and cyclic tests. In the fist group the load was increased until a maximum displacement, whereas in the second group, 6 cycles of loading and unloading were applied until a maximum displacement was obtained in the last cycle.

As the main mechanisms of failure for the beam-column connections are due to the shear parallel to the fibre and to the tensile perpendicular to the fibre, the connections were confinement with some wrapped metal hoops, and in order to prevent the crushing of the bamboos, polyurethane filler was used.

As was mentioned before, four groups of connections were tested. In a first group the connection had threaded rods; in a second group in addition to the rods, the connection had some hoop wrapped. In a third group, the connection had rods and polyurethane filler with some wood pieces. In the last group, known as full connection, were used rods, hoop wrapped, and filler. The number of experiments done was 15. The first group had 3 tests (1 monotonic and 2 cyclic), instead the other groups that had 4 tests (1 monotonic and 3 cyclic).

In the last stage of this initial project, the joint known as full connection was tested in three planar frames under cyclic load. The frames had two stories high, a spam of 4.05 m and because of space limitations, a total height of 4.6 m (2.1 high and 0.4 m of support). (figure 6)

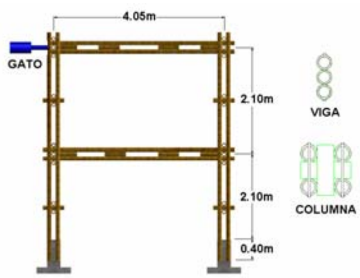


Figure 6. Test frame in guadua angustifolia

Numerical modelling

In the modelling of the connections was used the finite element method with the commercial software ANSYS. Because of the differences in the materials, was assumed an elastic behaviour for the bamboo and the polyurethane, instead of the steel rods which had elastoplastic behaviour. The mechanical properties obtained in the first part of the research were used to define the materials, assuming an orthotropic section. The confinement provided by the wrapped hoops was modelled as a pressure distribution over the element. (Figure 7)

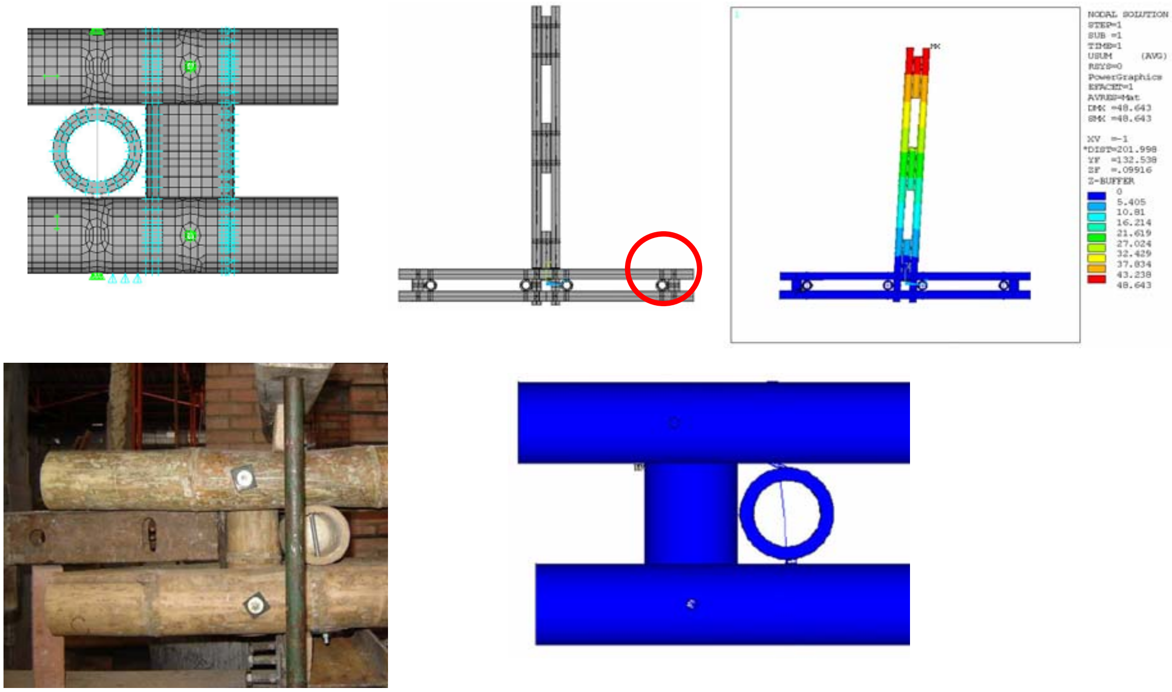


Figure 7. Numerical modeling of the beam-column connection. Comparison among numerical and experimental results

The frames were modelled using traditional structural matrix analysis with the commercial software SAP 2000. A linear elastic model was used. It was assumed that the bamboo is an isotropic material, in addition, was considered in the beam column joint a semi-rigid connection, where the stiffness spring constant was calculated from experimental data.

Conclusions

The main conclusions of this part of the research are summarized below.

The characteristic value of the shear strength parallel to the fibre was 4.38MPa, of the compression strength parallel to the fibre was 36.6MPa, of the tensile strength parallel to the fibre was 100.46MPa, and of the tensile strength perpendicular to the fibre was 0.46 MPa.

The elastic properties calculated from the tests were: longitudinal modulus of elasticity 14164.10 MPa, circumferential elastic modulus 668.51MPa, and shear modulus of rigidity 630MPa.

The rods used in the connections had an insufficient diameter. The deformation obtained was permanent and increased the bending rotation of the connection.

The slack that was left to the drilling rods also affected the relative rotation of the beam with respect to the column.

It was noted that the joint with the best behaviour was the full connection. The metal confinement was appropriate, avoiding failure by crushing or shear parallel to the fibre. In the same way, the Polyurethane filler avoided crushing failures in the connections.

The beam-column connection investigated is a Semi-rigid connection; the stiffness measured experimentally was 60.2 kN-m/rd. This value can be used in analytical models that use bamboo frames with this type of connection.

As the horizontal displacements measured in the frames were excessive, it is recommended to combine the structural system with walls or diagonals in order to restrict the horizontal displacements.

Stability of frames of guadua angustifolia braced with cables

Experimental methods

In this study, named "Stability of frames of guadua angustifolia braced with cables" (Malaver, 2007) the physical-mechanical properties of the guadua angustifolia used for the construction of the frames were found by means of 20 tests of compression parallel to the fibre, 20 tests of shear parallel to the fiber and 14 test of tension parallel to the fiber. The guadua had a natural drying to the environment for a period of six months.

6 planar frames of double height were tested with height of each floor of 2.1m and a spam of 4.05m under cyclic horizontal load applied at the nearest beam-column connection and the horizontal displacements were measured at the top, the first floor and the support and the vertical displacement measurement was taken at the support. 3 frames were tested without cables and 3 with cables, one of these with simple cable and the others with double cables. (figure 8)

Figure 8. Frame of guadua with diagonal cables. Diagonal cable leaving the joint

Conclusions

With the test of the six frames it was found that the structure is not unstable although the beam-column connections and the supports don't behave as rigid connection. The frames had a great displacement and once discharged they recovered their initial position.

The top beam transmitted the load appropriately to the far column, since it was not observed a buckling of the beam neither failure of the connections.

The frames braced with cables were more rigid than the frames without cables. The maximum drift of the first ones in the second floor was 6.7% while in the second case was of 9.5%.

In the case of the frames with cables a slight deformation outside of the plane was observed, this, because it exists the possibility that for the type of the connection in a side of the frame the cable transmitted more load that in the other one.

In the case of the frames with cables the system of the cable failed. In the case of the frame with simple cable this it broke, in the second case slip of the cable was presented in the last frame the failure was presented in the tension device. After the cable was broken the frames behave like the frames without cables.

Structural behavior of frames in guadua angustifolia, stiffened by means of panels prefabricated of “bahareque” and narrow sheets of guadua.

In the first study developed by Lamus (2008), it was found that the beam-column connection was a semi-rigid connection, reason why the drift of the frames was very high. In this study (Herrera, 2008), the behaviour of two different kinds of wall boards was investigated, in addition to the performance of the frame built with the panels.

Experimental methods

In the study, three types of boards of guadua were tested (3 boards for each type) which had a structure that consists of a wooden frame, a diagonal and some vertical elements in guadua. Of the three types of boards, two were covered, the first one with sheets of guaduas, combined with chicken steel meshes and plastered with cement mortar (bahareque encementado) and the second type with sheets of guadua of 5 cm of wide in a diagonal array. (Figure 9)

Figure 9. Structure of the guadua board. Board of guadua of bahareque encementado. Board with narrow sheets cover.

The frames of double height and simple spam, had a total height of 4.7 m and a width of 4 m. 3 frames were tested for each type of board (6 tests in total). After the frames were built, the boards were placed with one of the face covered. Then, the second face was applied (Figure 10).

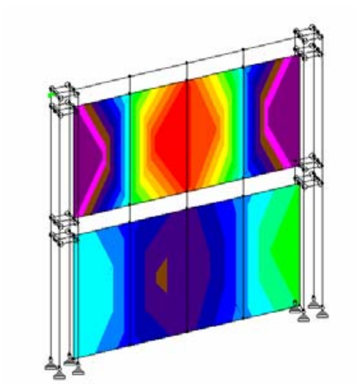
Figure 10. Drawing of guadua frame with the structure of four boards for floor. Frame with boards of bahareque encementado. Frame with board with narrow sheets cover.

The load was applied horizontally at the top of the frame. Horizontal displacement measurements were taken at the top, at the level of the first floor and at the supports, also vertical displacement measurements were taken at the supports. In each test, 6 load cycles were applied.

Numerical modelling

A lineal model was made for each one of the boards using the values of module of elasticity, density and poisson relation obtained experimentally in previous investigations. In the models the linear elements were “beam” elements with articulations in their ends. For the board with “bahareque encementado” the cover was analyzed with “shell” elements and for the other type of board the narrow sheets were considered as “beam” elements with articulations in their ends.

For the study of the frame with boards of bahareque encementado two lineal models were made (Figure 11). In the first one, each one of the guaduas   were analyzed as “beam” element and the cover as “shell” element as a whole. The second model included the structure of each board and its cover.



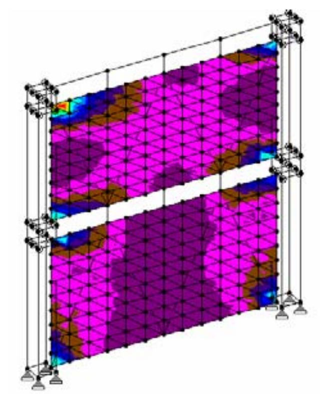
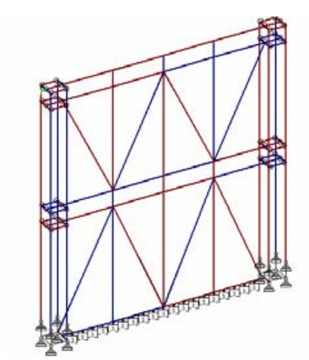


Figure 11. Models of analysis of guadua frames with boards of bahareque encementado

In the same way two models were carried out to study the behavior of the frames with sheets of guadua (Figure 12). In the first model it was considered the elements of the frames and the elements of the structure of each one of the páneles. In the second model it was considered each one of the sheets additionally.



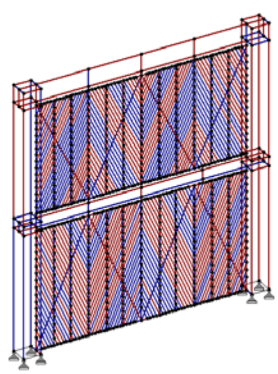


Figure 12. Models of analysis of guadua frames with boards with narrow sheets cover.

Conclusions

The cover increases the resistance of the boards; the last load of the panel with sheets was 41.6% of that of the panel without cover, in the case of the panel of “bahareque encementado” the resistance increment was of 50.4%

The simplified lineal model of the board was not the most appropriate because it was found that the boards had an inelastic behavior.

When comparing the results obtained in this study with the results obtained by Eng. Lamus it was found that the frames with boards are around 50 % more rigid.

The difference of displacements among the two types of boards is smaller than 25%. If it is considered that the weight of each panel of bahareque encementado is 105 kg and of each panel of sheets of guadua is 65 kg, additional at the biggest hand work and time that the first system implies, the panel with sheets of guadua is a good solution for system of stiffness of the system.

Structural behavior of frames in guadua, braced by means of guadua diagonals

In the last study, the behavior of frames in guadua braced with guadua diagonals was studied and it was found that they have enough rigidity so they can be used in the design of houses of two floors.

The experimental part of the study named " Structural behavior of frames in guadua, braced by means of guadua diagonals" (Rivera, 2009), included the characterization of the guadua, the test of connections of the diagonals with the frames, and the test of space frames.

The frames were modelled using traditional structural matrix analysis and with the results was suggested the best structural configuration for a two-story house.

Experimental methods

For the experimental part, not immunized Guadua Angustifolia Kunth was used, with ages among 4-5 years of age, extracted of the half part of the culmo. The diameter of the guadua varied between 9 and 13 cm.

For the characterization they were carried out test of compression, tension and shear parallel to the fibre following the procedures of the norm ISO 22157. Of each type, 10 samples were tested obtaining characteristic values of resistance to compression, tension and shear parallel to the fibre, as well as compression and tension longitudinal elastic modules. Also it was also carried out torsion test to find the module of rigidity.

Thinking of the geometry of the standard frame built in the investigations of Lamus (2008), Malaver (2007) and Herrera (2008), double diagonals of guadua were designed, with double height and an angle of inclination of 42º with to the vertical. The type of connection allowed the diagonals arrived to the joint in a concentric way and with a big contact area.

To study the behavior of the connection of the diagonals, they were carried out 12 tests of connections. Six of them had external reinforcement with glass fiber and six didn't have glass reinforcement. (figure 13)

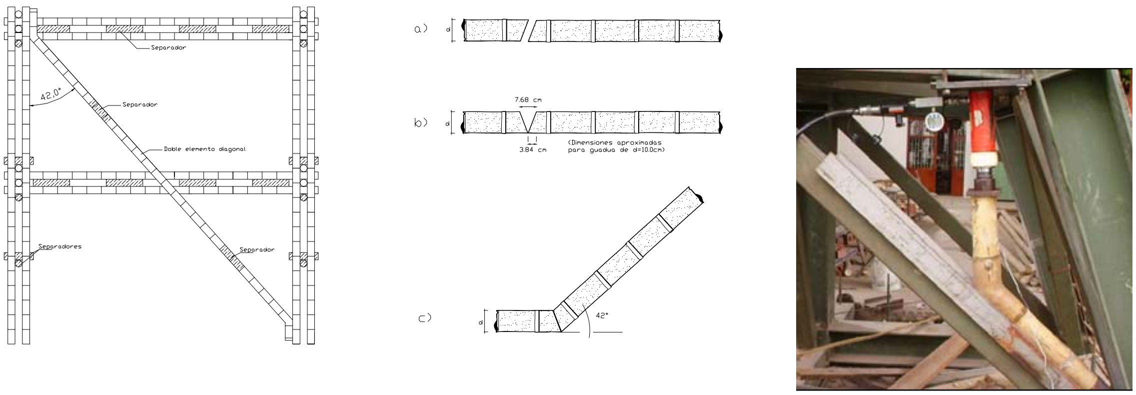


Figure 13. Drawing of the localization of the diagonal in the frame and the process of elaboration of the diagonal. Test of diagonal connection.

To study the behavior of the frames with diagonals they were test with cyclic load 6 space frames. The frame had a distance among column axes of 3.90 m, wide of 1.60 m and a total height of 4.40 m.

5 of the 6 frames were tested with diagonals and one without diagonals. Of the five frames with diagonals, three were loaded with vertical load 1,80kN/m2 at the first level and 0,50kN/m2 at the top like live loads in a typical housing. (Figure 14)

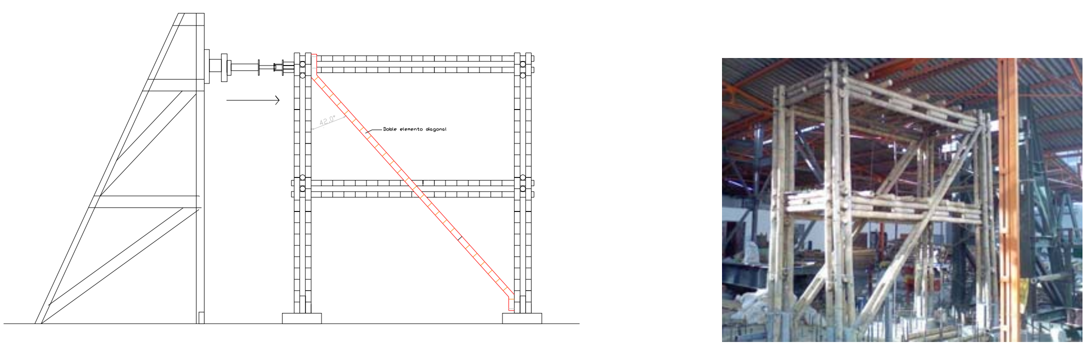


Figure 14. Drawing of the test frame with diagonal. Space frame with diagonal.

Numerical modelling

4 models were carried out; the first of them, a frame without diagonals, the second model included diagonals additionally, the third model corresponded to a structure for a housing, composed by four modules using

diagonals in all of the plane frames and the fourth model was similar to the former, but using diagonals only in the perimeter of the structure.

In the analysis, the guadua elements were in the elastic range, using a longitudinal elastic modulus obtained in the compression tests. The elements for the beams, columns and diagonals were type beam (with six grades of freedom in each end). The connections of the ends of the diagonals were considered plastic articulations. As the beam-column connection is semi-rigid it was used the value calculated in the research of the Eng. Lamus.

The first model (space frame without diagonals) was calibrated using the experimental data (figure 15).

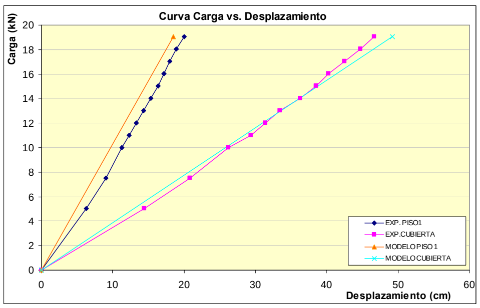


Figure 15. Numerical and experimental loads vs displacement diagram of the model 1.

To establish the parameters related with the diagonal in the second model a pushover analysis was made, where the diagonals were added so that they worked to compression with plastic articulations in their ends (Figure 16).

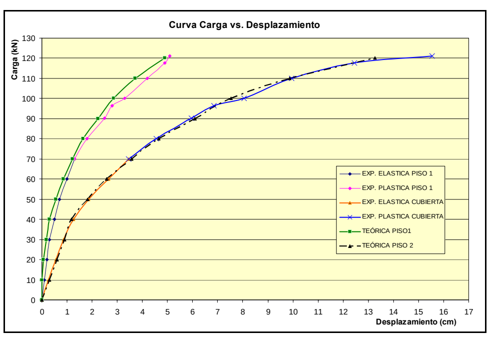


Figure 16. Numerical and experimental loads vs displacement diagram of the model 2.

Based on the second model it was carried out an pushover analysis for a third and fourth model for the structure projected. In the third model it was placed diagonals in all the plane frames while in the fourth model they were only located in the external perimeter.

The configuration of the previous structure and the analytical results allows the construction of two houses of two floors, with minimum areas to accommodate the basic facilities with a basic area of 67,2 m2 (Figures 17)

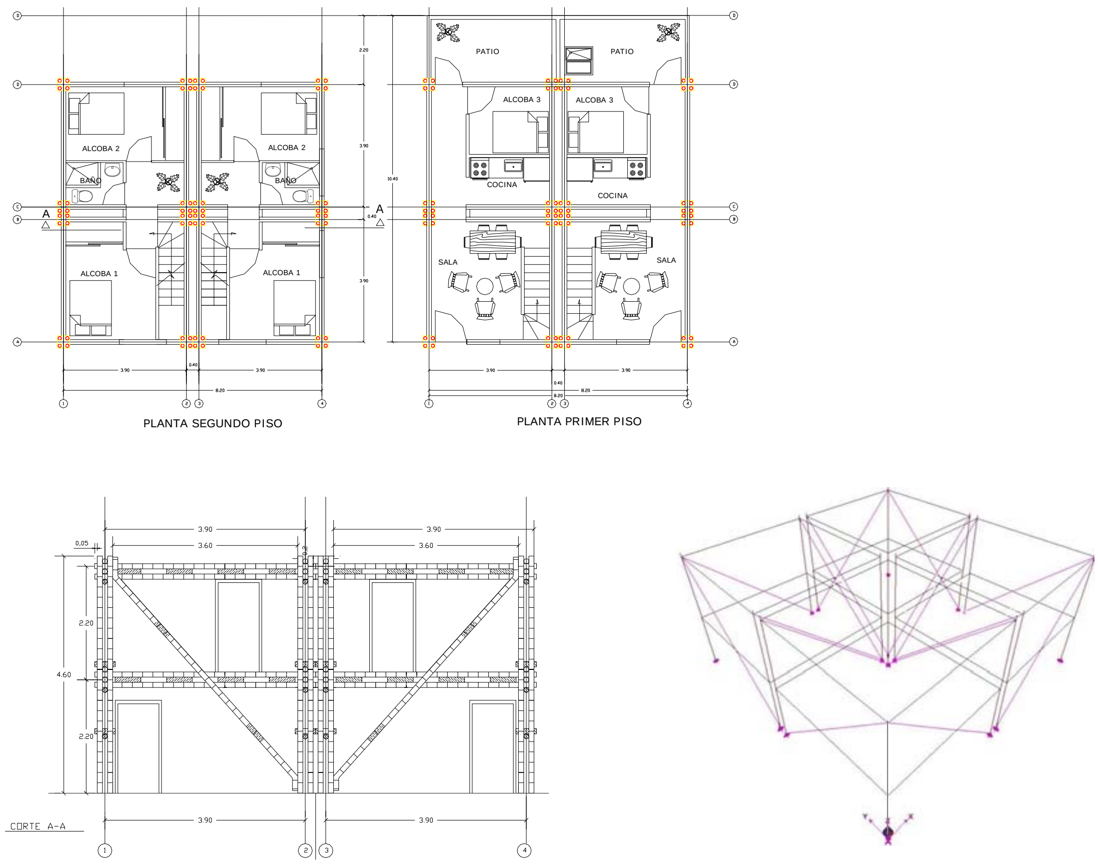


Figure 17. Distribution plants of first floor, second floor of the house. Drawing of the model 3.

Conclusions

The resistance to compression of connections without fibre glass reinforcement was 84% of the one obtained in the test with samples with fibre glass reinforcement.

The ultimate load of the frame without the diagonals, was 12,5% of the maximum load registered in the frames with diagonals tests.

Although comparatively the damages in the braced piazzas were bigger than in not braced structures, in any case they represented risk of collapse.

In the analyses of the structures proposed for a house, drifts obtained were smaller than 1%, that is the maximum drift value that prescribes the Colombia Construction Code NSR-98.

Considering the values of resistance found in the tests, the frames of the proposed structures support the loads appropriately.

The diagonal proposal, is a viable solution as brace suystem of the structures in guadua from the structural and architectural point of view, because to the being of double height, the diagonals don't interrupt the necessary holes for the disposition of doors and windows.

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Bamboo Composite Pole

Nachiket Thakur
Head, Product Design & Development, Mahindra Composites Ltd.

Abstract

In a nation of more than one billion people, India needs proper use of its resources and a strong back-up to its infrastructural needs. This is an attempt in providing a solution by incorporating abundantly available natural resource, a simple, cost effective manufacturing technique and understanding of composite technology applications. Bamboo is a naturally available renewable material. Bamboo is a natural 'composite' material having longitudinal fibers bonded by strong internodes. This inherent strength is further enhanced by winding glass fibers in transverse direction with polyester resin matrix to form a strong and durable member. The composite pole made in this process gives strength in longitudinal as well as transverse direction. This Bamboo Composite pole gives high strength to weight ratio and a cost effective product. It can be used for various applications such as Lamp poles, insulating connecting rods for Electricity distribution lines, structural members for rural & disaster housing.

The manufacturing process takes inspiration from Mahatma Gandhiji's principle of self reliance and involvement of grass root people. The equipment required for manufacturing of this pole runs without electricity and can be handled by an ordinary semi-skilled worker. It takes inspiration from the 'Charkha' promoted by Gandiji.

Various applications of this Bamboo Composite Pole has been worked out.

Overview

Concrete with reinforcing steel has a greater ability to be custom engineered for various specific applications. However the resulting products are extremely heavy and in case of load-carrying structures, such as bridges, the greatest portion of the structure is involved in holding itself. This extreme weight forces many concrete structures to be fabricated on-site as opposed to being built in the factory. This adds greatly to the cost of these products. Also, concrete is very sensitive to motion, such as caused by earthquakes. A lightweight load bearing beam, column or cross-tie that would not be sensitive to seismic or temperature changes would be very desirable replacement for concrete.

Structural steel is extensively used for beam and column applications due to its strength, and workability. Steel has an on-going problem due to rust and corrosion that shortens its life span. Also, energy costs to produce steel and to fabricate and maintain steel components are quite expensive, keeping the price of the materials and finished products high.

The Bamboo Composite Pole (BCP) seeks to provide an improved composite that has the ability to overcome the disadvantages of the presently available structural materials. It seeks to eliminate the disadvantages by providing a low cost, high strength composite formed from Bamboo pole bonded with thermosetting polymers.

Bamboo has been an integral part of Indian culture and has host of traditional uses in many regions in India, and in many other countries. Due to a large variety of traditional uses bamboo has been aptly described as poor man's timber, green gold, friend of people, cradle to coffin timber and green gasoline.

During the recent years, bamboo has emerged as a major source of renewable fiber for making high value added products as alternate to wood and other materials. Use of bamboo in manufacturing such products not only generates additional employment opportunities but also ensures better earning to the people engaged in various bamboo industries. Greater use of bamboo products will help in reducing the depletion of forests through wood substitution and also encourage bamboo cultivation and thus benefit the environment.

Being very fast growing woody grass, bamboo produces considerable amount of biomass and is very efficient for sequestering atmospheric carbon. It is stated that one hectare of bamboo plantation can absorb about 17 metric tons of carbon every year. The absorbed carbon returns to the atmosphere only when bamboo is burnt. On the other hand when bamboo is used for making durable products the absorbed carbon remains fixed as long as the product lasts.

Locally available *Bamboosa Tulda*, *Bamboosa Meleclona*, and Dendrocalamus Strictus is ideally suited for this application. These species have inherent structural strength and grow comparatively straight.

Bamboo is highly renewable and sustainable natural resource. It can be harvested from the same Culm (Plant) for almost 40 to 50 years. Bamboo is very strong due to its inherent construction.

Due to its unique structure Bamboo has inspired this project.

Material	Density Kg/ lit	Compressive Strength Kg/cm2	Strength to weight ratio
Bamboo	0.6 to 0.719	645	897
Teak Wood	0.604	532	880
Mild Steel	7.8	4250	544

The Bamboo has inbuilt longitudinal fibrous structure with intermediate diaphragm at the nodes.This natural construction gives Bamboo its strength. The unique combination of high strength and low weight made me to use this to create a structural module. The inherent character of bamboo was enhanced further by the use of glass fiber wound in transverse (90 deg) direction and resin.

This unique combination of naturally available renewable resource and innovative composite engineering methods gives us this Bamboo Composite Pole

Bamboo Treatment

Bamboo is easily attacked by insects and fungi due to presence of starch and sugar in abundance. Prophylactic treatment of bamboo is very essential to enhance its life, control uneven shrinkage, and avoid splitting.

Treating the bamboo properly is very critical to ensure the right kind of raw material for further processing. The bamboo will be embedded inside with glass fiber and resin layer. To ensure proper results of the Composite pole, the bamboo inside has to be treated with care.

There are two types of prophylactic treatments used.

(A) Traditional or Non-Chemical Treatment
(B) Chemical Treatment.

A. Traditional or Non-Chemical Treatment

Storage in Water:

Freshly cut bamboo is stored either in running water or in water pools for 3-4 weeks to leach out starch. This process prevents bamboo from insect attack. In case of water pool water has to be changed frequently to prevent fouling. Although traditionally treated bamboo show increased resistance to insect and fungal attack compared to freshly cut culms, these methods do not provide long term durability.

Smoking:

Smoking is carried out in chambers. This produces toxic agents and heat which destroy starch in bamboo thus making it immune to insect attack and also blackens the culms.

B. Chemical Treatment

Chemical treatment is more effective than traditional treatments. Typical chemical treatment methods uses water soluble preservatives like Gamma BHC 0.5%, Formalin 0.5% , Phenol+ 1 Copper sulphate (1: 2), sodium penta chlorophenate 0.5% and Borax 1.5%. The chemicals are dissolved in water. Bamboo or bamboo mats are either sprayed with the solution or dipped in the solution for 10 minutes. After treatment the bamboo mats are stored in shade till they are processed further.

Bamboo treated in such a way is ready to be used for further processing it into Composite Pole

Composite Pole Manufacturing Process

Filament winding using glass fiber and polyester resin. Winding of glass roving is done manually with a simple pulley arrangement. Resin is applied with a brush. The Bamboo Pole is held in a chuck as a mandrel. It is then rotated by hand.

Same process can be done on an automated Filament Winding machine. This involves high production cost, so is not considered for this project.

Glass Fiber Winding Machine (Figure 1)

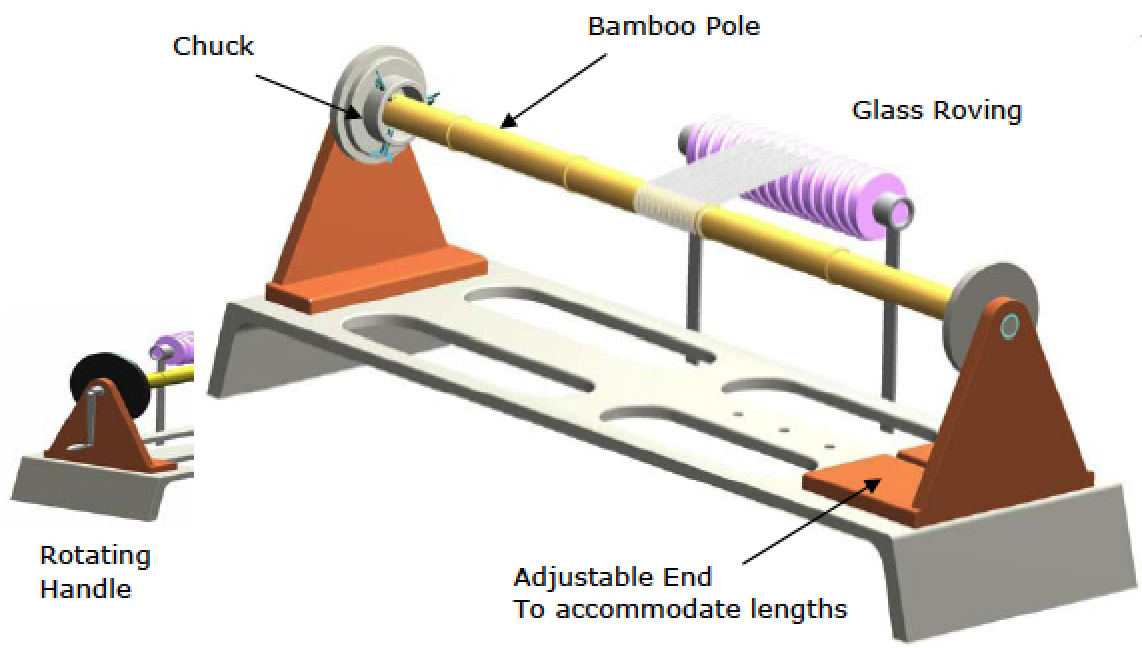


Figure 1 : Glass Fiber Winding Machine

This is a simple hand operated turntable used for winding glass fiber over the Bamboo Pole. It has a chuck to hold the bamboo at one end and an adjustable head at the other end. The chuck is fitted with a rotating handle. The harness for holding the glass roving spindle is on one side. This spindle slides along the length of the bamboo pole to ensure proper winding of the glass fiver over the Bamboo pole.

Composite Bamboo Pole Manufacturing Process:

Bamboo is held in between the circular chuck. The glass fibre rovings are tied at the starting end of the bamboo pole. Using the turn handle the roving's are wound along the entire length of the Bamboo pole. (Figure 2)

A mixture of Polyester resin with hardener (same way which is used for the Hand Lay Up process) is applied over this pole. Depending upon the length of the pole and the activation time, the glass fiber and the resin sets to form a strong hard surface over the bamboo. This is then allowed to cure for about 4-5 hours. (Figure 3)

The end of the poles is closed using glass matt and resin using hand lay-up process. In this way the bamboo pole is completely enclosed with glass and resin. This makes the bamboo pole completely safe from any degradation due to environment and due to the lateral winding of the

glass fiber it becomes extremely strong.

The Composite Bamboo Pole so formed is ready for use in various applications.

Figure 2 Figure 3

Figure 2 : Glass Fiber winding

Figure 3 : Fiber wound pole being covered with resin

Product Characteristics

The Composite Bamboo Pole manufactured has good strength in Compression and Tension. Properties of FRP and Bamboo gets enhanced multifold to give stronger product. (Figure 4)

Silent Characteristics / features

- • Cost effective – use of bamboo as core material and one layer of glass filament Winding
- • Insulating, light weight, non corrosive, long lasting poles for various applications
- • Effective use of natural, renewable, easily available material for commercial application using appropriate manufacturing technique.
- • Possibility of manufacturing at the remotest of the location by ordinary worker with no requirement of power

Table 1 : Physical Properties Comparison chart

	Natural Bamboo	Bamboo Composite Pole
Density	0.6	1.3
Modulus of Elasticity	1,59,460 kg / cm2	1,75,500 kg / cm 2
Compressive Strength	645 kg / cm 2	1350 kg / cm2
Moment of resistance	1184 kg / cm2	
Stiffness Factor	33	

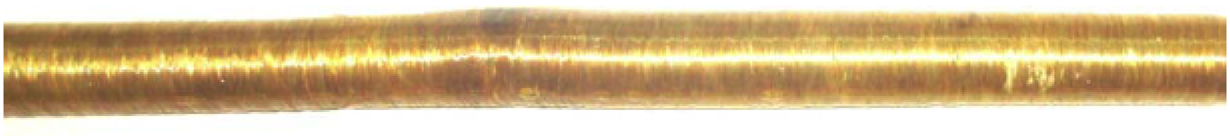


Figure 4 : Bamboo Composite Pole

The cross section of the ends of this pole needs to be made of same diameter, so that it can be standardised. A fiber Glass reinforced mould was made to make the ends of the pole of uniform diameter. Using this mould the ends of the poles are casted in resin and fiber glass. (Figure 5)

Figure 5 : Uniform End Diameter

Connectors

Various connectors are developed in Glass reinforcement process to suite the end diameters of the pole. (Figure 6)

Figure 6 : L – angle Connector

Various types of connectors are developed in Glass reinforcement process to suite the end diameters of the pole.(Figure 7)

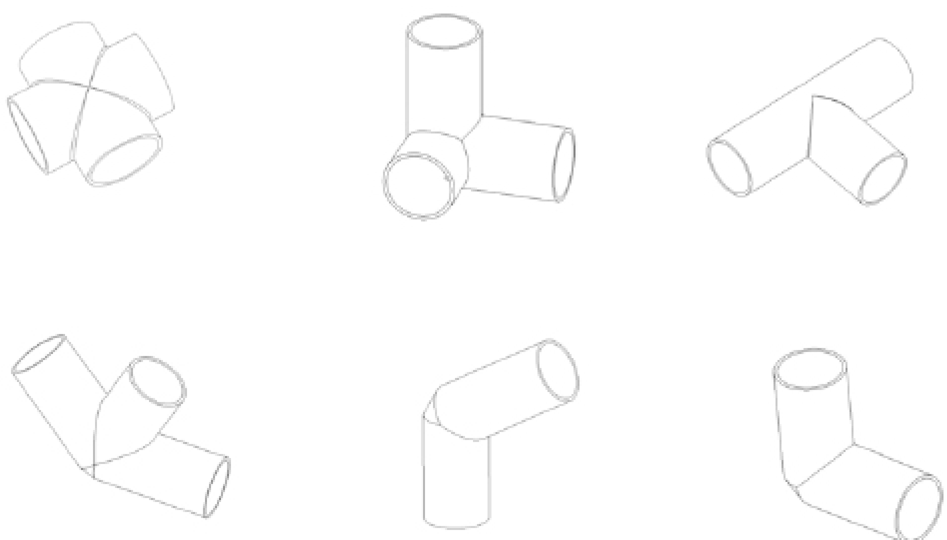


Figure 7 : FRP Connectors

Applications

Cost effective and durable solution for

(a) rural lighting poles,
(b) poles required in inaccessible areas for supporting cables for wind mills
(c) Structural members for rural , disaster housing

Rural Lighting Pole

These poles can be effectively used in Rural street lighting and in inaccessible areas where heavy poles cannot be transported. (Figure 8)

Wind Mill installations can use these poles for cable connections

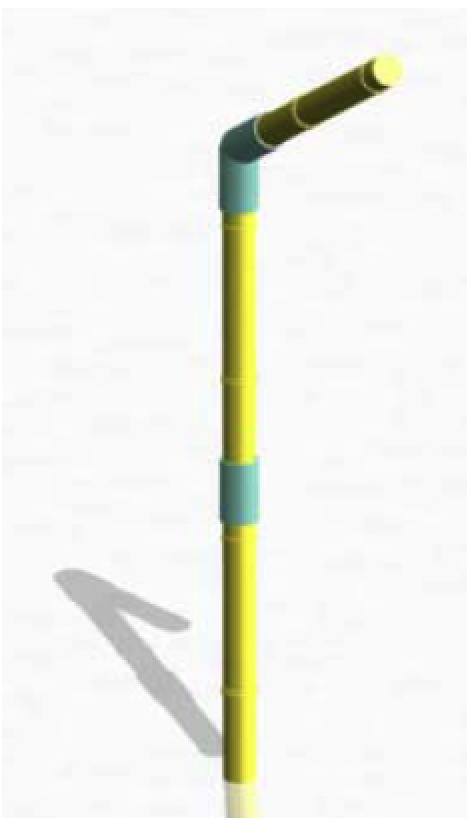


Figure 8 : Street Light Pole

Housing Structure Truss Module (figure 9)

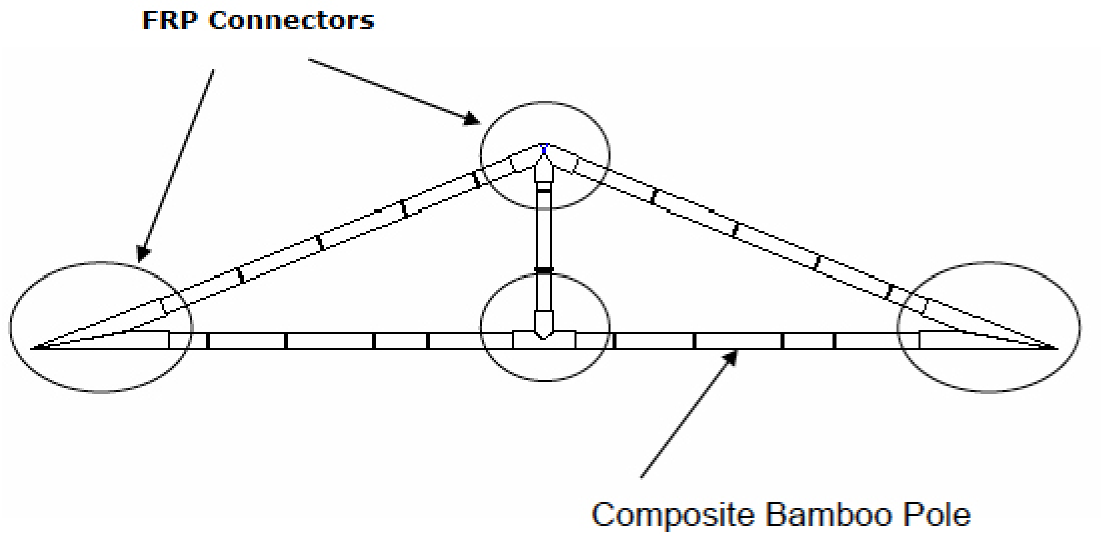


Figure 9 : Housing Structure Truss Module

Housing Structure

Using various connectors made out of reinforced glass fiber and the Bamboo composite poles a complete house structure is erected. This installation of a fully dis-mantalable system can be put in place in 2 hours (Figure 10)

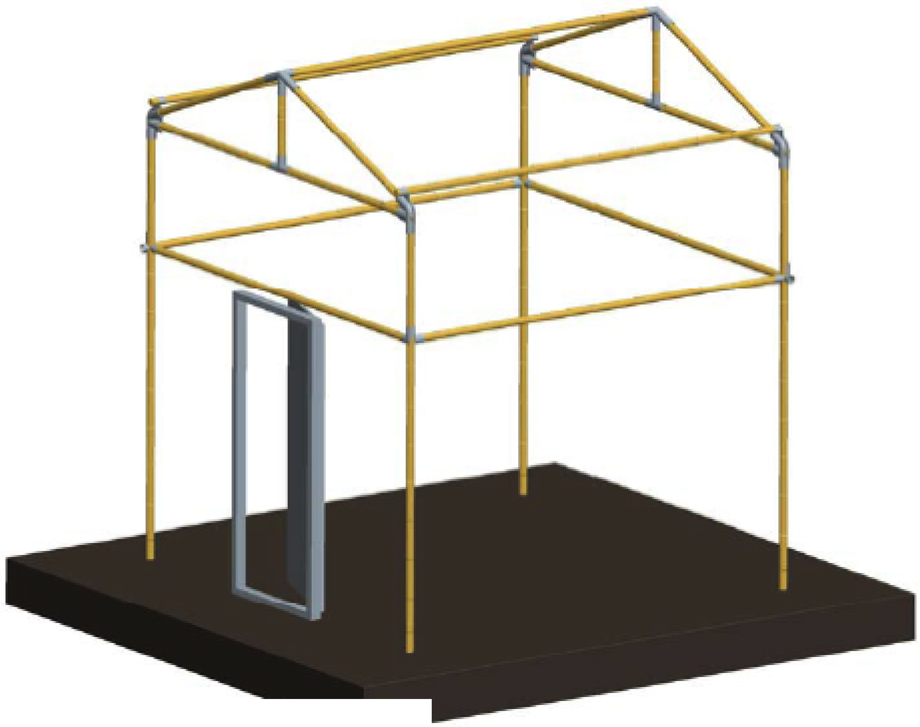


Figure 10 : Bamboo Composite Pole house structure

Connector Details (figure 11)

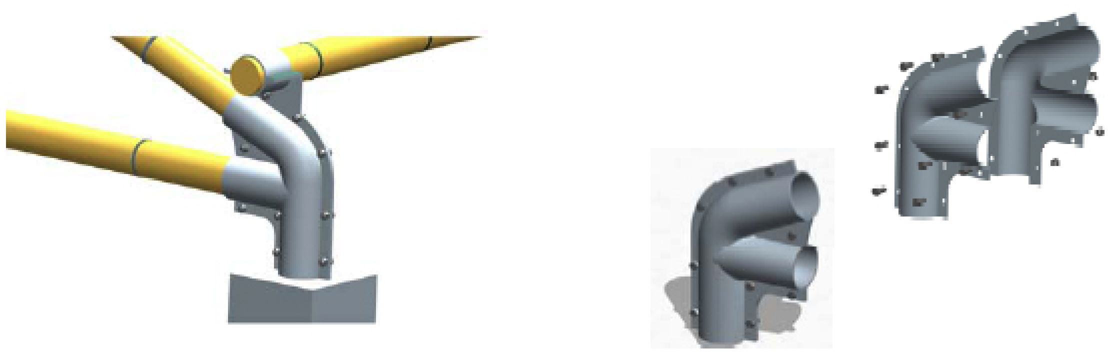


Figure 11 : Connector Details

Cement Reinforcement

The Composite Bamboo Pole is impregnated with Sand granules. This Sand Impregnated Bamboo Composite Pole is used as a structural reinforcement for casting the column in cement. (Figure 12 , 13, 14)

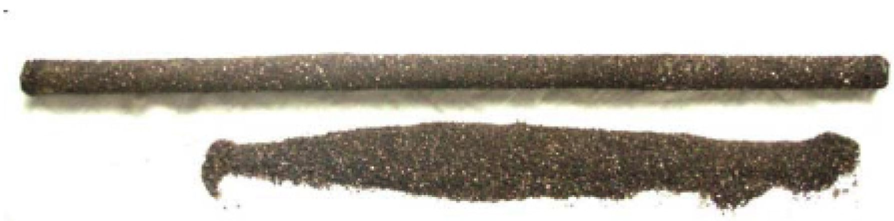


Figure 12 : Sand Impregnated Bamboo Composite

Figure 13 : Making of the Cememet Casted Bamboo Composite Pole

The Cement Casted Bamboo Composite Column is used with bare Bamboo Composite Pole to complete the structure of the house. Any method for constructing wall panels can be used. Brick, stone, mud masonry or Bamboo board panelling can be used to complete the house.

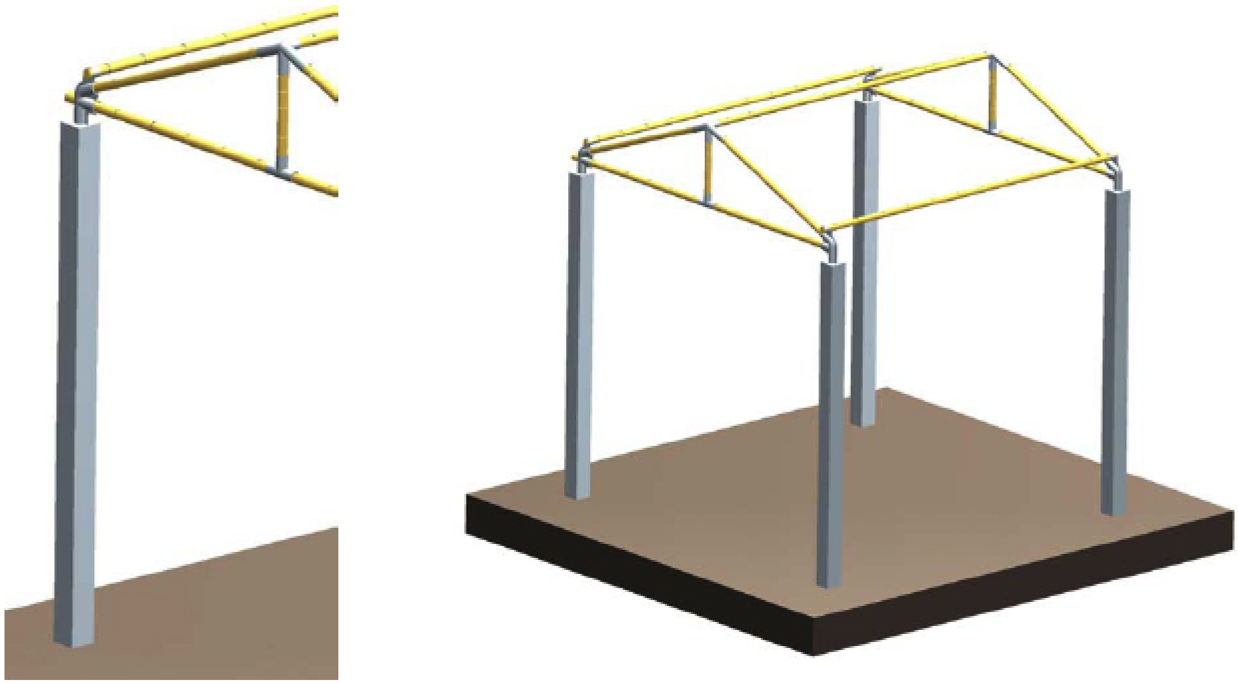


Figure 14 : Cement Casted Bamboo Composite Pole Column is grouted in the plinth

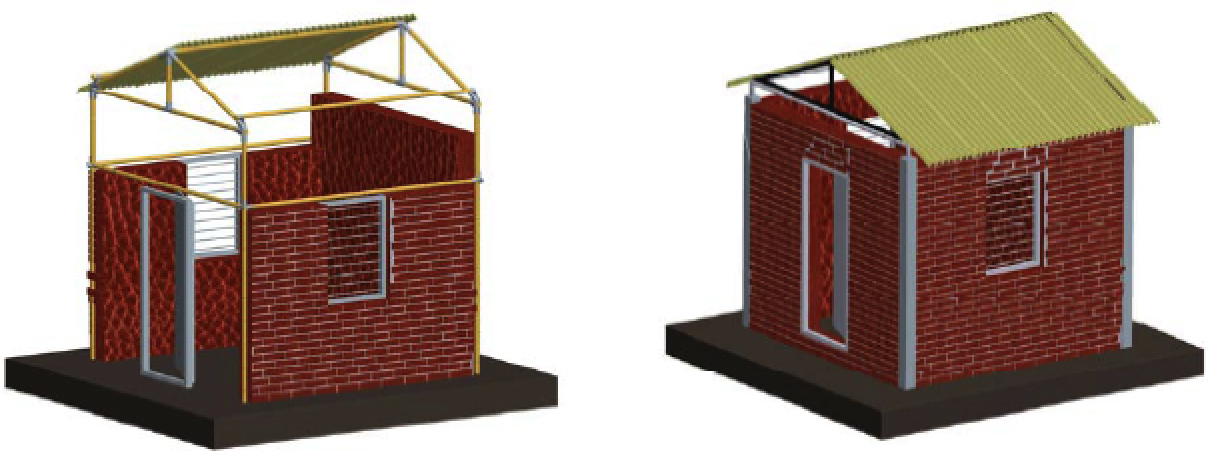


Figure 15 : A fully built house module using Bamboo Composite Pole structure

Conclusion

Bamboo Composite Pole module creates numerous innovative application possibilities.The modules so produced can be used in combination with various other materials and processes.

These modules are very light, durable, strong and cost effective. This will open up new areas of composite applications which are sustainable, long lasting and economical. The unique blend of naturally available material with optimal use of composite technology will give stimulus for overall development of product as well as the people at the grass root level.

These Bamboo Composite Poles can be used effectively for Disaster Housings in seismic zones. The unique manufacturing process also will help generate livelihood in the remotest of the areas and will also provide the much needed shelter for the needy.

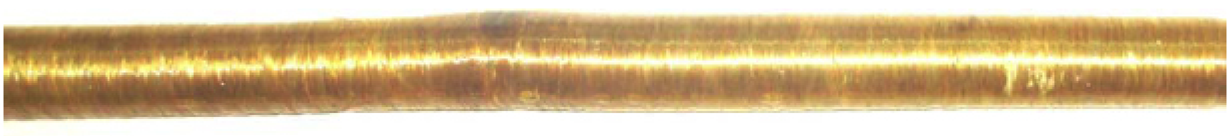


Figure 16 : Bamboo Composite PoleModules & Standardisation

Sustainable Utilization of Bamboo for Pulp and Paper Manufacturing

Ratana Mormanee
Forest research and development bureau, Royal forest department

Abstract

This research examined the potential of bamboo utilization and qualified the bamboo pulping for pulp and paper manufacturing. The following three pulping processes were developed namely formacell, sulfate and soda processes in various conditions. The results showed that the formacell pulping from *Cephalostachyum virgatum* Kurz gave 42.88% yield, 22.6% kappa number and at 40oSR freeness, then the physical properties of bamboo paper were analyzed which were 5,702.23 m breaking length, 431.43 KPa bursting strength, 88.8cN tearing strength and 20.7% ISO brightness. On the other hand, the sulfate pulping from C. *virgatum* had a 41.18% yield with 16.91%.kappa number. After beating for a few minute; the paper properties were measured which were 5,165.29 m breaking length, 330.44 KPa bursting strength, 81.5 cN tearing strength and 27.6% ISO brightness. For the soda pulping from C. *virgatum* had a 42.30 % yield with 31.29 %, kappa number after beaten, the paper strength gave 4,449.12 m breaking length, 272.78KPa bursting strength, 74.5cN tearing strength and 32.4%ISO brightness. Then, the comparisons of soda pulp quality among 13 species of bamboos were performed. It is shown that about 5 species [*Bambusa logispiculata* Kurz,*Bambusa blumeana* Schult,*Thysostachys siamensis* Gamble,*Bambusa arundinaceus* Wild, *Cephalostachyum virgatum* Kurz] gave significantly high yield, high strength and brightness. Finally, it was possible for bamboo to perform in any process with a good result. Particularly, five species of bamboo have had high potential and good quality for pulp and paper, especially high tearing strength and high brightness.

Keywords: bamboo pulping, formacell process, sulfate process, soda process

Introduction

Bamboo is a perennial, monocotyledon plant which is necessary of life for Thai-people from the past until now. All parts of bamboo give advantage to human for food, construction and raw material for industry such as basket, chopsticks, toothpick and pulp industry and so on. So bamboo is a special plant that is important both direct and indirect utilization but there are insufficient in knowledge of the conservation and management.

Bamboo is a group of genus namely Gransineae the same as grass. Bamboo has spread widely throughout the hot zone and the southeastern Asia, there are about 45 families (genus) 750 species. (Dransfield, 1980) In Thailand we have found about 13 genus 60 species which some are not discovery because they grow in the dense forest and lack of experts in breeding classification. Bamboo is the plant that can adapted to the new environment by exchanging phynotype for example. Often the same kind of bamboo can grow in the different geography and rainfall with different characters. Therefore, the classification of bamboo has to importantly point out some feature such as root, the leaf sheet , branching, the interval stem, stem size, roundness, color of the trunk, shoot and seed.

There are various kinds of bamboo and lots of advantages as mentioned but no specific utilization. The purpose of this study are to qualified bamboo pulping and gives result to bamboo utilization for pulp and paper manufacture by comparing the qualities some bamboos that found in the northern of Thailand. As Fiber produced by chemical processes varies in quality depending on the kind of material, method and condition during cooking. The two conventional pulping processes are soda process and the sulfate, in which the cooking liquor for the soda is a caustic soda. However, the cooking liquor for the sulfate process is essentially a mixture of caustic soda and sodium sulfide. Furthermore, the third chemical process is formacell process which employs an organic acid as the cooking liquor. In addition the important factors in cooking are temperature, time during cooking and the ratio of chemical to wood. These studies cover different cooking method of both conventional and the formacell cooking.

Materials and method

This investigation seeks to identify some bamboo species from the Northern of Thailand to be used as raw material pulping industry. Three potential pulping processes were performed in various conditions. The condition included temperature, chemical charge and wood per liquor ratio. Three pulping processes were formacell, sulfate and soda, the formacell process (Saake et al, 1995) is a chemical pulping using organic acid at 10%, formic acid, 160oC temperature, 120 min retention time, wood per liquor ratio of 1:7 and water content of 5% 10% 15% and 20% respectively. While the sulfate process is a process using mixture of caustic soda and sodium sulfide at 25% sulfidity, 170oC temperature and retention time of 2hrs. In which Soda process is a pulping of caustic soda at 150oC temperature, 90 min retention time, different wood per liquor ratio of 1:4 and 1:3 and also various sodium hydroxide concentration of 10% 15% 20%and 25%. (T1204 os-61)

Bamboo pulps from above three processes were examined a chemical testing, a sheet forming (Seiber, 1951), a physical testing and pulp evaluation relating to quality under standard test methods. Then the pulp properties of those three processes were compared. The following table is the standard method used in this paper.

Testing Method

Parameter	TAPPI and SCAN standards testing
Kappa number	T236m-60
ISO Brightness	SCAN-P3; 62
% Yield	weight
Beating Time	SCAN-C24; 67
Freeness	T227 os-68
Thickness and Apparent density	T411 os-68
Breaking Length	SCAN-P16; 65
Tear Factor	SCAN-P11; 64
Burst Factor	T403 ts-63

Results and discussion

Results of the bamboo pulping from the formacell, sulfate and soda processes and the quality of bamboo paper from three processes are shown in Figure 1-3 and Table 1-3 respectively. Then the comparison of pulp quality of 13 bamboo species from the soda is illustrated in Figure 4 and Table 4.

As can be seen in figure 1, it is found that formacell pulping from C.vergatum at 15% water content give high pulping yield and brightness.

From figure 2, it is obvious that 18% active alkali is the best condition for sulfate process.

For the soda process, it is found that 15% alkali and wood per liquor ratio of 1:3 give the highest at the brightness of 27%. However, the highest yield is found at 10% alkali.

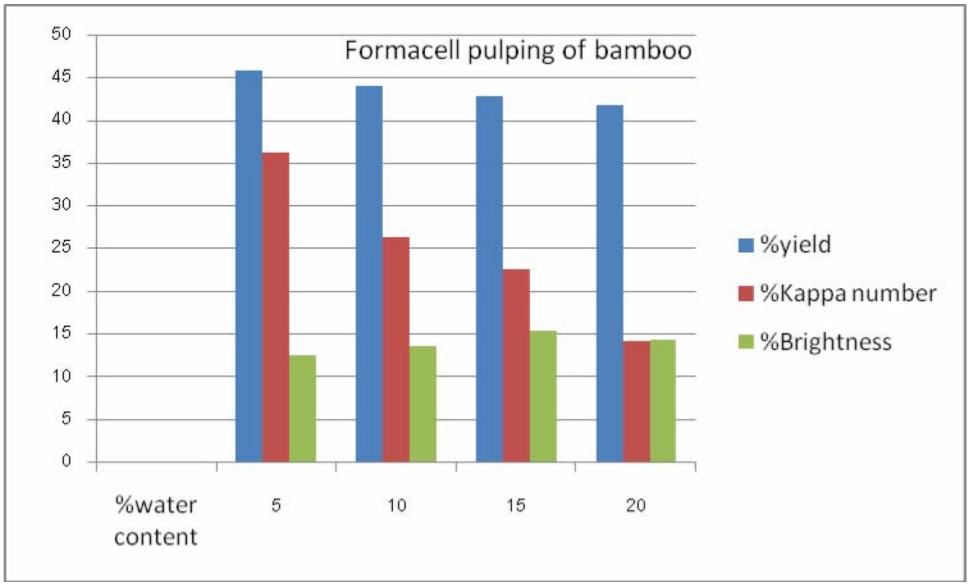


Figure1. Effect of % water content on Percentage of Yield, kappa number and brightness of formacell pulping at Formic acid of 10%, at temperature of 160oC, retention time of 120 minutes and wood per liquor ratio of 1:7

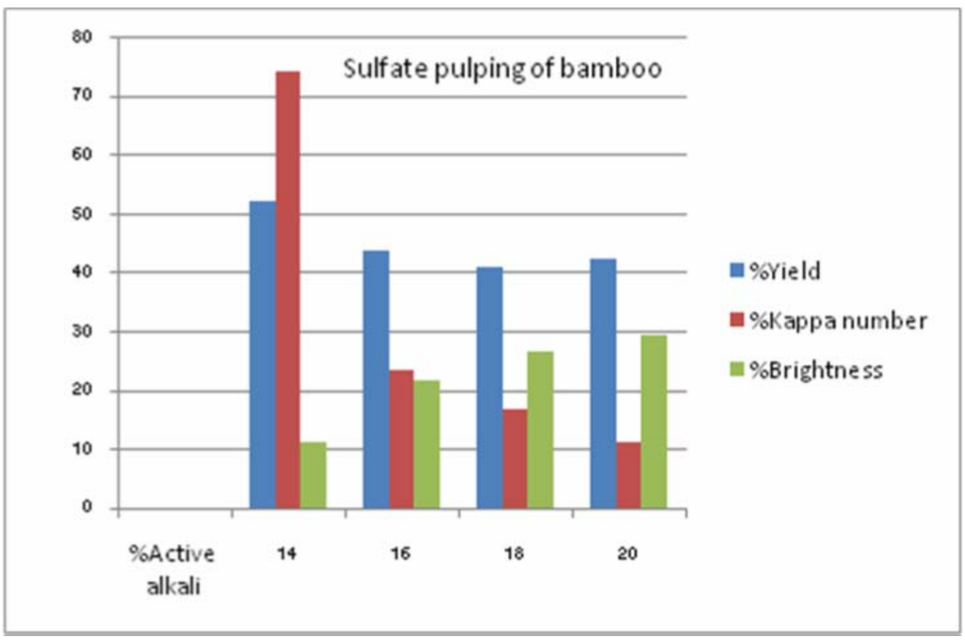
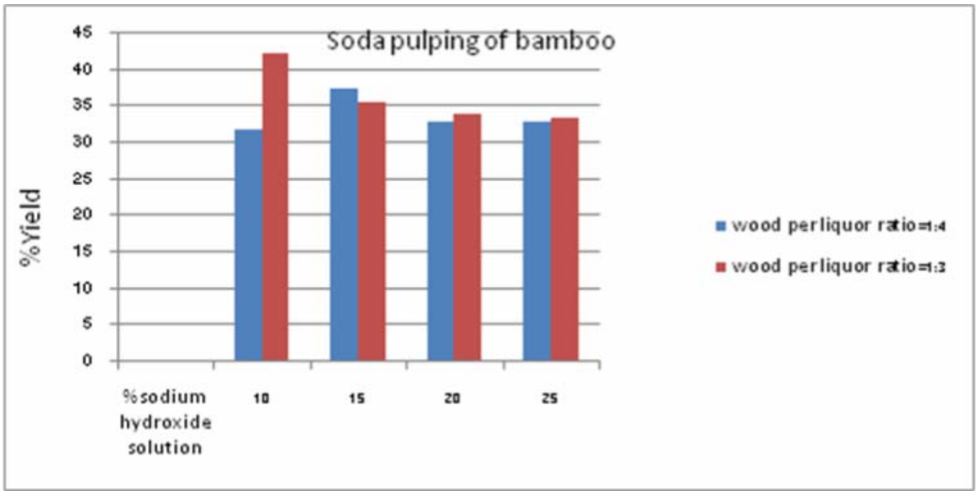
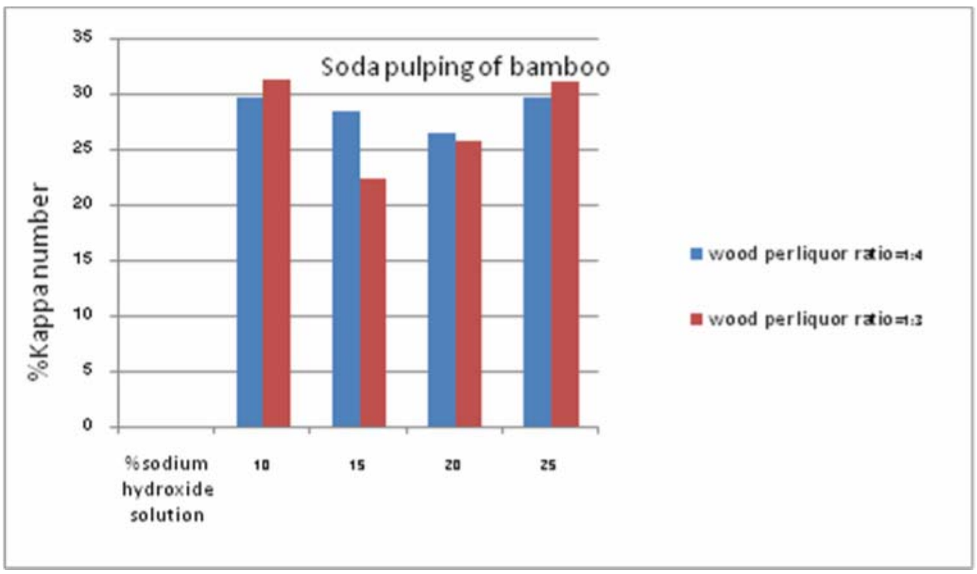


Figure2. Effect of % active alkali on Percentage of Yield, kappa number and brightness of sulfate pulping at sulfidity of 25%,temperature of 170oC,retention time of 2hrs.


Soda pulping of bamboo
%Yield
45
40
35
30
25
20
15
10
5
0
%sodium hydroxide solution
10
15
20
25
wood per liquor ratio=1:4
wood per liquor ratio=1:3


Soda pulping of bamboo
%Kappa number
35
30
25
20
15
10
5
0
%sodium hydroxide solution
10
15
20
25
wood per liquor ratio=1:4
wood per liquor ratio=1:3

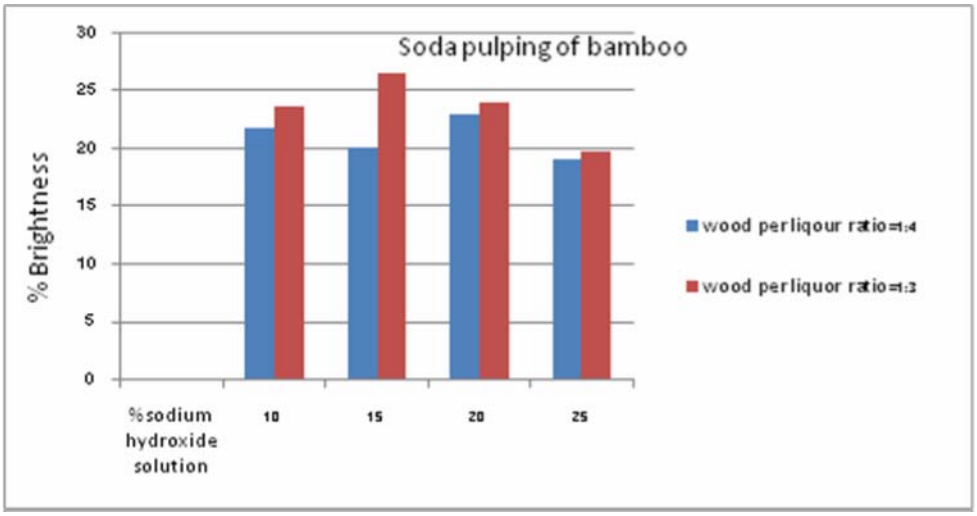


Figure3. Effect of % sodium hydroxide solution on Percentage of Yield, kappa number and brightness of soda pulping at temperature of 150oC,retention time of 90 minutes and different wood per liquor ratio of 1:4 and 1:3.

From the Table 1, a good bamboo paper quality from formacell pulping is found at 165oC, formic acid of 10% and water content of 10% with higher brightness.

It's can be seen in Table 2 the highest bamboo paper quality of sulfate pulping is given at active alkali of 18% with higher brightness.

From Table 3, a bamboo paper quality from soda pulping is given at a sodium hydroxide solution concentration of 10% and the ratio of wood to liquor 1:3 with higher brightness.

Table1 Physical properties of bamboo paper (C.vergatum) from formacell process in various conditions at different freeness

Condition	Freeness [oSR]	Tensile strength [m]	Bursting strength [KPa]	Tearing strength [cN]	Brightness [%ISO]
T=165oC FOH=10% H2O=5%	5-6 unbeat	1,905.59	53.92	56.6	16.3
	5-6 beat	2,735.93	154.38	103.7	13
	38-39	4,034.44	345.26	113.1	17
T=165oC FOH=10% H2O=10%	5-6	1,052.5	65.34	54.0	13.8
	10-11	2,435.19	81.90	65.4	18.6
	43-44	5,633.33	339.42	87.5	17.9
T=165oC FOH=10% H2O=15%	10-11	2,468.93	103.18	86.4	20.2
	40-40	5,702.23	431.43	88.8	20.7
T=165oC FOH=10% H2O=20%	9-10	2,863.21	122.84	85.7	19.8
	45-46	5,010.27	425.71	68.2	18.9

Note that T= temperature, FOH = formic acid, H2O = water content

Table 2 Physical properties of bamboo paper (C.*vergatum*) from Sulfate process in various conditions at different freeness.

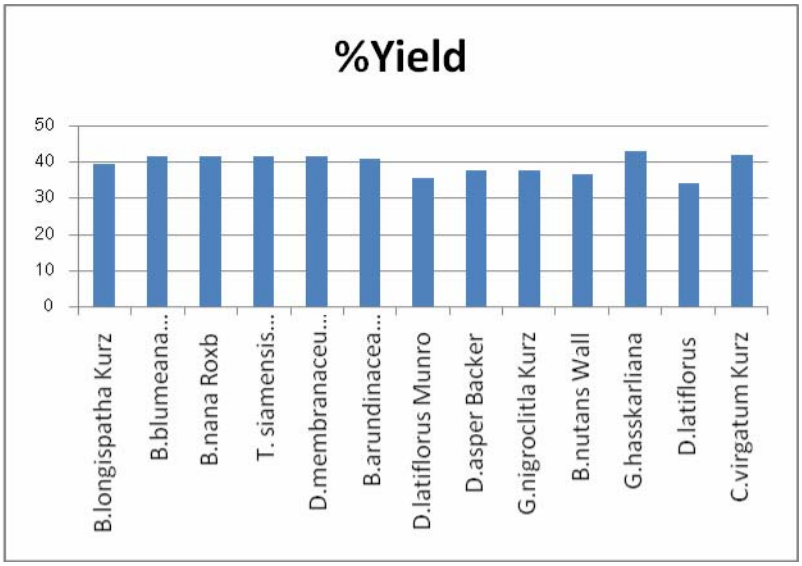
Condition	Freeness [oSR]	Tensile strength [m]	Bursting strength [KPa]	Tearing strength [cN]	Brightness [%ISO]
AA=14%	25-26	4,127	261.93	93.2	12.5
	72-72	6,086.51	418	66.6	15.3
AA=16%	11-12 unbeaten	1,792.08	95.28	61.4	23.3
	31-32	4,842.98	302.64	95.5	21.8
	36-37	5,168.55	441.67	75.8	23.4
AA=18%	11-12 unbeaten	1,091.90	91.22	52.4	30.2
	27-28	3,870.98	252.04	96.0	25.5
	44-45	4,940.60	427.05	53.1	30.6
	45-46	5,165.29	330.44	81.5	27.6
AA=20%	15-16 unbeaten	1,974.87	93.83	69.9	33.6
	20-21	3,040.54	161.86	86.3	31.6
	35-36	4,374.88	403.24	67.6	34.6
	48-48	4,530.80	248.64	61.6	32.8

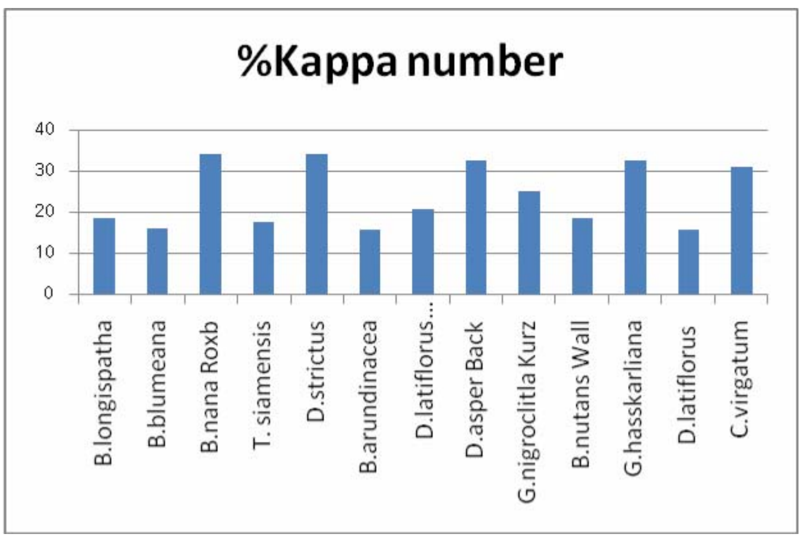
Note that: AA = Active alkali

Table 3 Physical properties of bamboo paper (C.vergatum) from Soda process in various conditions at different freeness.

Condition	Freeness [oSR]	Tensile strength [m]	Bursting strength [KPa]	Tearing strength [cN]	Brightness [%ISO]
10%NaOH aq. Wood per liquor ratio=1:4	13-14	2,036.58	105.34	54.4	28.7
	26-26	2,762.63	132.45	57.9	31.6
	38-38	2,829.10	145.18	52.5	31.8
	81-82	4,374.43	230.62	44.6	34.4
15%NaOH aq. Wood per liquor ratio=1:4	10-11	1,100.85	59.38	26.5	27
	39-40	1,260.45	69.62	14.8	30.6
20%NaOH aq. Wood per liquor ratio=1:4	4-5 unbeaten	3,80.27	37.13	25.4	26.5
	19-20	1,170.23	69.15	15.9	33.2
	38-39	1,354.28	71.26	11.1	34.8
25%NaOH aq. Wood per liquor ratio=1:4	4-5 unbeaten	160.85	31.67	20.5	22.4
	57-58	1,241.57	67.86	11.6	32.7
10%NaOH aq. Wood per liquor ratio=1:3	27-28	3,383.04	194	91.1	32.4
	51-52	4,449.12	272.78	74.5	32.4
15%NaOH aq. Wood per liquor ratio=1:3	29-30	2,090.47	100.31	27.1	34.8
	52-53	2,214.61	110.60	21.6	37.2
20%NaOH aq. Wood per liquor ratio=1:3	16-17	1,554.75	71.87	21.7	32.9
	72-72	2,407.53	123.21	19.3	35
	32-33	1,585.52	83.70	16.8	37.8
25%NaOH aq. Wood per liquor ratio=1:3	17-18	1,142.49	66.11	22.5	27.8
	39-40	1,305.74	71.92	16.3	31.5

Note that: NaOH = sodium hydroxide solution concentration


%Yield
50
40
30
20
10
0
B.longispatha Kurz
B.blumeana...
B.nana Roxb
T. siamensis...
D.membranaceu...
B.arundinacea...
D.latiflorus Munro
D.asper Backer
G.nigroclitla Kurz
B.nutans Wall
G.hasskarliana
D.latiflorus
C.virgatum Kurz


%Kappa number
40
30
20
10
0
B.longispatha
B.blumeana
B.nana Roxb
T. siamensis
D.strictus
B.arundinacea
D.latiflorus...
D.asper Back
G.nigroclitla Kurz
B.nutans Wall
G.hasskarliana
D.latiflorus
C.virgatum

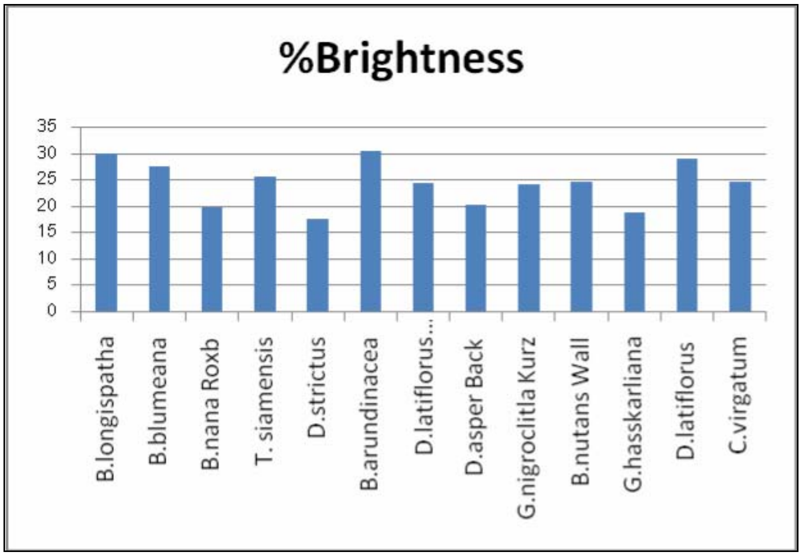


Figure 4 Comparison of soda pulping quality among 13 species of bamboo on yield, kappa number and brightness at the cooking temperature of 150oC, retention time of 90 min, 10% concentration of aqueous lime and wood per liquor ratio of 1:3

Table 4 Physical properties of paper from 13 species of bamboo with Soda process at the cooking is temperature of 150oC, retention time of 90 min, 10% concentration of aqueous lime and wood per liquor ratio of 1:3 in different freeness.

Type of bamboo	Freeness [oSR]	Tensile strength [m]	Bursting strength [KPa]	Tearing strength [mN]	Brightness [%]
Bambusa longispiculata Kurz..	2-3	1,013.97	64.34	439	30.4
	5-6	2,311.26	105.68	549	33.2
	18-18	2,405.77	123.02	531	34.9
	36-36	3,000.64	158.07	570	36.8
Bambusa blumeana Schult	3-4	707.70	47.40	323	26.4
	14-15	1,487.43	89.62	240	30.7
	21-22	2,040.2	107.99	213	32.5
	38-39	2,276.83	120.51	219	35
Bambusa nana Roxb	5-6	515.93	46.06	268	15.8
	13-14	1,843.20	101.68	296	22.5
	51-51	3,079.35	162.06	356	26.8
	61-61	3,067.80	169.45	311	27.9
Thyrsostachys siamensis Gamble	5-6	450.31	38.54	219	26.8
	15-16	2,250.50	110.71	281	32.7
	41-41	2,725.53	135.12	278	34.8
	51-51	3,218.95	167.54	297	36.4
Dendrocalamus membranaceus Munro	5-6	544.66	47.15	363	15
	3-4	1,495.80	79.95	246	20
	33-33	1,715.42	97.44	222	22.1
	41-41	1,842.78	94.35	190	23.5
Bambusa arundinacea Wild	4-5	753.45	57.42	427	29.8
	5-6	2,239.16	129.41	480	37.1
	37-38	2,583.12	146.75	419	38.6
	56-57	3,345.69	185.43	382	40.3
Dendrocalamus membranaceus Munro	5-6	846.47	58.73	401	23.5
	26-27	2,236.81	137.25	356	29.3
	53-54	2,832.25	165.0	322	31.7
Dendrocalamus asper Backer	4-5	875.19	66.57	577	20.2
	4-5	1,844.46	105.46	362	24.4
	41-41	2,212.5	118.93	260	27.3
	56-57	2,768.65	127.47	248	28.9
Bambusa affinis Mouro.	5-6	1,026.64	61.89	396	24.7
	14-15	2,169.74	111.95	388	26.3
	35-35	2,309.93	128.40	279	31.0
	46-47	2,499.33	122.66	232	30.2
Bambusa nutans Wall	5-6	476.36	51.31	518	23.8
	20-21	1,990.90	115.76	471	28.9

	42-42	2,730.50	148.24	426	32.2
	50-50	2,772.11	147.82	416	31.8
Gigantochloa hasskarliana	4-5	788.02	55.95	407	15.8
	25-26	2,046.88	113.52	395	22.7
	65-65	3,029.68	155.23	285	27.7
	65-65	3,118.01	155.27	302	27.7
Derdrocalamus Latiflorus	4-5	1,337.76	84.0	507	31.4
	35-35	3,142.88	171.59	340	35.8
	54-54	3,441.82	196.01	315	36.5
Cephalostachyum virgatum Kurz	27-28	3,383.04	194	911	32.4
	51-52	4,449.1	272.78	745	32.4

Pulp properties of the 13 species of bamboo are compared of under investigation at cooking condition [at 150oC temperature, 90 min retention time, 10% sodium hydroxide solution concentration and wood per liquor ratio of 1:3]. It was found that *B.longispiculata* Kurz, *B. blumeana* Schult, *Thyrostachys siamensis* Gamble, *Bambusa arundinacea* Wild, and *C. virgatum* Kurz provide high yield and high brightness. However, the soda pulps of *B.longispiculata* Kurz, *Thyrostachys siamensis* Gamble, *Bambusa arundinacea* Wild, *D.Latiflorus* and *C. virgatum* Kurz gave high strength.

Pulp quality of Bamboo can process by formacell pulping at 10% formic acid, 10%water content ,165oC temperature, 120 min retention time and 1:7 wood per liquor ratio. The pulp properties are 42.88 % yield , 22.60 % kappa number , the beating may produce at 40 oSR freeness, the physical properties of paper are 5,702.23 m tensile strength, 431.43 KPa bursting strength , 88.8 cN tearing strength and 20.7% ISO brightness .

Pulp quality of Bamboo can process by sulfate pulping at 25% sulfidity, 10%active alkali 170oC temperature, 120 min retention time and 1:4 wood per liquor ratio that gives 41.18 % yield, 16.91 % kappa number, the beating may produce at 45oSR freeness at this point the physical properties of paper are 5,165.29 m tensile strength, 330.44 KPa bursting strength, 81.5 cN tearing strength, and 27.6% ISO brightness.

Pulp quality of Bamboo can process by soda pulping at 10% NaOH solution, 165oC temperature, 90 min retention time and 1:7 wood per liquor ratio had provided a 42.30% yield, 31.29% kappa number, the beating may produce at 51 oSR freeness, the physical properties of paper are 4,449.12 m tensile strength, 272.78 KPa bursting strength, 74.5cN tearing strength and 32.4%ISO brightness.

Conclusion

It can be concluded that the soda process is preferable for bamboo pulping as it is known process and give the highest brightness. From 13 bamboo species investigated in this experiment, it is found that 5 species are good raw material for pulp and paper process. However, the method of cooking condition depends on the paper quality required from the end use.

Acknowledgement

I would like to thank Mr.Anirut udomkitti, Mr.Wasuthon malingun for their in wood chipping in laboratory contribution.

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Vocabulary/Parameter

- Pulp quality may represent in Yield, Kappa number, resistant, Degree of polymerization and Brightness etc.
- Physical properties of paper represent in Tensile strength, bursting strength and Tearing strength and Brightness etc.
- Brightness is the percentage reflectance of blue light only at a wavelength of 457 nm. The standards are per TAPPI T 452
- Tensile Strength is indicative of fiber strength, fiber bonding and fiber length.(TAPPI T 494)
- Bursting strength tells how much pressure paper can tolerate before rupture.(TAPPI T 403)
- Tearing Resistance/strengths is the ability of the paper to withstand any tearing force (expressed in cN, TAPPI T 414)
- Canadian Standard Freeness (CSF) is an arbitrary measure of the drainage properties of stock under specified conditions.

Bamboo Design Dialogue

Avinash Shende
Assistant Professor, Indian Institute of Technology Guwahati, Assam, India

Abstract

Bamboo is known for its tensile strength that has been compared with the steel. Moreover the various applications of bamboo from housing to handicrafts, using traditionally or in a contemporary way, and the role of industrialisation into bamboo sector tell us the story of its characteristic evolution through exploration.

Bamboo design dialogue reflects on various critical experiments done while design and development of processed bamboo furniture at Department of Design, Indian Institute of Technology Guwahati, India. It also established the dialogues by highlighting the application of philosophical thoughts, which helps to create new values in terms of functionality and aesthetic by understanding the real nature of bamboo.

The paper ends with the sharing of the experience of training workshop to the entrepreneur for fabricating processed bamboo furniture.

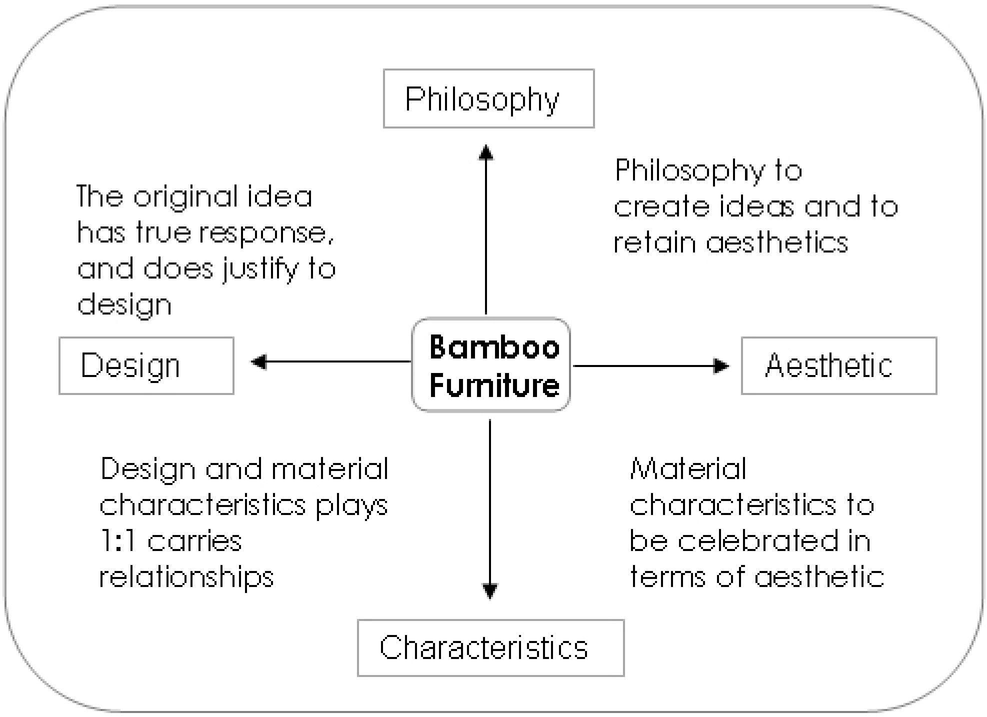
Keywords: Design, characteristics, joineries, jigs and fixtures, training

Introduction

Bamboo is the fastest growing grass, abundantly available in North Eastern India, more than 130 species of bamboo occurs in India. It has been diversely used traditionally for daily usages from bamboo shoots as diet to basket weaving or utilizing in construction.

Very recently in Indi, bamboo is being taken seriously to rethink as a potential material resource for the industrial products, which contributes towards the positive side of the society in terms of eco system and economy.

In general bamboo is being explored to a considerable level, whereas it is yet to explored in design per se. However, understanding the characteristics of bamboo and the process of the manufacturing of the industrial bamboo products opens up the door for creativity to convert bamboo in realisation of day to day products. Here is a trial of using bamboo board, flooring tiles and sticks to convert into furniture.



Bamboo Design Geography

Furniture 1: Mother Chair

Concept

'Mother' stands for 'Nature', who behaves/ reacts same with every creature and gives everything without expecting anything in returns.

This chair is designed with absolute natural (eco-friendly) material that is bamboo, in the form of bamboo board and bamboo sticks. The backrest of the chair is made of raw bamboo sticks, which is exposed to adjust as per the user's back profile. The number of layers of loosed bamboo sticks for backrest was estimated optimistically to fit between comfort and durability.

Material

Bamboo

Furniture 2: Ekatra - Modular Stool

Concept

”Ekatra” means “Together” in Marathi (a local language of Maharashtra State in India). The concept is inspired by a fact shared by Frijtof Capra in his book “Web of Life” - the multi-cellular organism, where each cell is separate but interconnected and interdependent to each other. A fertilized egg”new cell” undergoes multiple cell divisions repeatedly in the growth and development of a multi-cellular organism. Similarly in Ekatra Stool, the multi-pieces of board are derived from a single board.

They are separate but interconnected and interdependent to each other through the joints, and arranged as such to see in the form of a live product altogether.

Material

Bamboo
Spring Steel

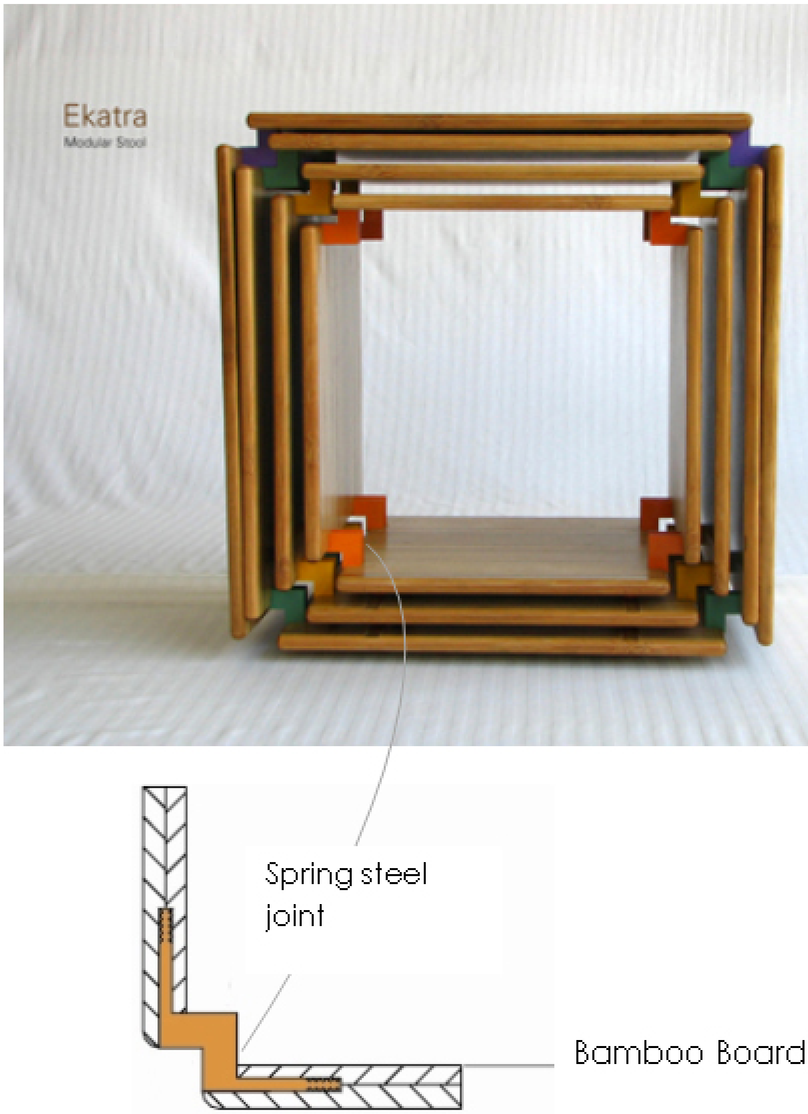


Illustration 1

Joint Detail

Laser cut spring steel joints are incorporated to interconnect the boards to each other.

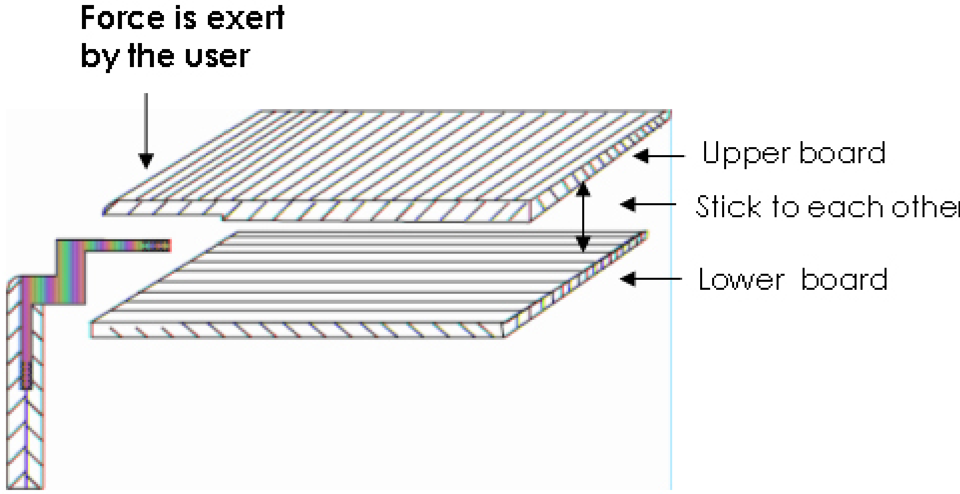


Illustration 2

This design is critical in two ways

1. Each plank consists of two separate bamboo boards, upper board (where the grains of the bamboo are perpendicular to the joints) and lower board (where the grains are perpendicular to the grains of the upper board). The manipulation of the grains "as said above" is important to withstand the force exerted by the user from the top that is distributed through the joint.
2. Spring steel Joinery element, which is very innovative and effective. A precise slot on the inner surfaces of the boards where the joinery element slips inside with the glue. The teeth profile on the joinery element doesn't allow the joints to come out.

The joints were given powder coat finish (rust proof) of different colour, chosen from the VIBGYOR colour pallets. Blue - Green - Yellow – Orange

Furniture 3: Bakda

Concept

Bakda stands for bench. The concept is inspired by the bench occurs in the local tea stall in India. It is solely made of bamboo flooring tiles (natural and carbonised). The two inclined legs are easy to slip from the two ends of the horizontal plank through the slots. The legs are designed to hold the plank stable and contribute to the feature of anti bending while sitting at the centre of the bench.

Material

Bamboo
Spring Steel

Furniture 4: Elephant Bench

Concept

The elephant bench is merely stands out for its surface finish. The water based stain and polyurethane coating used.

Material

Bamboo

Furniture 5: Foldable rack

Concept

The concept was generated with two factors

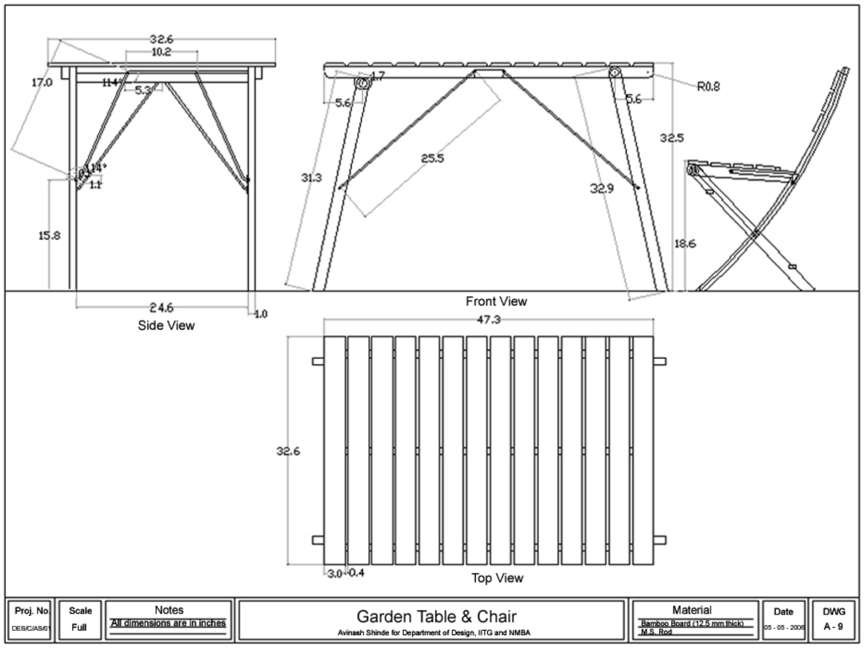
1. Compact packing while transportation, till the consumer end.
2. Short time to open and easy to unfold and use.

Such design is appreciated in the studio, hostels, offices and where the space is the prime constraint.

Furniture 6: Garden Furniture

Concept

Again the concept was generated for ease of transport and less Consumption of the space while storage.


Side View
Front View
Top View
32.6
10.2
17.0
5.3
15.8
24.6
1.0
1.7
5.6
5.6
R0.8
32.5
25.5
31.3
32.9
18.6
47.3
32.6
3.0
0.4
Proj. No
Scale
Full
Notes
All dimensions are in inches
Garden Table & Chair
Avinash Shinde for Department of Design, IITG and NMBA
Material
Bamboo Board (12.5 mm thick)
M.S. Rod
Date
DWG
A - 9


Garden
Furniture

The shape of curved leg of the chair was formed by using a cost effective spring steel jig. The different parts of jig are made of using laser cut technology and they are designed to fit each other to form a jig, without using any other fittings like nut bolts and screw (as shown below).

A defined bamboo strips come together with the glue and clamped inside the jig to get the required shape of the chair member. Such cost effective moulds could be thought of for making big furniture by using bamboo mats as shown in illustration 3.

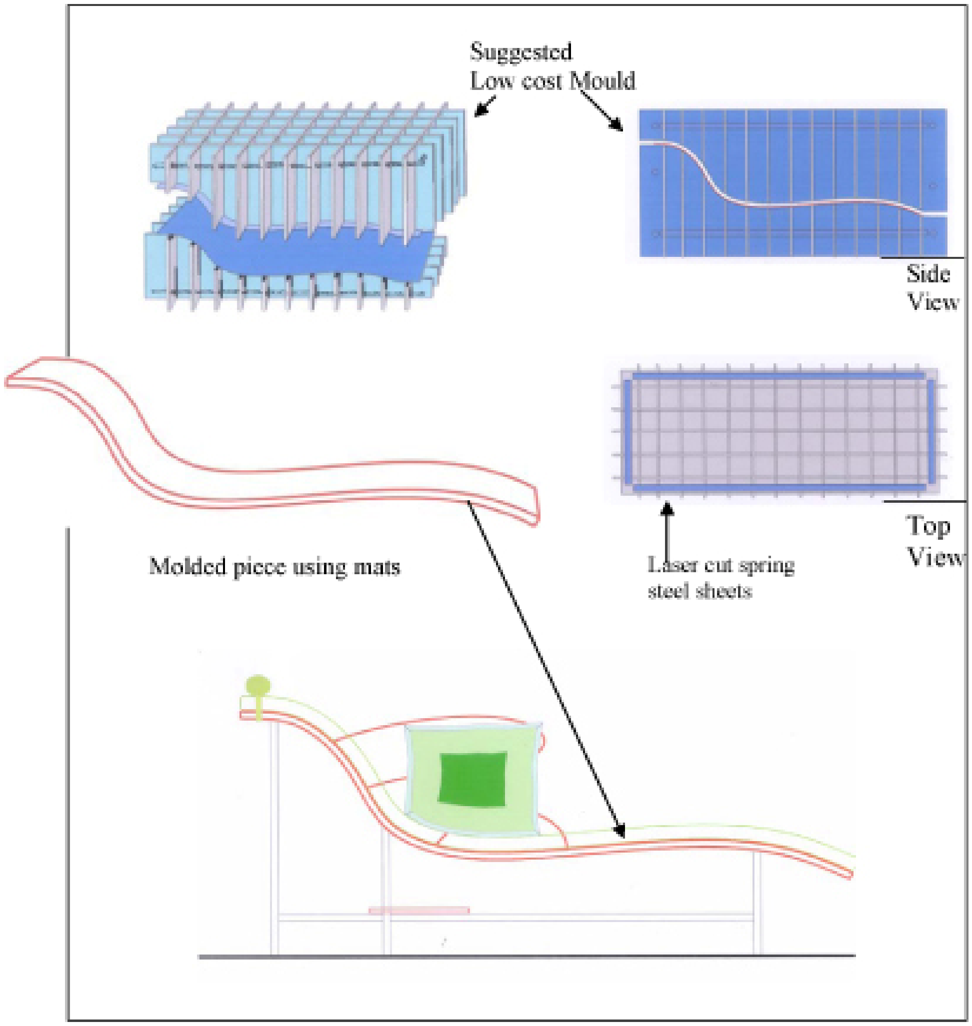


Illustration 3: Mould made with laser cut spring steel sheets and welded M.S. sheet

Furniture 7: Tree Book Shelve with Book Stopper

Concept

Design is an experiment as combination of material, which inspired by tree; a tree is organized by its own way, which provides space and shelters to birds and many living beings.

Similarly, Tree Book shelve can make even a single book to stand anywhere on the shelf. It gives user the liberty to think creatively while arranging the books as per mood or liking and help to generate different patterns. Tree book rack can also act as a room partition. The laser cut pattern incorporated in the stainless steel panels, depicts tree leaves.

Material

Bamboo
Stainless Steel

Workshop

10 days training Workshop to the entrepreneur on design and development of Bamboo Furniture

The workshop was started with understanding the design drawings of the furniture, followed by hands on training of using machineries, jigs and fixture. The key factors of starting of bamboo furniture were discussed as mentioned below.

1. ***Mass production of the various parts of furniture separately.***

Each furniture is different from the others. The manufacturing of the different parts of furniture should happen in batches. Similarly the joineries details should also take place in batches for mass production. There are standard wooden joineries like dove tail, finger joint and so on, for that the machines are readily available. Whereas for special joineries special customised jig and guides could be practised.

2. Assembly line of the furniture

Special clamps could be made for assembly of the furniture. It is important to retain the desire shape and to avoid the post hurdle of matching of one part to another part of the furniture.

3. Storage and Packaging

Proper tagging is needed while storage and packaging.

Conclusion

Bamboo has an immense potential to explore into furniture sector. New surface finishes and new texture provide a new flavour to the environment. This age is looking for new sensorial pleasure through either by concept of design or by the new material invention. The new material can be invented by mixing bamboo dust and bamboo charcoal with Polyurethane and silicon or with rubber or with different plastics. The furniture could be mould as similar as moulding done in plastics.

The new unconventional methods of experiments is needed which will help us to take bamboo into very new direction in new age.

Production of Manually-Oriented Strand-Cement Board from Bamboo

R.J. Cabangon, D.A. Eusebio, F.P. Soriano
Forest Products Research and Development Institute
Department of Science and Technology College, Laguna Philippines

P.D. Evans
Centre for Advanced Wood Processing
The University of British Columbia, Vancouver, BC, Canada

Abstract

Recently, it was found that the strength properties of wood wool cement board (WWCB) can be significantly improved by aligning the strands in a cross-ply manner within boards. In this study, the technical and economic feasibility of manufacturing oriented bamboo strand-cement board using manual strand orientation were assessed. Three-layer commercial-size oriented bamboo strand-cement boards (12 x 610 x 2440 mm) from kauayan tinik (*Bambusa blumeana* J.A. & J.H. Schultes) were manufactured wherein the strands at the surface layers were manually aligned along the length of the board while the strands at the core layer were randomly oriented. The properties of such boards were compared to the boards manufactured using the conventional method of manufacturing strand cement boards wherein single-layer boards contain randomly oriented strands.

The modulus of elasticity (MOE) and modulus of rupture (MOR) improved by 1.8 and 1.6 times, respectively as a result of aligning the strands within boards. The MOE and MOR of oriented bamboo strand cement boards that where tested wet had comparable properties to those of boards containing randomly oriented strands that were tested dry. The strength properties of bamboo strand cement boards were higher than boards made from yemane (*Gmelina arborea* Roxb.). On the other hand, thickness swelling (TS) and water absorption (WA) properties of boards were unaffected by strand orientation irrespective of species used to manufacture such boards.

The profitability analysis showed that the manufacture of oriented bamboo strand cement composite is economically viable with a return on investment (ROI) of 36% at a yearly production of 66,500 boards (250 boards per day).

This study signifies that manual strand orientation as a technique to improve the strength properties of strand-cement composites is technically and economically feasible in the Philippines. Manufacture of oriented bamboo strand-cement boards is also suitable to the socio-economic conditions of the country.

Introduction

The combination of long, thin strands of wood (wood wool) and Portland cement to produce a building material known as wood wool cement board (WWCB) dates back from the early 1900s (Kollman 1963). Since then, WWCBs have been used for non-structural applications such as for insulation and acoustical purposes and where the ingress of moisture is unavoidable. There has been limited research on improving the strength properties of WWCBs and extending their use for non-structural applications. Recently however, it was found that by aligning wood strands within boards in certain direction, a 100% increase in flexural strength of boards can be achieved (Cabangon and Evans 2001; Cabangon *et al*. 2002).

At present, there is no machinery available to orient wood wool strands. Meanwhile, in the Philippines, WWCBs are manufactured in small to medium scale plants using labor-intensive process. The mat-forming process is done by hand (Figure 1), and therefore, such technique may be used in aligning the strands in boards to improve their strength properties. Such strength improvement is important particularly in the Philippines because WWCBs are used for general-purpose construction.

Figure 1. Manual mat-forming of cement-coated wood wool strands in a commercial WWCB plant in the Philippines

It is known that bamboos have extremely high bending strength and stiffness properties. For example, Espinosa (1930) reported that *Bambusa blumeana* (30 cm circumference) can support a 500 kg load when loaded at the center of 1.5 m span. In addition, bamboo strands may be easier to align manually because of its stiffness compared to the curly nature of wood wool strands. Thus, the utilization of bamboo for the manufacture of oriented strand cement composite has great potentials to improve the strength properties of strand-cement boards. This study examined the feasibility of using bamboo as raw material for the production of oriented strand cement composite. It aims to (1) determine the flexural strength and water resistance properties of oriented bamboo strand-cement board; (2) compare the properties of boards manufactured from aligned and randomly oriented strands from bamboo and wood; (3) determine the economic viability of producing oriented bamboo strand cement board.

Materials and Methods

Materials

Three-year old plantation-grown kauayan tinik (*Bambusa blumeana* J.A. & J.H. Schultes) poles were collected from Pililia, Rizal. This bamboo species was chosen because of its widespread availability in the Philippines and posses a considerable culm wall thickness. On the other hand, five-year old yemane (*Gmelina arborea* Roxb.) was collected from a private plantation in Alaminos, Laguna. Type I Portland cement was used as binder during board manufacture.

Board Manufacture

The bamboo poles and yemane were cross-cut into 400 mm long billets and then shredded using a horizontal type reciprocating shredding machine in a WWCB plant in Bay, Laguna. The resulting bamboo strands measuring 0.4 x 4 x 400 mm were soaked in tap water, to remove water-soluble extractives that inhibit cement setting, in a soaking tank (1 [depth] x 2 [width] x 3 [length] m). The strands were air-dried by spreading on a concrete floor for two days to equilibrium moisture content of approximately 18 percent. The air-dried strands, Portland cement, and water were mixed in a drum-type mixer. The strand/cement ratio and water/cement ratio used were 0.8/1 and 1/1, respectively. Two types of boards were manufactured. The first board type contains strands with random orientation. The second has a three-layer structure wherein the strands at the surface layers were oriented parallel to board length while the strands at the core layer were randomly oriented (Cabangon and Evans 2002). Boards measuring 610 x 2440 mm with 12 mm thickness were manufactured at the WWCB pilot plant at the Forest Products Research and Development Institute (FPRDI) in Los Baños, Laguna.

Bamboo strands, cement, and water were mixed for a period of 3 to 5 minutes or until the strands are thoroughly coated with cement. Mats were formed by hand by evenly distributing the cement-coated strands into a detachable rectangular forming box placed on top of plywood caul plates lined with plastic sheets. In the case of three-layer oriented WWCBs, cement-coated strands of adjacent layers were manually formed into a mat one layer at a time. Formed mats were pre-pressed, followed by the careful removal of the forming box. The resulting mats on caul plates were placed on top of each other to form a batch of boards. Wood thickness stoppers, corresponding to the desired thickness of boards (12 mm), were placed at the long ends and in-between the caul plates. The resulting batch of boards was compacted in a 60-ton capacity hydraulic press by applying a pressure of 3000 psi or until the thickness stoppers have met the caul plates. The pressure was maintained for 24 h for the setting of cement to take place.

Board Conditioning and Property Tests

Each manufactured board was allowed to stand vertically on one of its longer sides in between wood stickers (12 mm thick) at ambient temperature and humidity for a period of 28 days. Conditioned boards were tested for their modulus of rupture (MOR), modulus of elasticity (MOE), thickness swelling (TS), and water absorption (WA). Test specimens were cut from each board parallel and perpendicular to board length. The dimensions of the test specimens were 50 x 230 mm. Specimens tested wet were soaked in water for 24 h, excess water wiped with a clean cloth, and then immediately tested for bending properties. TS and WA tests were conducted by measuring the respective thickness and weight of the 'wet' test specimens before and after soaking in water.

Experimental Design and Statistical Analysis

The two board types (random and oriented) were manufactured using bamboo and yemane with three replications. A total of 12 boards were manufactured over a period of six days. Boards from the two species with random strand orientation were manufactured on the first, third and fifth day while boards with a three-layer structure were manufactured on the second, fourth and sixth day. The order in which boards were manufactured was randomized.

Results of tests were subjected to an analysis of variance (ANOVA) appropriate for the design described above. A least significant difference bar was used to compare differences between means.

Results and Discussion

Board Properties

The effect of strand orientation, test condition, species, and their interactions on the MOE and MOR of boards are shown in Tables 1 and 2, respectively. Strand orientation, species and test condition significantly affected the MOE of boards (Table 1). Similar ANOVA was obtained for MOR except that the species did not affect the bending strength of boards (Table 2). The MOE (Figure 2a) and MOR (Figure 2b) of boards containing strands oriented parallel to the span were significantly higher than boards containing randomly oriented strands and the above board types were significantly higher than boards containing strands oriented perpendicular to the span. These results were in accord with the results of Cabangon and Evans (2001) and Cabangon *et al*. (2002).

Table 1. Analysis of variance on the effect of strand orientation (board type), test condition, species, and their interactions on the MOE of boards

Source of Variation	Df	Sum of Squares	Mean Square	F Value	Pr > F
Orientation (O)	2	9599601252	4799800626	273.58	0.0001 **
Test Condition (T)	1	2893829876	2893829876	164.94	0.0001 **
Species (S)	1	414734981	414734981	23.64	0.0001 **
O x T	2	750209160	375104580	21.38	0.0001 **
O x S	2	1699808920	849904460	48.44	0.0001 **
T x S	1	46815649	46815649	2.67	0.1029 ns
O x T x S	2	169397125	84698562	4.83	0.0083 **

** significant at the 0.01 level of probability

Table 2. Analysis of variance on the effect of strand orientation (board type), test condition, species, and their interactions on the modulus of rupture of boards

Source of Variation	Df	Sum of Squares	Mean Square	F Value	Pr > F
Orientation (O)	2	216386	108193	250.98	0.0001 **
Test Condition (T)	1	93208	93208	216.22	0.0001 **
Species (S)	1	228	228	0.53	0.4673 ns
O x T	2	13860	6930	16.08	0.0001 **
O x S	2	17416	8708	20.20	0.0001 **
T x S	1	1133	1133	2.63	0.1055 ns
O x T x S	2	2899	1449	3.36	0.0352 *

** significant at the 0.01 level of probability

* significant at the 0.05 level of probability

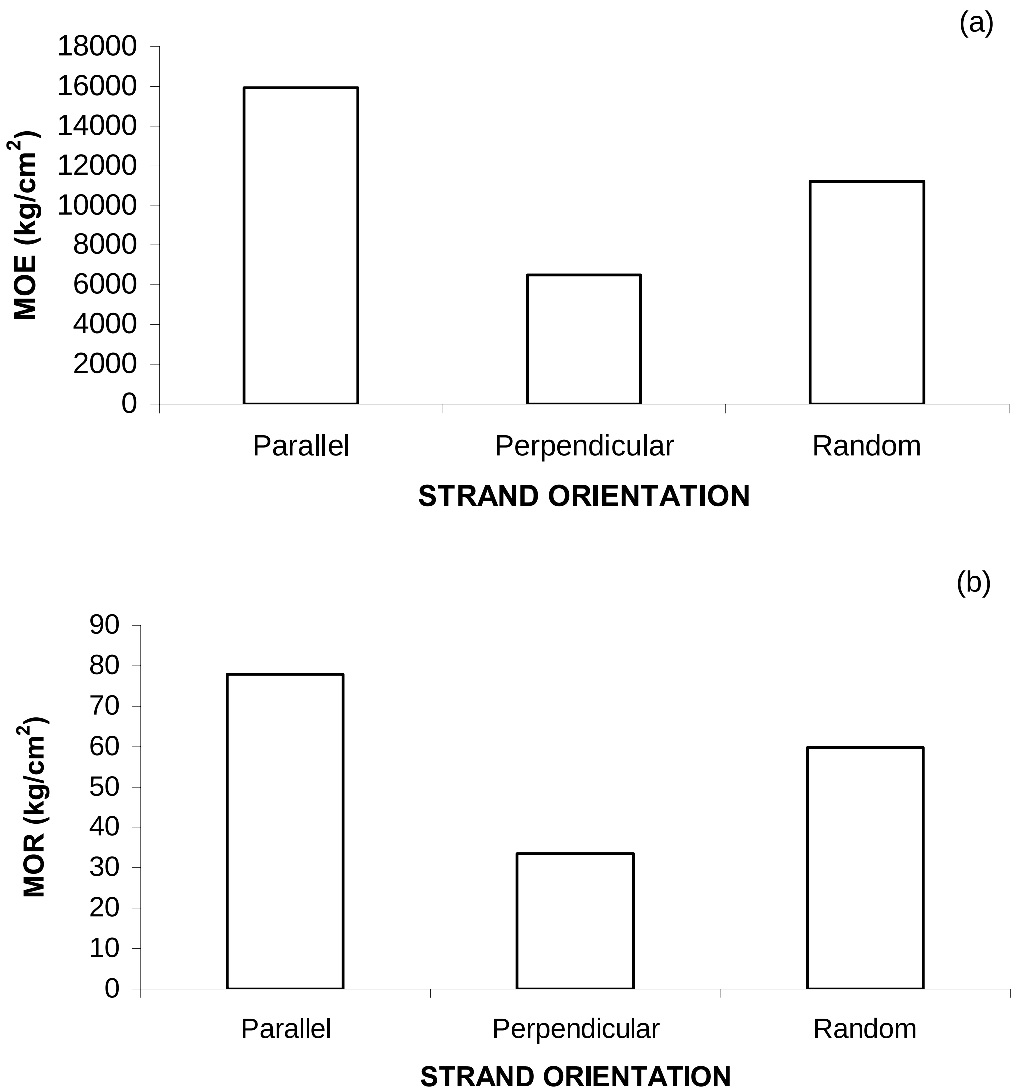


Figure 2. Influence of strand orientation on the MOE (a) and MOR (b) of boards

The MOE (Fig. 3a) and MOR (Fig. 3b) of boards tested wet were significantly lower than those boards that were tested dry, as expected. The overall reduction in MOE and MOR was 32 and 35 percent, respectively. On the other hand, only the MOE of boards was significantly influenced by species. The MOE of boards made from bamboo were 1.15 times higher than boards made from yemane (Fig. 4). This effect may be attributable to the high tensile strength of bamboo than wood in the longitudinal direction.

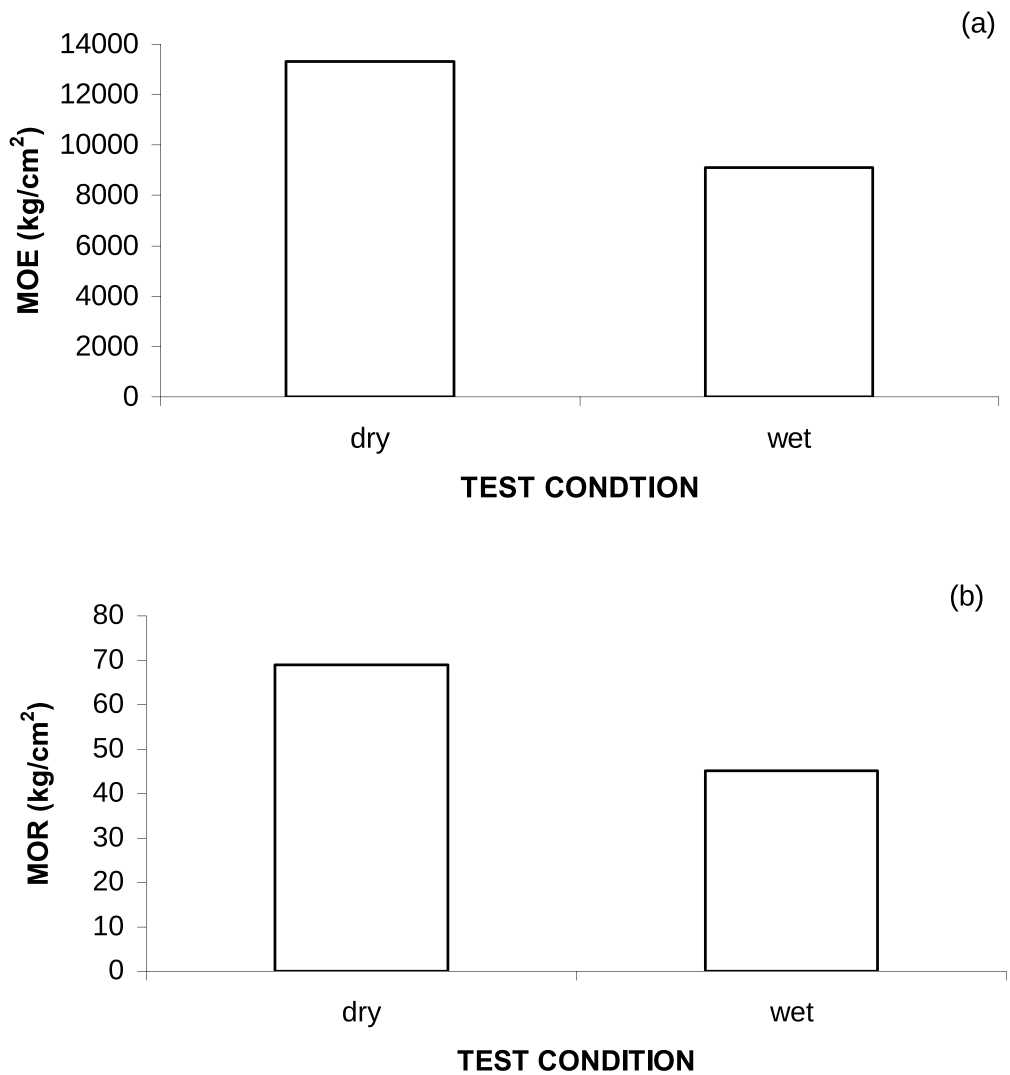


Figure 3. Influence of test condition on the MOE (a) and MOR (b) of boards

There was a significant interaction between the variables used in the study. Both MOE (Table 1) and MOR (Table 2) were affected by the interaction between strand orientation and test condition, orientation and species, and the interaction between strand orientation, species and test condition. On the other hand, the interaction between test condition and species was found to be insignificant suggesting that the MOE and MOR of boards made from bamboo and yemane did not differ in terms of reduction in strength when tested wet.

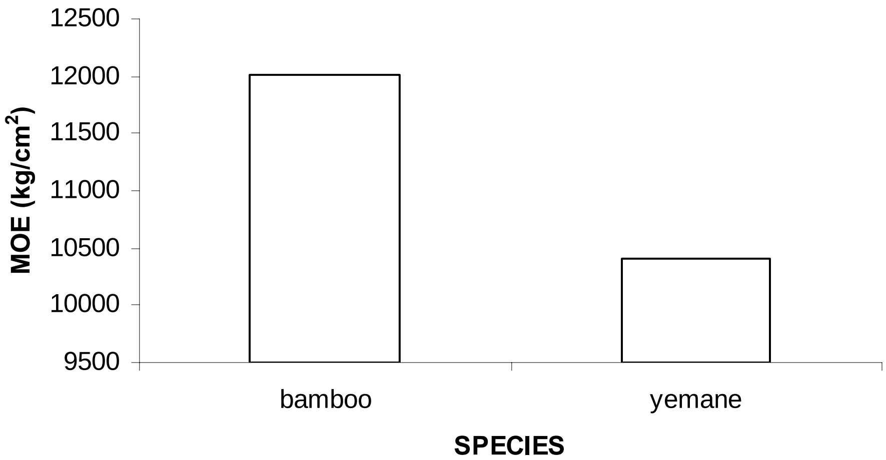


Figure 4. Influence of species on the MOE of boards

The interactive effect of strand orientation, species and test condition on the MOE and MOR of boards are shown in Figs. 5a and 5b, respectively. A least significance difference (LSD) bar is included in each graph to facilitate comparison of means. Boards made from bamboo exhibited the highest MOE and MOR. The dry MOE and MOR of boards from bamboo containing oriented strands were significantly higher than those of boards containing randomly oriented strands. The respective MOE and MOR of boards containing bamboo strands oriented parallel to the span was 1.8 times and 1.6 times higher than boards containing randomly oriented strands. The increase in board stiffness was comparable, while the increase in bending strength was lower, than those obtained by Cabangon *et al.* (2002). On the other hand, the increase in MOE and MOR of boards (compared to boards with random strand orientation) manufactured from yemane was only 1.27 and 1.2 times, respectively.

In Fig. 5, the dry strength properties of boards from yemane and bamboo containing randomly oriented strands did not differ. However, when, the strands were oriented in the preferred direction, higher increase in strength was exhibited by boards made from bamboo. During the manufacture of boards, yemane strands tend to break during mixing with cement resulting to increased difficulty in aligning the strands within boards. This could have been the reason for the lower increase in strength properties of boards from yemane. Such suggestion can also be supported by the lower dry strength parallel/perpendicular ratio of boards made from yemane compared to boards made from bamboo strands. The MOE and MOR parallel/perpendicular ratios were 3.5 and 3.1, respectively. Comparable figures for yemane, were 1.7 and 1.8, for MOE and MOR, respectively. The higher dry strength ratios from bamboo suggest higher strand alignment that could have been the reason for the higher strength increase.

In general, the wet flexural strength of boards was lower than those that were tested dry (Figs. 3 & 5). However, the strength of boards containing bamboo strands aligned to the preferred direction and tested wet did not differ to that of boards from yemane containing randomly oriented strands that were tested dry. This confirms the high strength properties of boards from aligned bamboo strands.

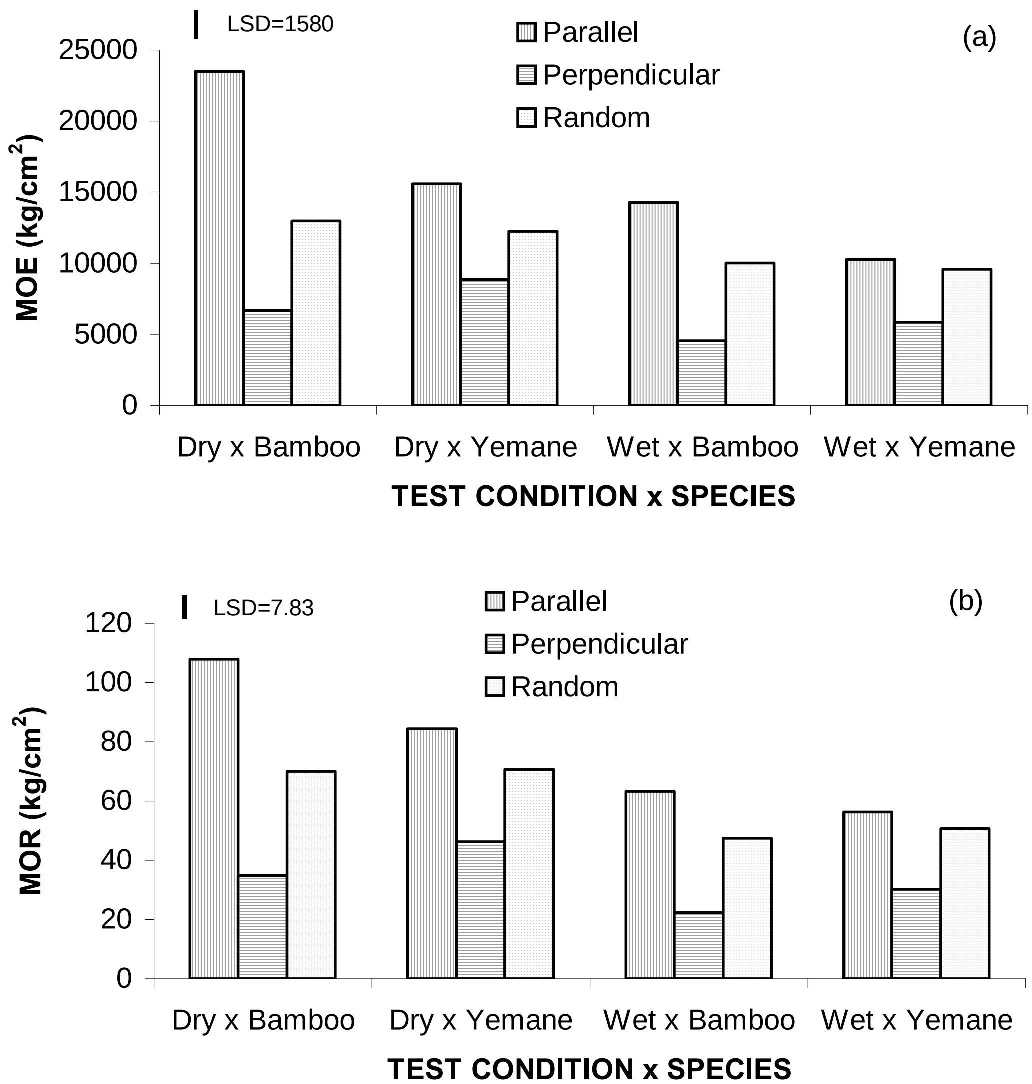


Figure 5. Interactive effect between strand orientation, species, and test condition on the MOE (a) and MOR (b) of boards

In order to examine whether the boards met the minimum strength specifications, the maximum breakage loads of test specimens were compared to the Philippine National Standard for Wood Wool Cement Board (PNS/CTP 07: 1990) (Table 3). PNS specifies a minimum failure of 180 N. Generally, all the manufactured boards passed the PNS specifications except those boards that were aligned perpendicular to the span. The strength properties of boards containing aligned and randomly oriented strands significantly exceeded (particularly boards made from bamboo) the minimum PNS specifications irrespective of test condition. This suggests that both bamboo and yemane are suitable for strand-cement board manufacture. However, where high flexural strength is required, oriented bamboo strands may be preferred.

Table 3. The maximum breaking load of boards compared to PNS (1990) for WWCB

Strand Orientation	Min. Breakage Load (N) (PNS 1990)	Max. Load (N)			
		Bamboo		Yemane	
		Dry	Wet	Dry	Wet
Parallel	180	423.4	247.7	331.0	221.0
Perpendicular		136.9	87.7	181.3	118.8
Random		274.6	186.1	277.5	198.9

The water resistance (TS and WA) properties of boards are shown in Fig. 6. TS (Fig. 6a) and WA (Fig. 6b) of boards were unaffected by species and strand orientation. The water resistance properties of WWCBs are highly dependent on the wood/cement ratio of boards (Cabangon 2003). Thus, the result obtained here may be attributable, in part, to the similarity in strand/cement ratio of 0.75/1 used in the study for both species and strand orientation.

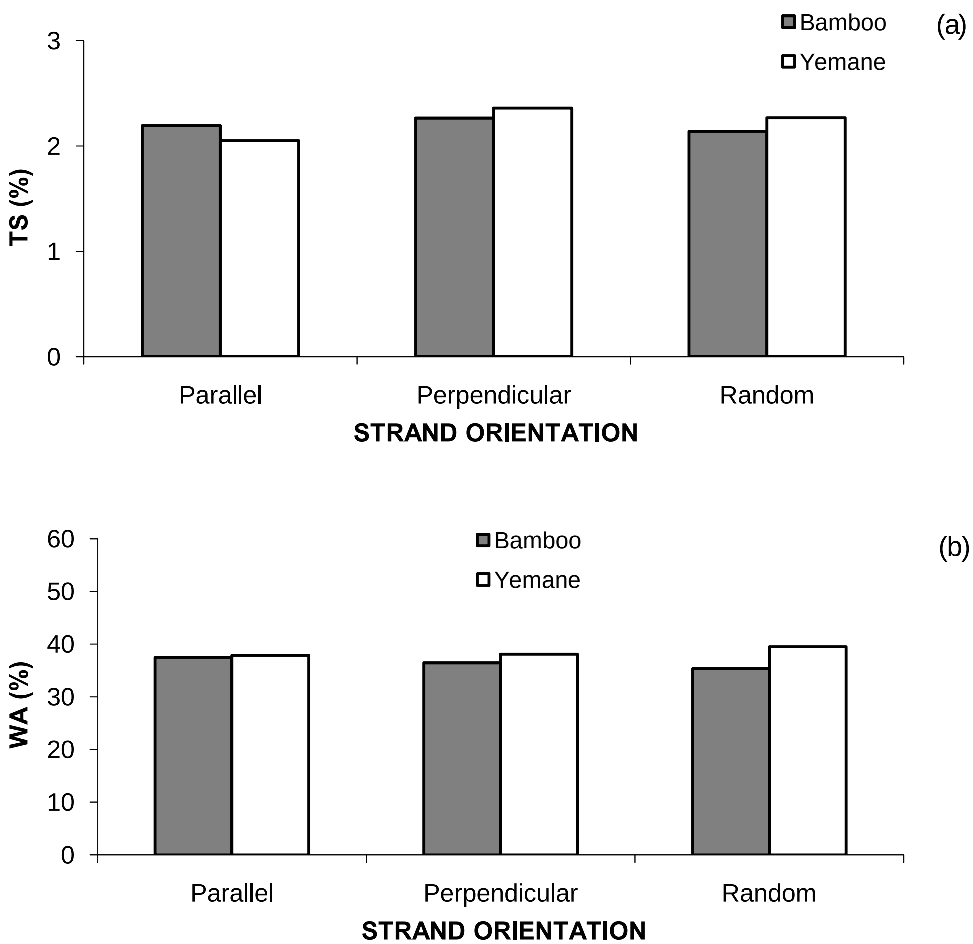


Figure 6. **TS (a) and WA (b) of boards from yemane and bamboo**

Profitability Analysis

The initial investment cost in putting up a plant is PhP 7.3 M excluding land acquisition. Initial investment includes machineries (e.g. shredding machine, mixer, hydraulic press, etc.), building, labor, materials, and pre-operating expenses. The plant is targeted to produce 66,500 panels per year operating at 22 days a month. The plant will employ 6 skilled workers, 10 laborers and one plant supervisor.

It is assumed in the financial evaluation that a market exists and that the outright sale of boards can be made. The average cost of producing a panel is PhP 109.45 and the selling price is about PhP 164.18 obtained by adding a 50% mark-up to the production cost per panel. The income statement indicates that the project will yield an average return on investment (ROI) of 36% Sales revenue is PhP 10.92M per year and the average net income after tax is PhP 2.6M. The cash flow from operations shows the result of the discounted cash flow analysis, which measures the benefit-cost ratio (BCR) and net present value (NPV) of the project. The flow of benefits in accord with the net cash flow was positive indicating a viable undertaking in producing oriented bamboo strand cement composite. The operation is acceptable as shown by the NPV of PhP 9.11 M.

Conclusion

The flexural strength of boards particularly MOE was significantly increased as a result of orienting the bamboo strands within boards. MOE of boards containing strands oriented parallel to the span was 2306 MPa while the MOE of boards containing randomly oriented strands was 1272 MPa. Boards containing bamboo strands oriented parallel to the span and tested wet were comparable to those of boards from yemane containing randomly oriented strands. The MOE of boards from bamboo was significantly higher than the MOE of boards from yemane. However, all boards manufactured using aligned (in the preferred direction) and randomly oriented strands met the minimum strength specifications of the Philippine National Standards for WWCB. TS and WA was unaffected by species and strand orientation.

In addition to enhancing the strength of boards, strand alignment provides a means of better utilizing raw materials for the manufacture of cement-bonded stand boards. For example, if strands are aligned in the prefereed direction, lower amounts of bamboo strands and cement will be required to make boards of a certain strength. This reduces the pressure on the resource base and provides raw materials savings. Moreover, manual strand alignment required no additional equipment or significant modification of the process currently used to manufacture boards in the Philippines. More importantly, the socio-economic conditions in certain countries, for example in the Philippines, permit the employment of hand-forming of cement-coated strands in a production situation.

Results of the study indicate that it is technically and economically feasible to manufacture oriented bamboo strand cement composite using manual strand orientation technique. It therefore appears possible to adopt manual manipulation of board structure to improve properties in commercial WWCB plants.

Acknowledgement

This study was funded by the Australian Centre for International Agricultural Research (ACIAR). The authors thank the ACIAR project staff in the Philippines in the collection of raw materials and manufacture of boards, and Ms. Ma. Soccoro Dizon for the statistical computations of data.

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Development of Oriented Strand Lumber made from *Dendrocalamus asper* Backer

Marius C. Barbu[1, 2], Pannipa Malanit[1, 3], Arno Frühwald[1]
[1]Department of Wood Science, University of Hamburg, Germany
[2]Faculty for Wood Industry, "Transilvania" University Brasov, Romania
[3] School of Engineering and Resources, Walailak University, Thailand

Abstract

The study was conducted to evaluate the suitability of using Sweet bamboo (*Dendrocalamus asper* Backer) for Oriented Strand Lumber (OSL) manufacturing. The boards were manufactured from bamboo-strands using four resin types (MUPF, MF, PF and pMDI) and three levels of resin content (7, 10 and 13%). The physical and mechanical properties of lab manufactured OSL were evaluated by ASTM 1037, ASTM 5456 and EN 300. It was found that OSL made from bamboo strands exhibit acceptable strength properties compared to the commercial products (i.e., Oriented Strand Board) and the engineered products (i.e., zephyr and Parallel Strand Lumber) made from bamboo and wood. The resin type and content have a significant effect on its properties. Regarding the internal bond, bamboo-based OSL shows less strength than others. Further improvements in the internal bond and thickness swelling may lead to OSL industrial for structural use. The best results were obtained by using 13% pMDI content at 750 kg/m³ density.

Introduction

Wood has distinct advantages over other construction materials because it is a renewable raw materials and also friendly to the environment. Moreover, wood has unique characteristics of being superior in strength-to-weight ratio, shock absorbance, vibration, and aesthetically appealing as well as warm touchable. Then, it has been used by humans for the varied requirement, especially for constructions. The availability of timber for the production of large size solid-sawn lumber has declined, while the demand for high quality wood has increased because of the increasing of the world population and restrictive harvesting regulation from natural forest. Thus, this has led to continuous efforts to find new resources as an alternative to wood. Bamboo can be a potentially usable alternative raw material.

Bamboo is one of the promising raw materials that can be used for wood composite manufacturing, because it is a fast-growing, short-rotation life and has similar ligno-cellulosic structure. It has better mechanical properties compared to some wood species. Bamboo has been used since thousands of years for building, especially in the Asia and Pacific region. Thailand is one of the richest areas of bamboo in Asia. There are 13 genera and 60 species. *Dendrocalamus asper* is one of the most popular bamboo species of Thailand planted in more than 60 provinces (Pungbun 2000). The utilization of *Dendrocalamus asper* can be divided into two fields, i.e. young bamboo shoots and bamboo culms. The young shoots are widely consumed as a vegetable. The culms are strong and durable and used as building material and for houses and bridges, also in furniture, musical instruments, chopsticks, household utensils and handicrafts (Dransfield and Widijaja 1995; Rao et al 1998). In many countries, the interest for bamboo utilization has increased after several studies have evaluated bamboo's properties and its potential as an alternative resource for wood composites industry, and regarded the effective use of bamboo for engineered products such as plywood (Chen 1985), oriented strand board (OSB) (Lee et al 1996 and 1997; Sumardi et al 2007 and 2008), waferboard (Zhang 2001), zephyr board (Nugroho and Ando 2000) and laminated bamboo lumber (Nugroho and Ando 2001). They confirmed that bamboo is able to provide high quality engineered wood products. At the same time, several researches in Thailand were carried out to use this species as raw material for fiberboard, pulp and paper (Kamthai 2003; Laemsak and Kungsuwan 2000). However, none of these studies researched bamboo as raw material for the Oriented Strand Lumber (OSL).

The primary objective of this study was to determine the physical and mechanical properties of OSL made from *Dendrocalamus asper* with the respect to the two processing parameters (resin type and resin content), and to compared its properties to standard requirements and previous researches.

Materials and methods

Materials

Three-year-old bamboo culms, with an average culm length of 19 m, and a culm-wall thickness in the range of 6-27 mm, were collected from bamboo plantations located in Nakorn Sri Thammarat, South of Thailand. They were used as raw material for the prototype bamboo-based OSL. Four exterior used resins were used in this research: Melamine Urea Phenol Formaldehyde (MUPF), Melamine Formaldehyde (MF), Phenol Formaldehyde (PF) and Isocyanate (pMDI). The MF resin (Prefere13H560, Liquid) was supplied by Dynea. The MUPF resin (KML 534, Liquid) was obtained from BASF. The PF resin (Bakelite 1279 HW, Liquid) was supplied by Hexion. The pMDI resin (Suprasec® 5025, Liquid) was provided by Huntsman. Their properties are presented in Table 1.

Table 1 Resin properties and manufacturing parameters of bamboo-based OSL

Resin types	Resin properties			Manufacturing parameters			
	Solid content (%)	pH at 20°C	Viscosity (mPa∗s)	Hardener	Mat moisture content (%)	Pressing temperature (⁰C)	Pressing time (s/mm)
MUPF	64±1	9.3-9.8	150-400	NH_4NO_3	9	210	16
MF	62.5	9.73	100-150	NH_4NO_3	9	190	12
PF	48	8.5-10.5	650-700	K_2CO_3	14	190	12
pMDI	-	-	180-240	-	6	220	10

Preparation of strands

Bamboo strands were prepared from green-state culms, with the moisture content in the range of 80-100%, having a culm-wall thickness more than 12.5 mm. The culms were crosscut to 140 mm long pieces and spited into half. Stranding was carried out on a CAE 6/36 Laboratory Disc Flaker. The average dimensions of bamboo strands were 140 mm long, 0.7 mm thick, and 12.5-20 mm wide. Strands were then graded by a Gilson Screen (Model TM-4) through meshes of 12.5 mm. Strands that passed through the 12.5 mm screen-mash and remained in the pan were considered as fine fractions. After these processes, all strands were dried with a laboratory-made rotary dryer to 2% final moisture content.

Lab manufacture of bamboo-based OSL

Uni-directional oriented strand boards with the dimension of 800 mm x 300 mm x 16 mm and 750 kg/m³ in target density were manufactured using laboratory equipment using four resin types and three levels of resin content. All commercial liquid resins were applied to strands using an inhouse-made paddle-type blender. No waxes or other additives were used. Hand-formed mats were transferred to a single-opening hydraulic lab hot press (Siempelkamp press) and pressed into boards. In this study, 36 boards were produced by using a pressing temperature and time following the suggestion of glue supplier, as presented in Table 1.

Properties evaluation of bamboo-based OSL

The lab boards were trimmed and cut into specimens for physical and mechanical properties testing. All specimens were conditioned for several weeks at 65% relative air humidity (RH) and 20°C until constant weight was attained. The property tests for Specific gravity (SG), Thickness swelling (TS), Water absorption (WA), Modulus of rupture (MOR), Modulus of elasticity (MOE) and Internal bond (IB) were conducted in accordance with the ASTM D 5456, ASTM D 1037 and EN 300. All data from the tests were statistically analyzed. A factorial analysis of variance was conducted to test level of significance in difference between factors and the test values.

Results and discussion

The results of the of resin type and resin content influence on bamboo-based OSL are graphically presented in this part. Table 2 shows the results of multifactor analysis variance for bamboo-based OSL properties based on two chosen parameters.

Table 2 Multifactor analyses of variance of resin type and resin content influence on the physical and mechanical properties of bamboo-based OSL

OSL properties	Source of variation	F-value	Significance level
	Resin type	84.75	**
Thickness swelling	Resin content	30.80	**
	Interaction	6.10	**
	Resin type	55.03	**
Water absorption	Resin content	13.17	**
	Interaction	4.30	**
	Resin type	6.52	**
Modulus of rupture	Resin content	41.49	**
	Interaction	0.86	NS
	Resin type	68.69	**
Modulus of elasticity	Resin content	50.57	**
	Interaction	3.17	*
	Resin type	87.70	**
Internal bond	Resin content	65.37	**
	Interaction	2.10	NS

Note:** indicates significance at the 1% level of probability.

* indicates significance at the 5% level of probability.

NS indicates not significant.

Specific gravity

The target specific gravity of the bamboo-based OSL is 0.75, while an average specific gravity is 0.72 at an average moisture content level of 6.64%. This result suggests that the average board specific gravity is lower than the target one (board specific gravity). It may provide an explanation as a spring-back phenomenon of the board after pressing, since the internal board strength cannot resist the internal stress due to excess steam pressure which could not escape from the mat during hot pressing. In this case, the board thickness after pressing increases around 11.92% and 6.50% for bamboo-based OSL bonded with 7% MUPF and 10% MUPF, respectively.

Thickness swelling

The result suggests that the thickness swelling (TS) value ranges from 2.3-26.4 % which is shown in Figure 1. It can be seen that pMDI-bonded board shows less thickness change than those of other boards. Moreover, board made with higher resin content results in improved dimensional stability similar to the findings of previous works (Lee et al 1996; Nugroho and Ando 2000). These results are further confirmed with the statistical analysis, as presented in Table 2. The result shows that the different resin type and resin content have a significant effect on TS value. Notable, the MUPF-bonded OSL shows a significant higher TS value than those of others. It can be explained as a result of the higher hydrolysis sensitivity of the MUPF resin. The lack of resistance to high moisture content is attributed to the presence of hydrolysable group between carbon of the methylene linkage and nitrogen of urea (Pizzi 1994).

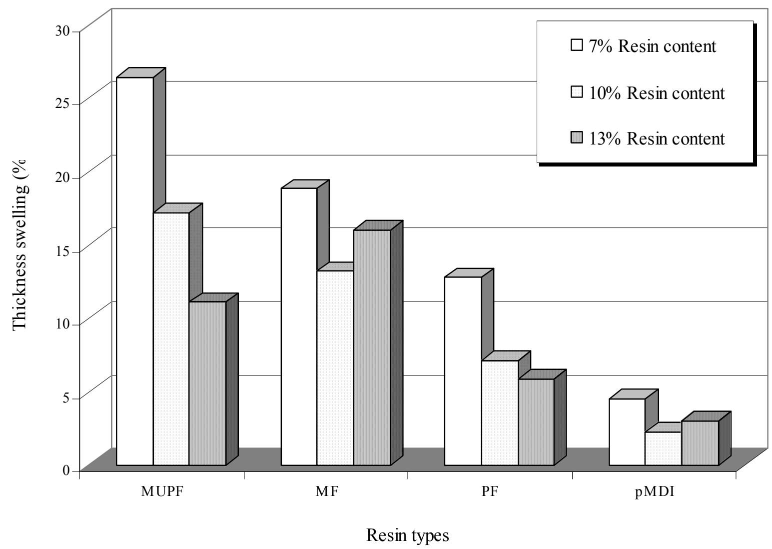

Figure 1 Effect of resin type and content on thickness swelling after 24h water soaking (20°C) of bamboo-based OSL

In accordance with the requirement of OSB/3 type by EN 300 standard, the allowed maximum TS value (24 hours water soaking) is 15%. The MUPF-bonded OSL does not achieve this requirement. It can be explained by no wax or other treatments were done. Accordingly, it requires the wax adding or additional strands pretreatments to improve the dimensional stability of bamboo-based OSL.

Water absorption

The WA of bamboo-based OSL is shown in Figure 2. The value ranges from 16.9 to 40.5%. Analysis variance based on resin type and content is presented in the Table 2. From these data, it may be concluded that the resin type and resin content have a significant effect on this property. The results suggest that OSL made with 13% pMDI resin shows the significant lowest WA, as presented in Fig. 3. A distinctly increase in hydrophobic characteristic observed for pMDI-bonded OSL can be explained by the highly strong bonds between NCO groups of resin and -OH groups of the bamboo cellulose. Furthermore, the obtained values show a slight decreasing trend along with the increase in their resin content in boards.

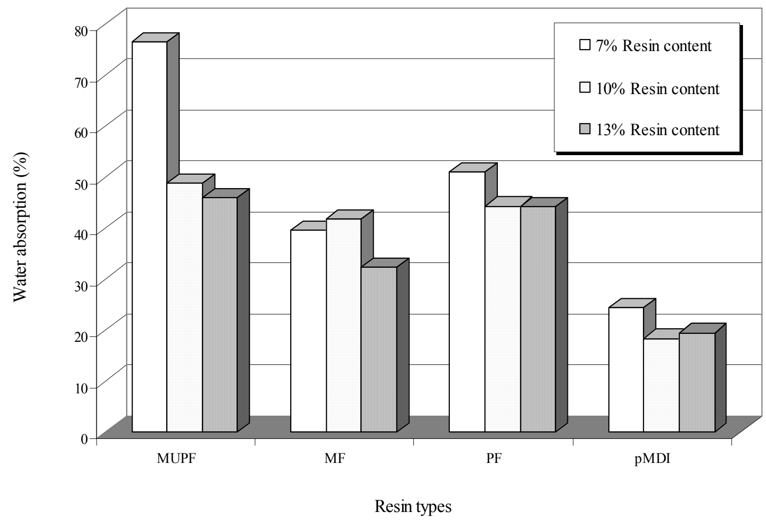

Figure 2 Effect of resin type and content on water absorption after 24h soaking of bamboo-based OSL

This result is consistent with the TS, 7% MUPF-bonded OSL shows a higher WA value than the others. This might be due to its lower specific gravity. Then, more water can be absorbed. Moreover, MUPF resin is low hydrolysis resistance. In distinct contrast to the TS, the WA for PF-bonded OSL is higher than that of MF-bonded OSL. This phenomenon can be suggested by the hydroscopic behavior of the alkali in the PF resin. Thus, a greater amount of water is absorbed without affecting the TS (Pizzi 1994).

Compared to previous reports, the bamboo-based OSL made from pMDI resin show a quit similar WA value to that of bamboo-zephyr (Nugroho and Ando, 2000), while bamboo-based OSL bonded with MUPF and PF resins show smaller values than those of other bamboo-strand based boards (Lee et al. 1996) and Scots pine-based OSB (Paul et al. 2006). The reason of this circumstance has not been addressed.

Static bending

The static bending strengths of bamboo-based OSL are illustrated Figure 3 and 4. The MOR and MOE values are in the range of 29.1 to 65.2 MPa and 3,280 to 11,109 MPa, respectively. The analysis of variance testing conducted on the effect of the two factors and their interaction (Table 2), confirms here that the resin type and resin content significantly influence on both of MOR and MOE.

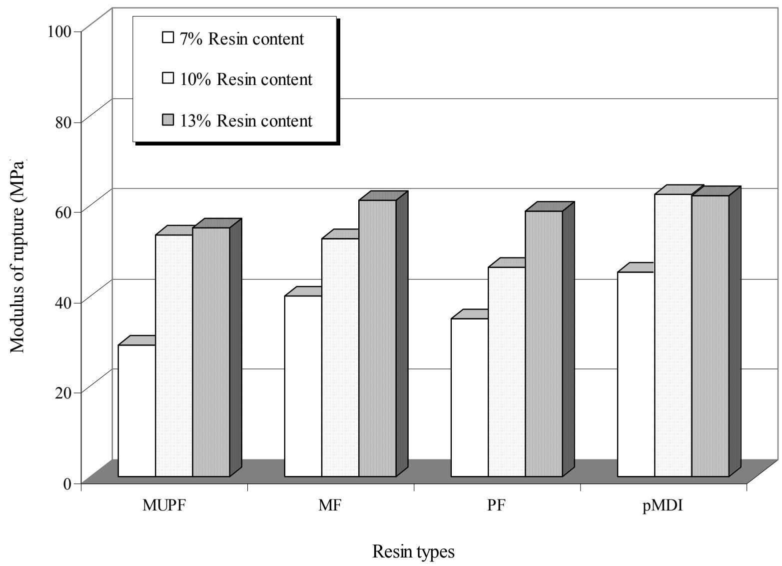

Figure 3 Effect of resin type and content on modulus of rupture of bamboo-based OSL

From Figure 3, it can be seen that the MOR value of pMDI-bonded OSL is highest, while those of MF and PF-bonded OSL are quit similar, and that of MUPF-bonded OSL is lowest. One explanation may lie in the high bonding strength of the cross linked polyurea network of pMDI resin, as mentioned earlier. As well, the resin content contributes to improve board strength and stiffness. In basic knowledge, it can be described the relationship between resin content and product strength that with the increasing of resin content, the product strength will improve by the increase of the intimate contact area between adjacent bamboo strands in the board. These results are also in agreement with the result of Barnes (2000) and Post (1958) who show that with higher resin content of composite board, the physical and mechanical properties of board increase.

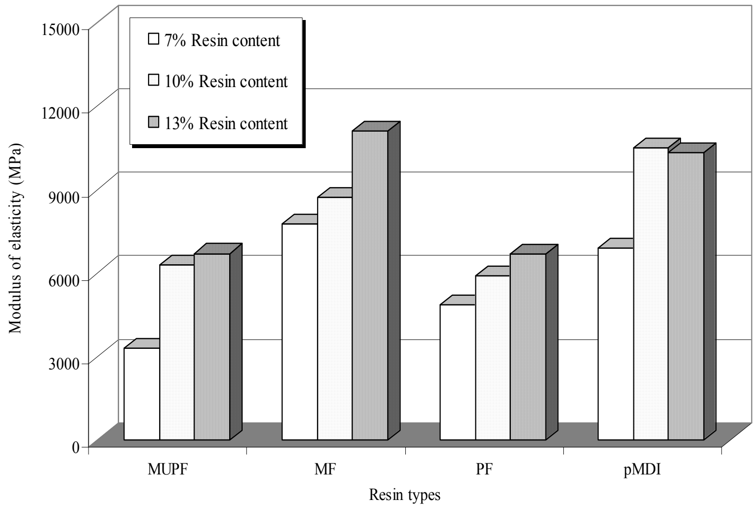

Figure 4 Effect of resin type and content on modulus of elasticity of bamboo-based OSL

From Figure 4, the result suggests that MOE of bamboo-based OSL are mainly influenced by the resin type. The strengths increase in the order MUPF, PF, pMDI and MF bonded OSL. Moreover, they also increase with the resin level. The maximum value is 11,109 MPa for MF at 13% resin content, while the minimum value is 3,290 MPa for MUPF at 7% resin content at the target density of 750 kg/m³. It is impossible to distinguish the difference between MF- and pMDI-bonded OSL and they are approximately 35% higher value than MUPF and PF bonded board at the same level of resin content.

The comparison of MOR and MOE values between bamboo-based OSL and several engineered wood products in the previous researches (Liu and Lee 2003; Malanit et al. 2005; Nugroho and Ando 2000). The average MOR of bamboo-based OSL is quit similar to bamboo-zephyr, but slightly lower than those of wood-based boards. The MOE of bamboo-based OSL is also quit similar to bamboo-zephyr, but approximately 50 to 75% lower than wood-based boards, while the average specific gravity of all products are quit similar. Although bamboo-based OSL was found to be less rigid, but it exhibits acceptable strength property, as indicated by its high MOR value.

Internal bond

The internal bond strength (IB) of bamboo-based OSL made with different resin types and content is shown in Figure 5. The minimum value is 0.06 MPa for the board made with 7% MUPF resin content which shows lower density than those of other and occurs the blisters inside the board., while the maximum value is 0.67 MPa for the board made with 13% pMDI resin content. The analysis of variance result (Table 2) conducted on the effect of two factors and their interaction shows that the resin type and resin content significantly influences the internal bond. The IB of the MF-bonded OSL is quite similar to PF-bonded OSL. Their values are approximately 35% lower than pMDI-bonded OSL because of the high strength of covalent bonds between strands, as mentioned above.

Compare to other engineered composite products (Liu and Lee 2003; Nugroho and Ando 2000; Malanit et al. 2005), PF-bonded bamboo-based OSL shows approximate 3 to 9 time smaller IB value than Rubberwood-OSL. The average IB value of bamboo-based OSL made from pMDI resin is approximate 2 times smaller than those of bamboo-zephyr and Rubberwood-OSL. A possible explanation might rest for this situation. The bamboo specific gravity varies within the horizontal and vertical of culm (Liese 1985). This variation could influence the glue penetration and bonding.

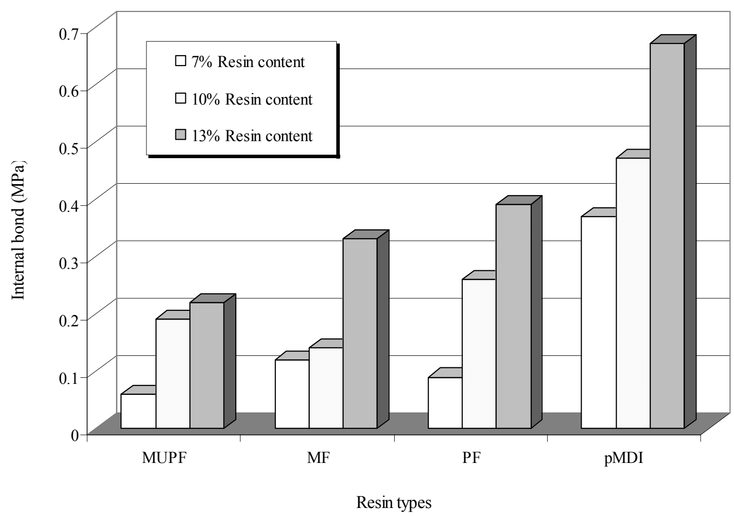

Figure 5 Effect of resin type and content on internal bond of bamboo-based OSL

The minimum IB required by the EN 300 standard for OSB/3 is 0.35 MPa. The result demonstrates that, only the IB value obtained from pMDI-bonded OSL is higher than that of the standard requirement (EN300). It seems likely that the OSL made from *Dendrocalamus asper* shows low internal bond strength. Further experiments to improve of board with special consideration in strands preparation are necessary.

Conclusions

From the results of this study on the physical and mechanical properties of OSL made from *Dendrocalamus asper* conclusions are drawn as follows:

1. Resin type and content are dominant parameters controlling physical and mechanical properties of OSL. The pMDI-bonded OSL show better physical and mechanical properties than MF, MUPF and PF-bonded one. All properties are improving with the increase of resin content.
2. The best parameters of this study are achieved for 13% pMDI resin content.
3. Compare to the commercial products and other engineered wood products, bamboo-base OSL exhibit acceptable strength properties. Then, bamboo-based OSL can be used for structural purposes.
4. *Dendrocalamus asper* can be promoted as an alternative raw material for OSL manufactures, but the special improvements like strand pretreatment and equipment adaptation/pressing optimization are necessary.

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Study on Manufacture and Properties of Bamboo-Chip Binderless Board

Kanok-on Wansanook[a,*]
Masatoshi Sato[b], Associate Professor
a,bAddress: Department of Global Agricultural Sciences, Graduate School of Agricultural and Life Sciences,
The University of Tokyo, Yayoi, Bunkyo-ku, Tokyo, Japan
*Corresponding author

Abstract:

The development of bamboo utilization as renewable alternative raw material as well as bamboo-chip binderless board manufacturing was explored. In this study, the manufacture of bamboo-chip binderless board was described and the investigation of board performances was presented. Board performances were assessed for different pressing temperatures, 160^{o}C, 180^{o}C and 200^{o}C, with fine (designated by F, 0.5mm) and coarse (C, 2.0mm) chips mixed in ratios of 0:100, 50:50 or 100:0. The increase in pressing temperature led to the increased internal bonding (IB) and IB retention in boards after wet conditions. Increase in F and C mixing ratios also increased IB but hardly affected on IB retention. Bending properties including modulus of rupture (MOR) and elasticity (MOE), thickness swelling (TS), and water absorption (WA) of boards were increased as a result of the increasing bond strength. Even though these boards met the requirements for mechanical properties of type 8 JIS A 5908-1994 (Particleboards) the TS and WA were observed rather high.

Keywords: bamboo, bamboo-chip binderless board, pressing temperature

Introduction

The increasing trend of enormous wood-based composites consumption leads to a worldwide interest, especially in many developing countries where the progress towards the infrastructure build-up and massive building construction has been accelerated significantly. Wood-based composites such as wood-based panels are being continuously enhanced to satisfy the high demands imposed by the mobilized construction. However, this enhancement in both quantity and quality has been marked by the production technology as well as many new trends concerning with the environmental aspects, i.e., the attention to renewable alternative raw materials sources for manufacturing, the increasing environmental requirements and the utilization of technology with reduced wastes. Bamboo, a fast growing plant, has attracted a growing attention as the interesting resources for wood substitution in the wood industry. Bamboo is considered as an abundant resource and could be used as substitute raw materials in the wood industry, especially in Asian countries which have limitation in wood supply but enormous agricultural wastes. In Thailand, bamboo is an important economic crop as bamboo shoot utilized for food commodities is increasing the export share in the world market. Consequently, bamboo plantations are expanding rapidly in order to serve the high demands of bamboo shoots[1]. These plantations produce culm as waste from pruning and thinning operations. The bamboo which is considered as waste from plantation might be a potential raw material in the wood industry.

Currently, bamboo was used to produce panel composites at an industrial scale, i.e., bamboo composites boards and laminates[1]. The technology such as bamboo mat laminates is still being developed and scaled-up, and some studies concerned with bamboo products are still under progress[2].

These studies have been stressed mainly to investigate the feasibility of producing bamboo boards with adhesives such as bamboo strand boards bonded with phenol formaldehyde[3] and bamboo particleboard bonded with urea formaldehyde[4]. The study[5] also confirmed that bamboo could be used as a substitute raw material in place of wood species due to its compatibility with commonly available adhesives.

Despite intensive attention repeatedly emphasized on producing adhesive-bonded boards, the high cost of synthetic adhesive, health and environment concerns and formaldehyde emission are regarded as the major issues for developing the wood industry technology. Bamboo-chip binderless board could be one way to develop bamboo utilization as well as wood technology which will allow the production without the dependence on synthetic adhesives and will also be the alternative technology for wood industry. This manufacturing has several potential advantages, i.e., reduction in adhesive costs and also a suitable technology for any country that has petroleum resource limitations. Several researchers have been dealt with binderless boards as well. Study[6] suggested that lignin-fufural linkages of steam exploded-fiber, generating during hot pressing, was the main bonding strength of board. One study[7] confirmed that binderless panels made from softwood pretreated by steam explosion had better mechanical properties than panels made from non-pretreated materials. Moreover, steam-injection press was used for developing kenaf core binderless board[8]. In another recent study[9], kenaf binderless board was produced from kenaf core flour. To date, even though there have been many studies about binderless board, the processing conditions reported in these different raw materials may not be suitable for bamboo. In order to use bamboo effectively to produce bamboo-chip binderless board further research is needed. This study was aimed to explore the possibility of producing bamboo-chip binderless board. Ground chip were selected to produce bamboo-chip binderless board as they were small chip that might provide large surface area. Consequently, the chemical components of chip with large exposed-surface area may be activated easily during hot pressing without pretreatment.

The objective was to investigate the possibility of manufacturing bamboo-chip binderless board concerned with the effects of manufacturing conditions including pressing temperature during hot pressing and the mixing ratio in different size of chip on the basic performance of binderless board.

Materials and Methods

Materials

Four years old bamboo culm, Madake (*Phyllostachys reticulate*) collected from Chiba prefecture, Japan, with specific gravity 0.7, was used as the raw material. The bamboo culms were cut to 50 mm in length, and then sliced by cutter into coarse particle of approximately 5 mm thickness. These coarse particles were ground to pass through the sieve in a willey mill to obtain fine chip with grain size 0.5 mm (F) and coarse chip with grain size 2.0 mm (C). The mixing ratios of F and C (F/C) at 100:0, 50:50, and 0: 100 were prepared for producing boards. The moisture content of these particles was around 10-12%.

Board Manufacturing and Testing

The F/C mixtures were manually formed into homogeneous single-layered mats of 300 mm × 300 mm × 6 mm (using a forming box and covering the top and bottom surface of the mats with aluminum foil) with a target board density of 0.8 g cm^{-3}. Afterward the mats were pre-pressed by hand and were then pressed for 10min at the pressing pressure of 4.7 MPa by a hot press with various pressing temperatures (PT) of 160, 180, 200 and 220^{o}C. Four replications of boards were made for each manufacturing condition.

Before testing the properties, the boards were conditioned at room temperature for about 2 weeks during which time they reached a moisture content of 7-8%. After that, the boards were cut into various test specimens and were tested for mechanical (internal bonding, IB and bending strength including modulus of rupture, MOR and modulus of elasticity, MOE) and physical (thickness swelling, TS and water absorption, WA) properties. In each condition, five specimens with the size of 50 mm × 200 mm were tested for MOR and MOE. Eight specimens with the size of 50 mm × 50 mm were tested IB. Twelve specimens with the size of 50 mm × 50 mm were tested for TS and WA. The procedure of testing was done according to JIS A 5908-1994 (Particleboards)[10]. In each condition, bending strength and IB values were measured additionally from five and eight specimens, respectively, after the wet conditions. The wet conditions were performed firstly by soaking the specimens in water at 70^{o}C for 2 h and then water at 20^{o}C for 1 h.

Results and Discussion

Board Appearance

Most of the binderless boards made from given manufacturing conditions were successfully manufactured except board pressed with pressing temperature of 220 ^{o}C. The specimens of boards pressed with 220 ^{o}C could not be obtained as the board exploded during pressing. Boards pressed with higher platen temperature were more darkly colored. These indicated a greater degree of hydrolysis of the chemical components during hot pressing process. All boards had odor, smooth and glossy surface, and tight edges.

Internal Bonding

Fig 1 shows the effect of PT on IB and IB retention with the different F/C mixing ratios. On the whole, IB values had a trend to increase with the increasing PT. This increasing trend is similar to those reported in studies[7,9]. These IBs were improved because the increasing PT might be contributed well to activate the chemical components in board constitute and then would be brought about the increasing IB. In this study, the result suggested that at PT of 200^{o}C, IB was higher than using PTs of 160 and 180^{o}C. This indicated that the favorable PT for developing the highest IB in this study was at 200^{o}C. This PT of 200^{o}C corresponded to the glass transition (Tg) values, in dry state, of cellulose (around 220°C), hemicellulose (around 170°C) and native lignin (around 200°C)[11]. Therefore, PT of 200°C may be the temperature that could make bamboo soften and develop bond area which provided the highest IB. This phenomenon could possibly be interpreted from the explanations given in the previous study[11]. They suggested that at temperature above the Tg of wood polymers, viscosity of wood would drop and present the flow characteristic, then the diffusion would take place and promote the bonding area, especially under the pressure applied. Furthermore, the increase in PT also had trend to increase the percentages of IB retention and at PT of 200°C it also showed the higher retention than other PT conditions as well. From this result, the increasing PT could improve some extent of the water resistant properties of board which were indicated by the increase in IB retention. The residual bonding strength in boards after wet condition could be assumed as the bond type that could resist the water. As in the report[11] the bond that would resist the water was thought to be the covalent bond forming between the wood polymer chains to some extent during hot pressing, and they suggested that lignin appeared to be the most reactive in this type of autocrosslinking. Therefore, this reaction of lignin might improve the water resistant property of boards. Nevertheless, the highest IB retention obtained in this study remained somewhat low, only about 30%. A similar result was also observed in binderless board made from kenaf in one study[9].

Fig 1 also shows IB values in different F/C mixing ratios. Board made from F/C mixing ratio = 100:0 provided the highest IBs. These highest IBs were observed due to the greater amount of fine chip in mixing ratio of boards. The fine chip might provide more bonding contact between chips due to its greater surface area compared to that of coarse chip. Therefore, the fine chip could improve IBs and could also lead to the higher IB retentions. In addition, at the same PT, IB retentions were nearly similar in all mixing ratios. This indicated that F/C mixing ratio hardly affected the development of water resistant properties in boards. This suggested that using chip with more surface area could develop IB values but hardly induce the bond that could resist the water. The reason may be attributed to the property of bond, which is sensitive to the water. The exact property of this bond occurring when particles were activated under heat is not known clearly. However, these potential interparticle-bonding might predominately be the secondary bond which is sensitive to water as suggested by one study[11]

Thickness Swelling and Water Absorption

Fig 2 shows the effect of PT on TS and WA in different F/C mixing ratios. At higher PT, less TS values were noted as a result of an increase in IB retention. Furthermore, TS values were improved due to two possible reasons. First, increasing PT might make bamboo more soften and boards could produce less stress, and thus less stress relaxation might be occurred. Another, as in one study[12], increasing PT could degraded hygroscopic hemicellulose in greater extent which decreased the hygroscopic components in boards. The WA values had also the similar trend as TS values which were related to an increase in IB values of the boards. Again, when bamboo becomes more soften and diffusive flow characteristics occurs due to the increasing PT, the contact area would be developed. This made the boards to possess few porosity inside, and this could explain the reason of less water absorbed in boards due to the increasing PT.

It could be observed that, at higher PT, the effect of F/C mixing ratio on TS values was not distinctly observed. This might be because the F/C mixing ratios had a slight effect on the improvement of the water resistant property of boards. For WA values in each F/C mixing ratio, there seemed to be a slight difference. Boards made from greater coarse chip in F/C ratio showed little greater WA values since the coarse chip provided lower IB in boards and hence there would be more porosity inside the boards.

Bending Strength

Figs 3-4 show the effect of PT on bending strength (MOR and MOE) and on their retention after wet conditions, respectively. The bending strength had the same trend as IB. The PT of 200°C provided higher MOR and MOE than other PT conditions. MOR and MOE retentions also tended to increase with the increasing PT. However, boards were rather low in bending properties when compared to the requirements of the JIS A 5908-1994 (Particleboards) standard[10]. This was probably caused by the small grain-shape of chip that did not contribute to bending strength. If the chip does not create the bond sufficiently well, boards made from these chip type might not then develop sufficient bending strength.

The F/C mixing ratios also had effect on bending strength. Boards made from the higher coarse chip in F/C ratio showed higher MOR values and MOE values because the coarse chip could provide the larger length of contact among the chips. Thereby coarse chips could favorably withstand the shear stress and create the continuous contacts among the chips. A little difference of retention among various F/C mixing ratios was observed and this might be caused by almost same IB retention in all cases of F/C mixing ratios. From these results, coarse chip could support the strength. Further research should be done for developing the particle types, which is contributed to bending strength as well as this particle could also develop the sufficient bond strength.

Conclusions

The following conclusions could be drawn from the study:

1. There is the possibility to develop the bamboo utilization for manufacturing bamboo-chip binderless board. Under the given conditions, pressing temperature of 200°C and fine and coarse chips mixing ratio of 0:100 provide board properties, which achieve the required mechanical properties of type 8 JIS A 5908-1994 (Particleboards). However, the low strength retention in wet conditions as well as the high values of TS and WA may indicate the low water resistant properties, suggesting that bamboo-chip binderless boards are suitable for nonstructural application with service in indoor not exposed to wet condition. The results suggest that the further development related to the water resistant properties needs to be considered.

2. The increasing in pressing temperature would develop the bonding strength of boards. Improved bonding strength retention also implicates that pressing temperature may be an important parameter to induce the bond that resists water.

3. Using the greater extent of coarse chip could improve the bending properties although bonding strength appears lower than using fine chip. This suggests that further research for development of shape and/or type of particle in inducing bending properties should be considered.

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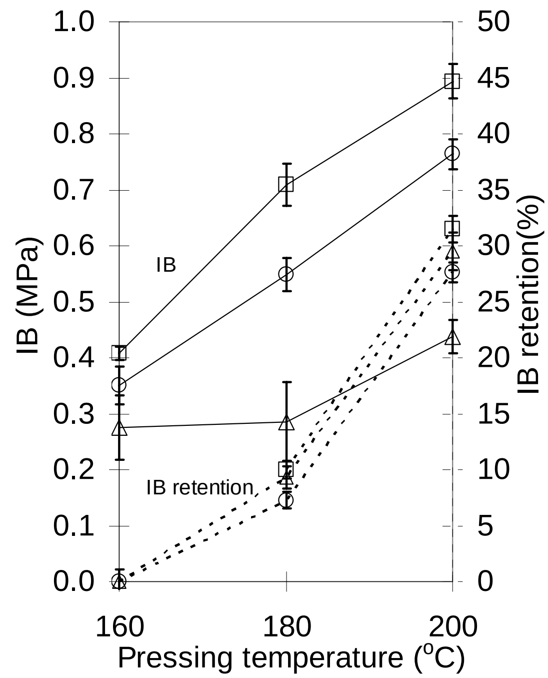

Fig 1. Effect of pressing temperature (PT) on the internal bonding (IB, symbols with full line) and IB retention (symbols with dash line) of boards with different fine (size 0.5 mm) and coarse (size 2.0 mm) chips mixing ratios.

□ 100:0, O 50:50, Δ 0:100, vertical lines with the bars represent the standard deviation from the mean

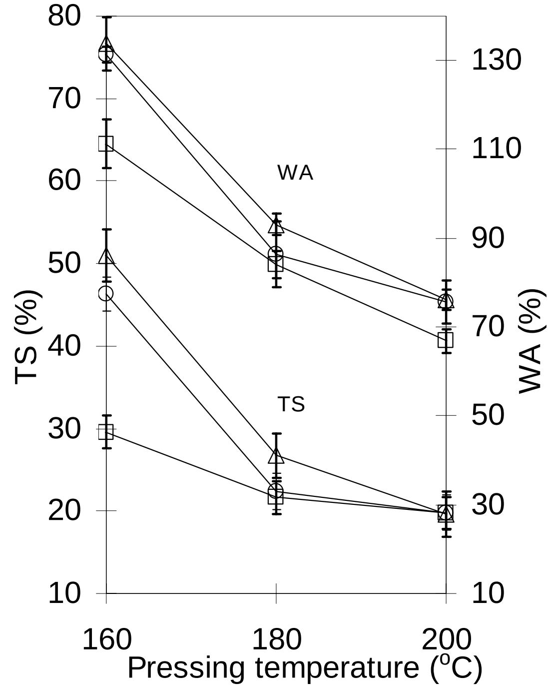

Fig 2. Effect of PT on the thickness swelling (TS) and water absorption (WA) of bamboo binderless board with different fine (size 0.5 mm) and coarse (size 2.0 mm) chips mixing ratios.

□ 100:0, O 50:50, Δ 0:100, vertical lines with the bars represent the standard deviation from the mean

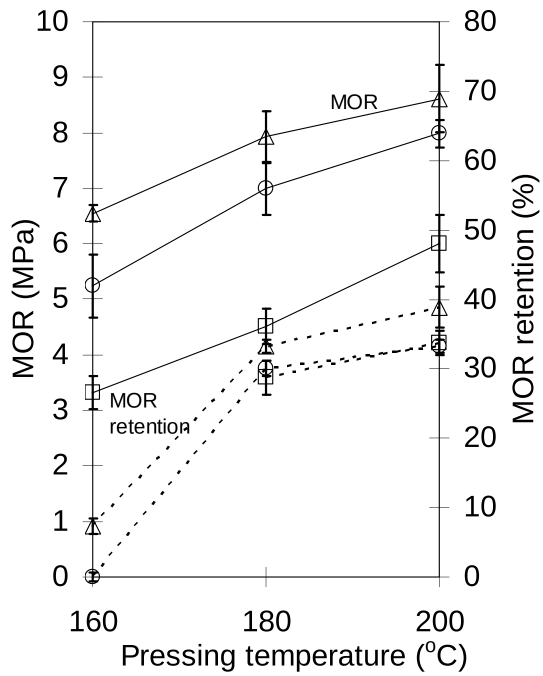

Fig 3. Effect of PT on the modulus of rupture (MOR, symbols with full line) and MOR retention (symbols with dash line) of boards with different fine (size 0.5 mm) and coarse (size 2.0 mm) chips mixing ratios.

□ 100:0, O 50:50, Δ 0:100, vertical lines with the bars represent the standard deviation from the mean

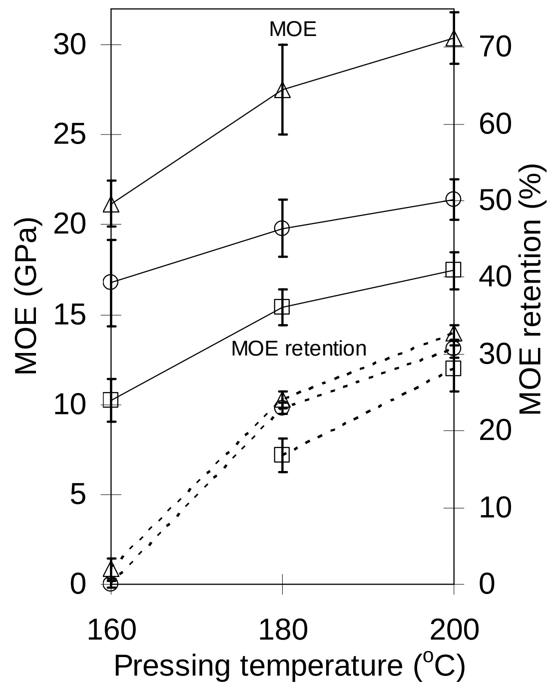

Fig 4. Effect of PT on the modulus of elasticity (MOE, symbols with full line) and MOE retention (symbols with dash line) of boards with different fine (size 0.5 mm) and coarse (size 2.0 mm) chips mixing ratios.

□ 100:0, O 50:50, Δ 0:100, vertical lines with the bars represent the standard deviation from the mean

Bambu Project:
Mechanical Characteristics of the Glued Laminated Bamboo

Dr. Marco Antonio dos Reis Pereira
São Paulo State University-UNESP/ School of Engineering/Mechanical department

Dr. Obede Borges Faria
São Paulo State University-UNESP/ School of Engineering/Civil department

Abstract

With the growing of forest deforestation it is becoming necessary to search alternative materials and solutions that can help reduce this process. The bamboo culture is millenary in many regions of the planet but it has its utilization and research restrict mainly to oriental countries. The bamboo is a tropical culture renew resource, with fast growing, annual production and hundreds of species and thousands of applications sprayed around the world. The bamboo is considered a great carbon sequester and with physical and mechanical characteristics that makes possible to use it as products usually made with wood, as to: civil construction components, furniture, tools, panels, etc. This work intended to determine some mechanical characteristics of resistance and elasticity of the glued laminated bamboo using mature culms from clumps locally cultivated in the Universidade Estadual Paulista-UNESP, campus of Bauru, São Paulo state. The specie used was the giant bamboo (*Dendrocalamus giganteus*) that has good characteristics and dimensions to strips confection. The culms were processed to obtain the laminated bamboo strip nearest possible to the skin part. These strips were glued to specimens confection and study. The specimens were made according to Brazilian wood standard -NBR 7190/1997. The results showed that the glued laminated bamboo has good resistance and elasticity characteristics that make possible the use of this material for many purposes, like some objects and furniture confection. Thus, some glued laminated bamboo products were made to show some possibilities of the material.

Keywords: bamboo strips, glued laminated bamboo, mechanical characteristics, products.

Introduction

Historically, the bamboo has accompanied the human being providing food, shelter, tools, utensils and an infinity of other items. Nowadays, it contributes to the livelihoods of more than one billion people. Equally important alongside the traditional practices, it has been the development of industrial uses of bamboo (Sastry, 1999).

With the increasing deforestation and pressure on tropical forests, as well as on the areas of reforestation, makes it increasingly necessary to search for renewable materials and alternative solutions capable of partially alleviate this process. Today, few people doubt that the ecological problems will be a necessary condition for industrial processes, human settlements and development, and the 21st century can be considered as the century of the environment. Thus, the search for non conventional materials and renewable energy sources has been converted into a global priority at the beginning of this century (Saleme & Viruel, 1995).

In accordance with Zhou (2000), in the past 50 years the devastation of the forests got to 24.9 million ha/year, or the equivalent to 47.41 ha/minute, a condition which must also contribute to the increase in the area for cultivating bamboo in world that today is about 22 million hectares. Newspaper Folha de São Paulo (09 /08/2000) mentions the FAO data where for the period between 1990 and 1997 a speed of deforestation equivalent to 12.17 ha/minute is presented. Another newspaper reportage (Newspaper Folha de São Paulo, 09-09-2002), showed data supplied by the Secretary of State for Agriculture and the Brazilian Society of Forestry, where a fall of 5% in the reforested area of the Sao Paulo state was reported and indicates the necessity of the duplication of the annual wood reforestation planting in the country.

Pauli (1996 ; 2001), highlights the bamboo as an efficient carbon fixer, converting the carbon-via photosynthetic in cellulose, hemi-cellulose and lignin, with rapid growth and harvests, long fibers and strong and high mechanical strength using minimum energy, and also, an entire industrial conglomerate around the bamboo can really be developed.

Bamboo is the natural resource that needs less time to be renewed, as there are no forest species that can compete in growth rate and utilization per area (Jaramillo, 1992). The decreasing of the quantity and quality of forest resources has increased the interest to low cost and renewed materials like bamboo, with applications involving composite bamboo panels and wood/bamboo panels, as well as glued laminated bamboo, bamboo mats; bamboo plates made by mold pressure, compounds of bamboo-epoxy and bamboo-polymer, bamboo particles and others. However, to maximize the use of bamboo, it is necessary that their physical and mechanical properties be better understood (Lee et al, 1994).

Products made with glued laminated bamboo such as floors, boards, panels, handle tools, plywood, furniture, construction components, among others, can be explored by the culms processing. Although we do not think bamboo as an exclusive solution to problems related to the environment and/or the sharp decrease of our forest resources, it may be considered and studied as an alternate and low cost material to be explored. The culms production is very fast, without the need of replant, its culture and exploitation in the field may be quickly implemented (Pereira, 2001)

Even though the bamboo has been used and studied for centuries in oriental countries, China Bamboo Research Center (CBRC, 2001), underlines that since the 1980s the use of bamboo has been intensified in several industrial areas, highlighting food, paper, engineering, chemicals and products based on processed bamboo (wood of bamboo) which may replace/prevent the cutting and use of tropical forests, highlighting among others, products such as coal, activated charcoal, sticks, sheets, panels, glued laminated bamboo products, mats, composite, plates of oriented fiber (OSB), components for construction/housing and furniture industry, among others. In China many bamboo products are investigated and produced (industrialized) such as: floors, ceilings, sidings, furniture, strips plates and parquet, curtains, concrete forms (ply bamboo). (Qisheng & Shenxue , 2001).

The bamboo project has been developed since the year 1994 when the first species were planted in the Unesp campus. Since the year 1998 bamboo culms have been harvested and used for research purposes (Pereira & Beraldo, 2007). Studies with bamboo as a laminated material are still incipient in Brazil, and even in terms of world its study is fairly recent. Laboratory data, concerning the determination of physical and mechanical resistance, are important for assessing the quality of the material and its technological potential, aiming later use in applications. As the data on bamboo management, development and production as well as physical and mechanical characteristics are scarce in Brazil, the determination of these characteristics for future uses and bamboo development is very important.

The mechanical characteristics determination is important not only for quality of the material but also for a future standardization of the tests.

The main objective of this work was to determine such mechanical characteristics as the compressive, tensile and bending strength together with the elasticity modulus, using for this the wood Brazilian standard – NBR 7190/97 (ABNT, 1997).

Experimental procedure

The bamboo is a different material from wood in terms of its anatomy, morphology, growth and properties of resistance, having significant variations in their properties both in the vertical-height direction (from the base of culms toward its tip), as well as toward horizontal thickness direction (through the wall of the culms). Variations that occur also in despite of species studied, the local conditions of cultivation and especially also in relation with of the age of culms. Thus, in this work, some parameters were fixed, to standardize the obtaining of the specimens in relation to the culms age, culms location along the height and its position through the wall of the culms.

2.1 Research location

The work is being developed in Bauru city (23°S, 48°W), São Paulo state, where the clumps are cultivated and managed. The laboratory studies are carried out in the Laboratory of Wood Processing, of the Mechanical Engineering Department and in the Laboratory of Construction Materials, of the Civil Engineering Department, in the São Paulo State University-Unesp/ School of Engineering

2.2 Bamboo specie

The laboratory, has a collection with approximately 23 bamboo species, being 13 of them priority (INBAR, 1985). The specie used in this work is the giant bamboo (*Dendrocalamus giganteus*), which is relatively common in the Brazilian rural environment. The clumps of this specie were cultivated in the summer of the years 1994-1995, and since the year 1998 have produced culms with adequate dimensions for processing. Figure 1 shows a clump of this specie.

Figure 1 - Clump of giant bamboo.

Age of Culm

It was fixed the culms age of 3 years old because this age is cited by many authors (Liese, 1998; Hidalgo Lopez 2003; Beraldo et al., 2004; Janssen, 2000; Zhou, 2000 and CNBRC, 2001), as that in which the culms are mature in terms of their mechanical strength characteristics. Figure 2 shows the letter system adopted to make the age of the culms known.

Figure 2 - Age identification of the culms.

Useful height of culms

Defined as one where the wall thickness is at least 10 mm. maximizing this way the use of culms in terms of its height. The thickness of 10 mm is the minimum necessary for the processing and obtaining of the final strips that are used in the specimen composition, with a final thickness between 5 and 6 mm, in accordance with the preliminary experience developed (Pereira & Beraldo, 2007). All the specimens were made using strips with the presence of nodes.

Culms processing

After the harvest in the field the culms were processed to obtain the strips, as follows (shown in the figures 3 and 4):

- Transversal cutting in a ripsaw machine getting sections with 90 cm in length.

- Longitudinal cutting in a double ripsaw for the strips obtaining

- Removal of the protuberance caused by the presence of the nodes using a ripsaw

- Air drying the strips up to the equilibrium humidity

- Processing using a four faces shaper machine for laminated strips obtaining

- Gluing of the strips for a specimens obtaining

Figure 3 - Transversal cutting and longitudinal cutting.

Figure 4 - Nodes removal and four face shaper

Dimensions of the strips

The thickness of the strips defined at the moment as being between 5 and 6 mm, so as to maximize the use in height of the culms. The width of the strips defined at the moment as being 20 mm (for this kind of bamboo and their physical characteristics of diameter and wall thickness), and this way getting the strips as close as possible to the most external region of the wall.

Strips position through the culms wall

The specimens were made using strips from positions as close as possible to the skin, seeking the richest region in fibers and theoretically more resistant along the wall, being discarded at this time the material from regions more internal of the wall, richest in parenchyma and theoretically less resistant. The most external wall of culms (peel) was also removed in order to make the gluing process easier. Figure 5 shows the position where the strips were removed.

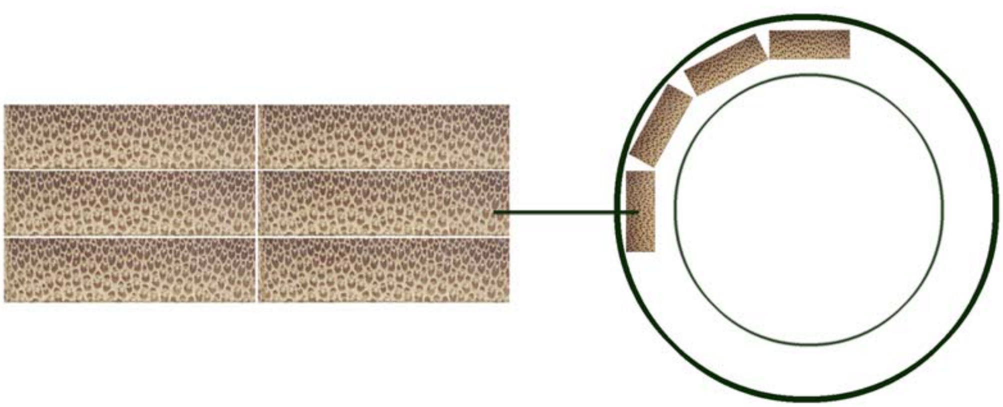

Figure 5 – Position of the strips through the culms wall

Mechanical Tests performed, specimens dimensions and moisture

The mechanical characterization was done by the resistance and longitudinal elasticity modulus, obtained from three tests that are: fiber parallel compression, fiber parallel tension and simple bending; all performed according to Brazilian wood standard NBR 7190/97 (ABNT, 1997), because there aren't Brazilian standards to the bamboo.

The specimens and the samples were made according to the standard dimensions. The cross section dimensions for the parallel compressive test are 5 cm x 5 cm and 15 cm length. For the simple bending test, 5 cm x 5 cm at cross section and 115 cm length (with 105cm at distance between supports). The cross section for the parallel tensile test is 5cm x 0.7 cm and 42 cm length, as shown in figure 10. All specimens were made with the bamboos in the equilibrium moisture.

Results and discussion

In this section the main results of the mechanical characterization tests are presented, besides illustrations that can show the shape of the adopted specimens.

Resistance and elasticity in the parallel compressive test

The specimen appearance and the deformation measure instrument are shown in figure 6.

Figure 7 shows the two patterns of severing observed in specimens of parallel compressive test. The image on the left shows a pattern of diagonal severing (angle of 45º, more or less) observed in most specimens and similar to that observed in tests with solid wood. The image on the right shows a severing without a well defined diagonal and that occurred in some specimens. In terms of safety it shows a rupture which may be considered ductile.

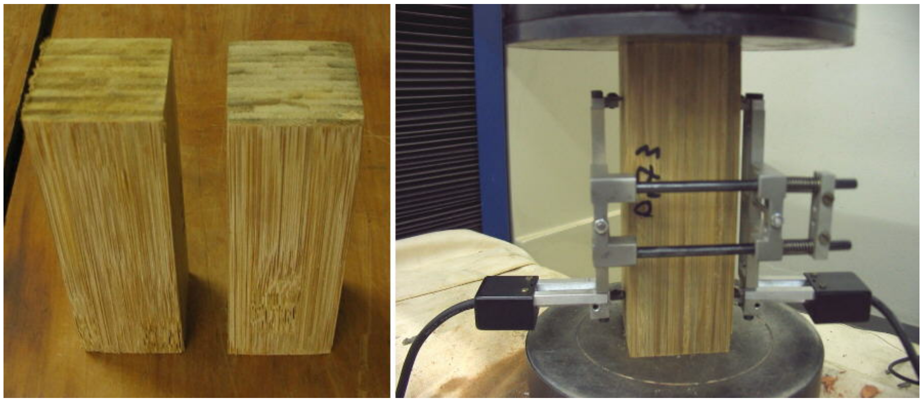

Figure 6 – Specimens in parallel compressive test, with the deformation measure instrument.

Figure 7 – Specimens after the test.

Table 1 shows the results obtained to strength (f_{co}) and longitudinal modulus of elasticity (E_{co}), in parallel compressive test, using the adhesive cascorez 2590 (PVA), at the rate of moisture U.

Table 1 – Results of the parallel compressive tests, in glued laminated bamboo.

Specimens	f_{co} (MPa)	E_{co} (GPa)	U (%)
1	67	17.0	11.2
2	62	17.8	11.1
3	64	17.2	11.1
4	68	18.6	10.8
5	63	19.8	10.9
6	61	22.5	11.4
7	63	16.2	10.9
8	64	17.2	10.9
9	65	17.7	11.3
10	67	17.9	11.4
11	66	18.1	10.9
12	73	19.4	11.4
13	63	15.2	11.2
14	75	20.6	11.4
15	61	20.0	11.5
16	64	15.2	11.3
average	65.5	18.1	11.2
standard deviation	3.9	1.9	0.2
variation coefficient (%)	5.9	10.7	2.1

Table 1 shows the variation range of resistance obtained in parallel compressive tests with values ranging between 61 and 75 MPa, with an average of 65.5 MPa. The average modulus of elasticity in the compression was of the order of 18.1 GPa, with variations between 15.6 and 22.5 GPa. The resistance values obtained are above native or reforestation coniferous wood, as for example, Pine of the Paraná (*Angustifólia Araucária*) with 40.9 MPa or *Pinus elliottii* with 40.4 MPa or superior to some native or reforestation dicotyledon wood species, as for example *Eucalyptus saligna* with 46.8 MPa, *Eucalyptus grandis* with 40.3 MPa, Cupiúba (*Goupia glabra*) with 54.4 MPa or Angelim Rock (*Hymenolobium petraeum*) with 59.8 or still comparable to *Eucalyptis citriodora* with 62.2 MPa.

Resistance and elasticity in the simple bending test

The specimen appearance and the test set are shown in figure 8 and figure 9 shows the pattern of severing observed in specimens of bending. The image on the left shows the usual pattern of severing observed (shearing between the bamboo strips near to neutral line). The image on the right also shows an usual severing with shearing of bamboo strips and nodes break for tension (below the neutral line). In terms of safety it shows a rupture which may be considered ductile.

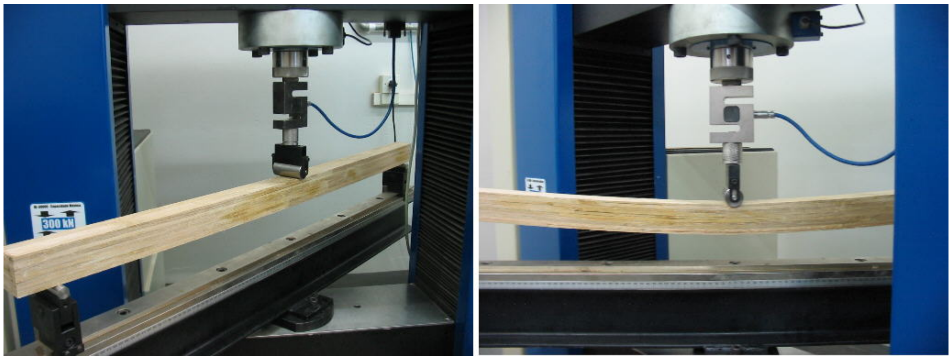

Figure 8 – Specimen in the simple bending test.

Figure 9 – Specimens after the simple bending test

Table 2 shows the results obtained for strength ($f_f o$) and longitudinal modulus of elasticity ($E_f o$), in simple bending test, using the adhesive cascorez 2590 (PVA), at the rate of moisture U.

Table 2 – Results of the simple bending tests in glued laminated bamboo.

Specimens	f_{fo} (MPa)	E_{fo} (GPa)	U (%)
1	112	16.4	11.3
2	95	14.4	11.0
3	107	14.8	11.4
4	104	14.2	11.4
5	108	15.1	11.4
6	105	14.2	11.2
7	104	12.8	10.9
8	105	12.3	11.1
9	89	12.7	11.3
10	96	12.4	11.5
11	105	14.2	11.2
12	83	12.4	11.4
13	89	13.0	11.2
14	84	11.9	11.4
15	97	13.0	11.5
average	98.9	13.6	11.3
standard deviation	9.2	1.3	0.2
variation coefficient (%)	9.3	9.4	1.6

Table 2 shows the variation range of resistance obtained in simple bending tests with values ranged between 83 and 112 MPa, with an average of 98.9 MPa. The average modulus of elasticity in the bending was of the order of 13.6 GPa, with variations between 11.9 e 16.4 GPa. The resistance values obtained are above native or reforestation coniferous wood, as for example, *Pinus elliottii* with 69.6 MPa or superior to some native or reforestation dicotyledon wood species, as for example *Eucalyptus grantis with* 7.6 MPa or Cedrinho (*Dipteryx odorata*) with 80.2 MPa.

Resistance and elasticity in the parallel tensile test

Figure 10 shows the tests performed and figure 11 shows the pattern of severing observed in specimens of parallel tensile test. The image on the left and the right (figure 11) shows the usual pattern of severing observed, in all specimens the disruption was observed on nodes and on fibers.

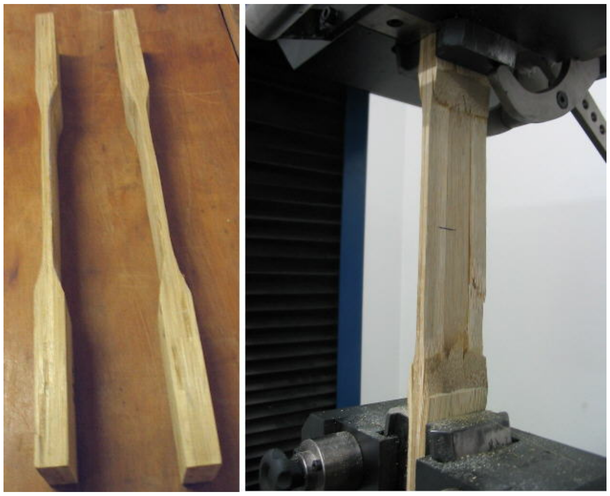

Figure 10 - Specimens in parallel tensile test

Figure 11 – Specimens after the test

Table 3 shows the results obtained for parallel tensile strength (fto) and longitudinal modulus of elasticity (E_{to}), using the adhesive cascorez 2590 (PVA), at the rate of moisture U

Table 3 – Results of the parallel tensile tests in glued laminated bamboo.

Specimens	f_{to} (MPa)	E_{to} (GPa)	U (%)
1	142	21.8	11.0
2	147	19.9	11.4
3	143	21.4	11.0
4	147	17.9	10.9
5	130	20.7	11.2
6	147	18.6	11.3
7	152	21.0	10.9
8	200	20.1	11.3
9	147	21.1	11.1
10	117	20.3	11.3
11	120	21.2	11.1
12	141	22.8	11.5
13	166	21.6	11.3
14	132	22.3	11.2
15	128	19.2	11.4
16	142	18.1	11.1
average	143.7	20.6	11.2
standard deviation	19.4	1.4	0.2
variation coefficient (%)	13.5	7.1	1.6

Table 3 shows the variation range of strength obtained in parallel tensile tests with values ranged between 130 and 200 MPa, with an average of 143.9 MPa. The average modulus of elasticity in the tension was of the order of 20.6 GPa, with variations between 18 and 22 GPa. The resistance values obtained are above native or reforestation coniferous wood, as for example, Pinho do Paraná (*Araucária angustifólia*) with 93.1 MPa or *Pinus elliottii* with 66 MPa or superior to some native or reforestation dicotyledon wood species, as for example *Eucalyptus saligna* with 95.5 MPa, *Eucalyptus grandis* with 70.2 MPa, *Eucalyptus citriodora* with 123.6 MPa, or Ipê (*Tabebuia serratifolia*) with 96.8 MPa or still comparable to Maçaranduba (*Manilkara spp*) with 138.5 MPa.

Table 4 summarizes the mechanical characteristics of the glued laminated bamboo, presenting the average values in the compressive, bending and tensile tests, also showing the absolute density (ρ)

Table 4 – Average values of the mechanical characteristics of the glued laminated bamboo (ρ = 0.79 g/cm³).

	Strength (MPa)	Elasticity modulus (GPa)	U (%)
Tensile	f_{t0} = 143.7	E_{t0} = 20.6	11.2
Simple bending	f_f = 98.9	E_f = 13.6	11.3
Compressive	f_{c0} = 65.5	E_{c0} = 18.1	11.2

Example of some bamboo products developed

Figure 12 shows some glued laminated bamboo products produced by the first author together with students of the design course.

Figure 12 - Some prototype of glued laminated bamboo products.

Conclusions

In accordance to the conditions where the work was developed it can be considered that:

- The Brazilian wood standard was revealed satisfactory for the bamboo mechanical characterization;

- The specie *Dendrocalamus giganteus* used in this work revealed satisfactory for the confection of the laminated strips.

- The limit established for the useful height of the culms (wall with at least 10 mm of thickness) was satisfactory for the processing and maximum exploitation in height of the culms. The 4 face planer used for the final processing of the strips revealed adequate for this use.

- The adhesive (PVA) used for the strips glue presented a very good performance.

- The mechanical characteristics obtained in this work are good enough for a confection of the glued laminated bamboo products, as furniture, tools, etc.

Gratefulness

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Bamboo (*Dendrocalamus asper*) as Raw Material for Interior Composite Panel Manufacture in Thailand

Piyawade Bauchongkol
Forest Products Division, Royal Forest Department, Bangkok,Thailand.

Salim Hiziroglu
Department of Natural Resource Ecology & Management
Oklahoma State University, Stillwater, OK U.S.A.

Vallayuth Fueangvivat
Forest Products Division, Royal Forest Department, Bangkok,Thailand

Songklod Jarusombuti
Department of Forest Products, Kasetsart University, Bangkok, Thailand

Worakit Soontonbura
Forest Products Division, Royal Forest Department, Bangkok,Thailand.

Abstract

This study reviews some of the findings of various past and ongoing research projects carried out to manufacture composite panels from bamboo (*Denrocalamus asper*) in Thailand. Experimental panels including particleboard, medium density fiberboard (MDF), and sandwich type panels having fibers on the face layers and particles in the core layer were made. Both physical and mechanical properties of above boards were evaluated. Average values of modulus of elasticity and modulus of rupture of particleboard and MDF samples were determined as 2,424 MPa, 22.57 MPa, 2,200 MPa, and 22.70 MPa, respectively. In the case of sandwich type panels such values were 1,840 MPa and 20.91 MPa. In addition to the bending properties, internal bond strength and physical properties including thickness swelling, water absorption of all types of samples resulted in satisfactory values based on Japanese Industrial Standards (JIS) for panels use for interior purposes. Surface roughness of MDF and sandwich type panels was also determined using a stylus type equipment. It appears that bamboo which is considered as under-utilized specie may provide profitable and marketable panels products in Thailand. Such panels are not only environmentally friendly but also one of the alternative ways to convert bamboo in a value-added product.

Introduction

Non-wood material based resources such as bamboo and agricultural fibers including wheat straw, kenaf, rice husk, and rice straw are getting more important as raw material to manufacture composite panels. Thailand has rich natural biological resources and diverse ecosystems that contain many non-wood materials. Unfortunately similar to many developing Asian countries deforestation and over harvesting in Thailand also created environmental awareness which focused exploratory research using non-wood renewable resources in composite panel production.

Bamboo is one of the most diverse groups of plants in the grass family which belongs to the sub-family of Bambusoidae (Zheng and Guo 2003). It is widely recognized as an important non-wood forest resource due to not only its excellent mechanical properties but also its high socioeconomic benefits. Housing, packaging and transportation are only few examples its common utilization for many years in Asian countries (Zhang and Yonglan 1988; Xuhe 2005;Sumardi et al.2005; Wang and Joe 1983). Currently, bamboo is still considered as under-utilized non-wood species, although it has additional limited use as scaffolding, furniture units, plywood, and flooring in Thai constructional industries (Ye 1991; Ganapathy et al. 1992). Its fast growth rate and better characteristics than many other wood species makes this resource an alternative raw material for various composite panel manufacture. One of the first bamboo composite panels developed was in 1940's in China and since then, at least 28 different types of bamboo composite products have been developed (Ganapathy et al.1992). Also there have been several attempts to explore the possibility to produce panel products including particleboard, oriented standboard, plywood, and laminated composite panels from bamboo at commercial level (Bai 1996 ; Hiziroglu et al. 2005; Lee et al. 1996, Li et al. 1994; Li 2004; Chow et al. 1993, Chew et al. 1994, Chen and Hua; 1991).

Although particleboard is also used as substrate for overlays its rough surface may create certain problems resulting show through the thin films or direct finishing applications. Medium density fiberboard which is prime substrate product for furniture and cabinet manufacture is the most widely used interior type of panel in many countries including Thailand. However overall cost of MDF is more expensive and has more complicated manufacturing process than that of particleboard. Combination of fibers and particle in the form of sandwich type of panel would possibly solve this cost problem. Experimental panels with a sandwich configuration were also manufactured from bamboo. Since fibers were used on the face layers it is expected such panels had not only smooth surface with thin layer of fibers on board faces but also their overall properties were enhanced.

The main objective of this study was to explore potential suitability of bamboo to develop value-added interior panel products, namely particleboard, medium density fiberboard (MDF), and sandwich type panels having fibers on the face layers and the coarse particles in the core layer. Both basic physical and mechanical properties of experimental panels made from bamboo were tested to find if bamboo could be used to produce experimental panels with accepted properties.

Materials and Methods

Bamboo (*Dendrocalamus asper*) samples were harvested in Khon Khen, Prachin Buri bamboo plantation in Thailand. The specimens were reduced into chips using a commercial chipper before they were hammermilled for particle production. Figure 1 shows particle and fibers of bamboo used in this study. A laboratory type defibrator illustrated in Figure 2 was employed for disintegration of bamboo chips into the fibers using a pressure of 0.75 MPa, at a temperature of 160 ^{o}C for 1.5 min. before particles and fibers were dried in a kiln at a temperature of 80 °C until the furnish reached to 4 % moisture content. Later dried fibers were mixed for 4 min with 9 % urea-formaldehyde resin with a specific gravity of 1.27 and solid content of 84.8% in a rotating drum type mixer fitted with a pneumatic spray gun. Half percent wax was also added during resin spraying for the furnish. Twenty and 50% rice straw fibers and particles were also added into the various types of panels to evaluate interaction between two types of materials. Table 1 displays experimental schedule of the study involved with MDF manufacture.

The sandwich type samples with fibers on the face layers and the particles in the core layer were also manufactured using the above set-up. The core of the panels had homogeneous mix of 95% bamboo and 5% rice straw as filler using a 8% urea formaldehyde resin. Fibers of both type of raw material were used at the same ratios for the face layer of the panels using 10 % urea formaldehyde. Particles and fibers were mixed with the adhesive and 0.5% wax in the rotating mixer equipped with pressurized spray gun. Ten replicas for each type of panel in 35 cm by 35 cm by 1.0 cm were manually formed in a plexiglass box and pressed in a hot-press at a temperature of 165 °C using a pressure of 5.2 MPa for 5 min. Average target density of the panels ranged from 0.65 g/cm^3 to 0.80 g/cm^3. Panels were conditioned in a climate room with a temperature of 20 °C and a relative humidity of 65% for about two weeks before any tests were carried out. Modulus of elasticity, modulus of rupture, and internal bond strength properties were tested on an Instron Testing Machine Model-22, 5500-R equipped with a load cell capacity of 5,000 kg. Two and six samples were cut from each panel for bending and internal bond strength tests, respectively. Figures 3 and 4 illustrate unpressed MDF and sandwich type mats. Density profile samples were then determined on Quintek Density Profilometer, Model QDP-01X. This instrument can be set to a minimum linear increment of 0.25 mm depending on the sample thickness. Four samples with a size of 15.2 cm by 15.2 cm were used to determine thickness swelling of the panels. Thickness of each sample was measured at four-point midway along each side 2.5 cm from the edge of the specimen. Later samples were submerged in distilled water for 2-h and 24-h before thickness measurements were taken from the same location to calculate thickness swelling (TS) values. Table 2 shows experimental design of sandwich type panels.

Surface roughness of the samples was evaluated using portable stylus type equipment, Hommel T-500 profilometer as shown in Figure 5. Eight specimens with a size of 5 cm by 5 cm were randomly taken from each type of panel for roughness measurements. The profilometer equipment consisted of a main unit with a pick-up drive which has a skid-type diamond stylus with a 5-μm tip radius and 90° tip angle. The stylus traverses the surface at a constant speed of

1 mm/sec over a 12.0-mm tracing length. The vertical displacement of the stylus is converted into electrical signals by a linear displacement detector before the signal is amplified and converted into digital information. Various roughness parameters such as average roughness (R_a), mean peak-to- valley height (R_z), and maximum roughness (R_{max}) can be calculated from the digital information. Typical roughness profiles of samples from four types of panels are shown in Figure 6. Definition of these parameters is discussed in detail in previous studies (ANSI 1985; Hiziroglu et al. 1996, 2004; Mummery 1993). Four random measurements were taken from each side of the samples to evaluate their roughness characteristics. Analysis of variance was used for statistical analysis of the data from the tests.

Results

Results of physical and mechanical properties of different types of panels made from bamboo are displayed in Tables 3 and 4. Medium density fiberboard samples had an average MOE and MOR values of 2273 MPa and 28.66 MPa, respectively. A previous study showed that experimental bamboo particleboard panels had 2,424 MPa and 22.57 MPa for above tests (Hiziroglu et al. 2005). In the case of sandwich type panels MOE and MOR values of the samples ranged from 1,287 MPa to 1,910 MPa and 13.77 MPa to 26.30 MPa depending on panels density as displayed in Table 4. Based on the Japanese Industrial Standard (JIS-A 5905) 13.0 MPa is the minimum requirement for interior particleboard. Based on American National Standards (ANSI-A 208) minimum MOE and MOR requirement for grade 110 MDF for interior applications are 1,400 MPa and 14 MPa. It seems that panels manufactured in such studies, including sandwich type panels satisfied MOR strength requirements for general used based on both standards. Panel type-A with sandwich cross section had the lowest strength properties which can be related to its very low density of 0.65 g/cm^3.

Internal bond strength of the samples followed the similar trend of bending properties of the panels. Overall IB strength values of sandwich type panels ranged from 0.51 MPa to 0.84 MPa satisfying the IB strength requirements based on the JIS for general use of particleboard. Thickness swelling values of both types of samples were found to be acceptable based on the standards. The panels made from 100% bamboo fibers had 7.84% thickness swelling as a result of 2-hr water soaking. Corresponding value for sandwich type panels was 10.25 MPa with 0.75 g/cm^3 density level. Using rice straw furnish as filler in the panels reduced both strength and dimensional properties of the samples.

In general single-layer particleboard with rough surface are not used for thin overlays as substrate for cabinet and furniture manufacture. Average roughness value of bamboo particleboard was within the range of 19 µm. However both MDF and sandwich type panels resulted in much smoother surface with and average R_a values ranging from 5.08 µm to 7.50 µm. It appears that having only 5% rice straw fiber on face layers of three-layers panels did not influence significantly their surface characteristics. Panel density was found to be one of the important parameter controlling surface quality. Samples had better surface roughness with their increasing density which can be related to compactness of face layers. Based on the roughness measurement it is expected that both types of panels having fibers on the face layers can be used as substrate for even ultra thin overlay papers without having any telegraphing effect .

Conclusions

This study briefly reviewed some of the findings of several experimental works related to manufacture different types of composite panels from bamboo. In the light of preliminary results of such studies bamboo which is an under-utilized non-wood resource can be used to produce interior composite panels with accepted physical and mechanical properties. It appears that manufacturing composites from bamboo would provide a profitable and marketable interior panel products in Thailand. Such panels are not environmentally friendly but also provide an alternative way to convert this resource into panel products for furniture manufacture.

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Table 1. Sampling schedule of MDF panel manufacture.

Panel Type	Raw material	Number of panels	Test Samples				
			MOE and MOR	IB Strength	TS	Density Profiles	Surface roughness
A	100% Bamboo	5	10	30	10	10	10
B	80% Bamboo-20% Rice straw	5	10	30	10	10	10
C	50% Bamboo-50% Rice straw	5	10	30	10	10	10

Table 2. Sampling schedule of sandwich type panels.

Panel Type	Face/Core Ratio	Density (g/cm^3)	Number of panels	Bending (MOE&MOR)	IB	TS	Roughness
A	10/80/10	0.65	8	40	35	40	80
B	10/80/10	0.75	8	40	35	40	80
C	25/50/25	0.70	8	40	35	40	80
D	25/50/25	0.80	8	40	35	40	80

Table 3. Results of the physical and mechanical properties of MDF samples.

Panel Type	MOE (MPa)	MOR (MPa)	IB (MPa)	Thickness swelling (%)		Density g/cm^3	Roughness parameters (µm)		
				2-h	24-h		R_a	R_z	R_{max}
(A) 100% Bamboo	2273	28.66	0.71	7.84	19.96	0.73	5.50	40.73	49.02
(B) 100% Rice straw	1484	15.65	0.23	33.03	40.95	0.74	5.20	39.23	46.65
(C) 80 % Bamboo 20 %Rice straw	1936	23.29	0.52	18.52	24.40	0.73	4.88	36.10	43.61
(D) 50 % Bamboo 50 % Rice straw	1850	22.23	0.38	22.26	27.46	0.72	5.20	39.23	46.64

Table 4. Results of the physical and mechanical properties of sandwich type samples.

Panel type	Density (g/cm^3)	MOE MPa	MOR MPa	IB MPa	TS (%)	WA (%)	Roughness (µm)		
							R_a	R_z	R_{max}
A	0.65	1,325	13.77	0.68	9.98	38.35	7.5	39.31	54.50
B	0.75	1,840	20.91	0.84	10.25	33.90	6.25	36.82	40.81
C	0.70	1,287	17.17	0.51	23.39	90.11	6.57	38.33	43.62
D	0.85	1,910	26.30	0.73	24.78	72.53	5.08	25.34	36.53

Figure 1. Bamboo and rice straw particles and fibers

Figure 2. Laboratory type defibrator.

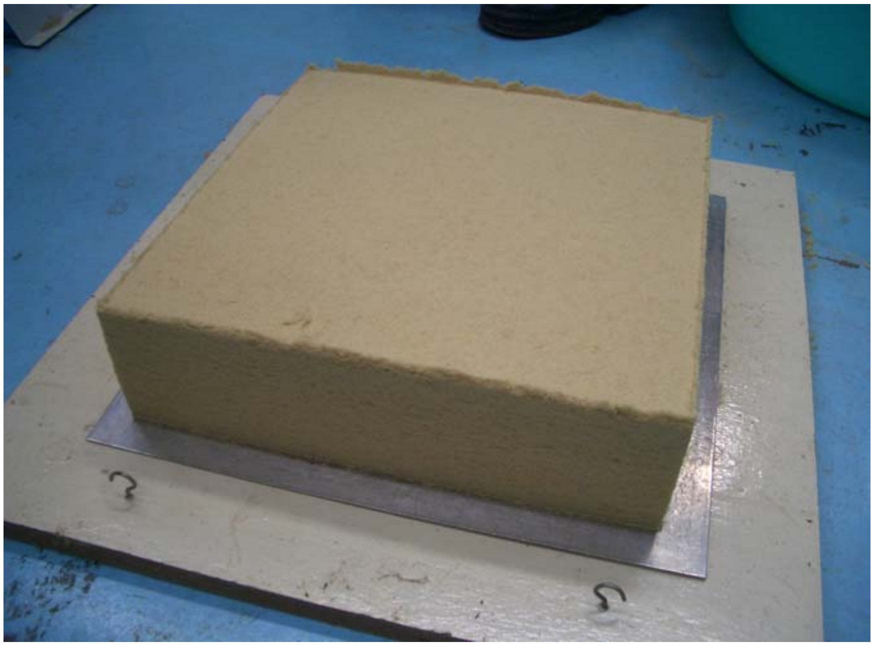

Figure 3. Unpressed MDF mat.

Figure 4. Unpressed sandwich type mat.

Figure 5. Stylus type roughness profilometer.

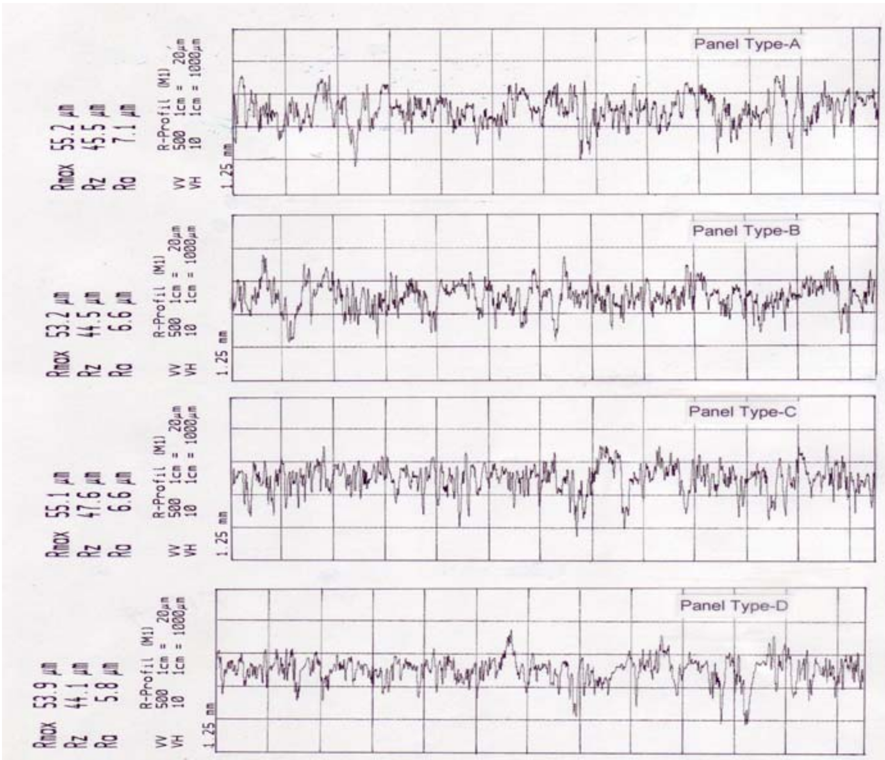

Figure 6. Typical roughness profiles of MDF samples.

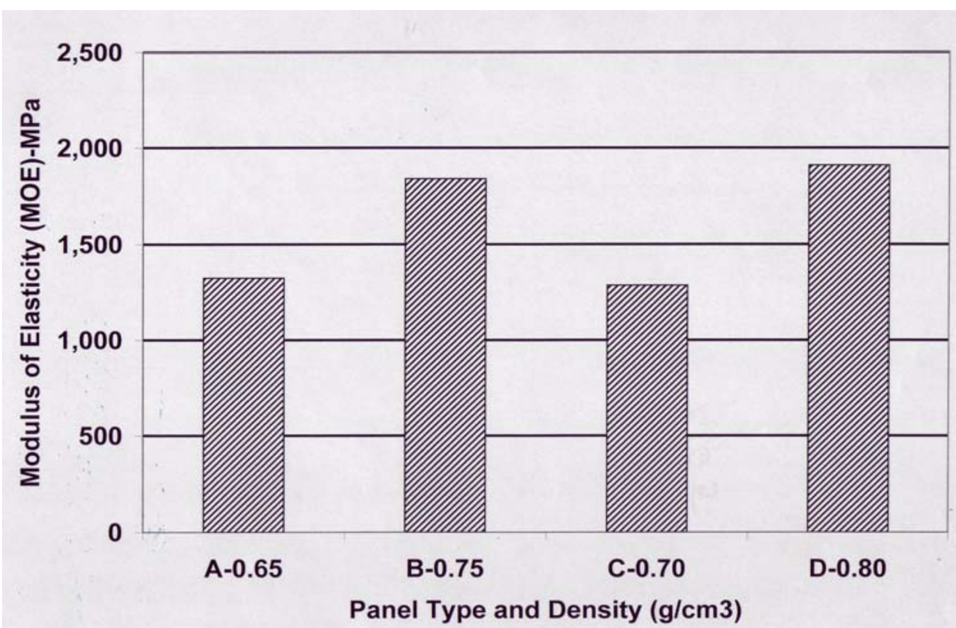

Figure 7. Modulus of elasticity of the sandwich type of samples.