Use of Lignocellulosic Biomaterials for Sustainable Development of Bamboo Strand Lumber for Structural Applications

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Bamboo is one of the fastest growing plants and has mechanical properties similar to timber. The main reasons for the popularity of bamboo in construction can be attributed to its low cost, local availability, and adequacy of simple, local tools, and skills for fabrication. Application of bamboo in construction is, however, normally limited to low-cost housing and temporary structures due to several factors including irregular shapes, hollow circular cross sections, and durability issues. This report presents the results of an investigation into production of an engineered bamboo lumber product. Bamboo culms were cut into smaller strands and were re-constituted into rectangular sections by gluing and pressing at 140 °C to 145 °C. This approach overcomes the presence of the inherent hollow core and randomizes the inter-nodes and other growth characteristics found in bamboo. The reconstituted bamboo strand lumber (RBSL) was developed using crushed *Bambusa bambos* species and phenol formaldehyde resin. The physical and mechanical properties of reconstituted bamboo strand lumber were evaluated as per IS 1734 (1983). From the results it was found that the BSL can be used as an alternate to timber to meet Sustainable Development Goals (SDGs) for building applications that will effectively transform the world.

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INTRODUCTION

India has the world's second highest resource of bamboo in the world. About 148 bamboo species in 29 genera have been found in India (Sharma and Nirmala 2015). Northeastern India holds the largest stock and diversity of bamboos. Bamboo is a naturally occurring composite material that grows abundantly in most of the tropical countries (Tewari *et al*. 2019). Cellulose fibres are aligned along the length of the bamboo, providing maximum tensile flexural strength and rigidity in that direction. Bamboo is also one of the oldest building materials used by mankind. It is used widely for household products and extended to industrial applications due to advances in processing technology and increased market demand. In Asian countries, bamboo has been used for household utilities such as containers, chopsticks, woven mats, fishing poles, cricket boxes, handicrafts, and chairs, *etc*. It has also been widely used in building applications, such as flooring, ceiling, walls, windows, doors, fences, housing roofs, trusses, and rafters. It is also used in construction as structural materials for bridges, water transportation facilities, and skyscraper scaffoldings. There are about 35 species that are currently being used as raw materials for the pulp and paper industry. Massive plantations of bamboo provide an increasingly important source of raw material for pulp and paper. As resource availability declines and the demand for the resource increases in today's modern industrialized world, the need to explore new opportunities in the near future is important for sustainable building materials (Meadows *et al.* 1992). Wood, for example, has recently gained popularity in the green building community because of its environmentally beneficial characteristics: wood is promoted as renewable, biodegradable, sequestering carbon from the atmosphere, low in embodied energy, and creating less pollution in production than steel or concrete (Falk 2009). Bamboo has similar environmental characteristics (Lee *et al*. 1994; Van der Lugt *et al.* 2006; Rittironk and Elnieiri 2008; Nath *et al*. 2009). Most notably, it is highly renewable, as bamboo stalks attain maturity in eight years. Its strength is comparable to that of wood, which reveals it as an appealing candidate for a structural material.

It is evident that bamboo has the potential, quite similar to timber, in construction to improve some of its undesirable properties. A number of studies have investigated this potential. In 2001, Nugroho and Ando studied the feasibility of using hot-pressed bamboo mat for manufacturing laminated bamboo lumber and found that the modulus of rupture and modulus of elasticity were comparable to laminated veneer lumber products, whilst Ahmad and Kamke (2003) reported that improved durability of parallel strand lumber (PSL) manufactured from Calcutta bamboo against accelerated aging. Laminated bamboo lumber with properties comparable to laminated wood products have been reported by Mahdavi *et al.* (2011), while the effect of type and amount of adhesive on mechanical properties glue laminated guadua (GLG) was reported by Correal *et al.* (2010).

It has also been observed that tested mechanical properties of bamboo have been found to be comparable to sawn timber, but bamboo possesses a number of features, such as an irregular and hollow cross section and the presence of nodes, which create variability and make it difficult to use bamboo as a construction material. A number of studies have also highlighted durability issues associated with bamboo when used in its natural form (Lakkad and Patel 1980). Low resistance against fungal and insect attack, rapid absorption of water, and susceptibility to insects of starch being present in bamboo have also been reported (Liese 1987). Bamboo, however, also possesses a number of unique properties that make it attractive for use as a construction material (Sharma *et al.* 2015; Huang *et al*. 2019; Shu *et al*. 2020; Chen *et al*. 2021; Kelkar *et al*. 2021). Unlike most hardwoods, which take 50 to 60 years to fully mature, bamboo only takes between 3 to 6 years to fully mature; with daily growth rates of up to 100 cm having been reported (Liese 1987; Chung and Yu 2002). Bamboo grows naturally on all continents except Europe. Some bamboo species can tolerate temperatures in excess of 40°, while other species can withstand prolonged frost (Liese 1987). The carbon sequestration rate for bamboo is similar to that of a hardwood forest and the material can therefore act as a carbon sink (Janssen 2000). Furthermore, bamboo does not require pesticides and needs only a limited amount of fertilizer for growth. As such, the environmental benefits of using bamboo in construction are similar to that of wood. Mechanical properties of bamboo are comparable to timber (Wang and Shen 1987; Mohmod *et al.* 1990; Rajput *et al.* 1991; Janssen 1995; Amada *et al.* 1997; Wenji 2001; Gielis 2002). Lakkad and Patel (1980) reported that the strength to weight ratio of bamboo is similar to that of steel and glass reinforced plastic based on their experimental investigation. Nath *et al*. (2009) reported an oven-dried density between 500 and 800 kg/m^3 for bamboo, which is very much similar to most softwood species. Additionally, metabolic processes in bamboo do not produce organic and inorganic by-products such as polyphenols, resins, and waxes, and this absence can lead to favorable shrinkage, durability, and gluability properties (Liese 1992).

With adequate research, it is conceivable that bamboo could become a sustainable alternative to current building materials in several parts of the world. The scope of this paper is to develop the high strength materials from bamboo strands and reduce the pressure on natural forests for the demand of solid wood in building sustainable cities and communities that ultimately will help to achieve the Sustainable Development Goals (SDGs).

EXPERIMENTAL

Material and Methods

For the manufacturing of bamboo strand lumber (BSL), the following two raw materials were used: *Bambusa bambos* species of bamboo (from institute -Indian Plywood Industries Research & Training Institute, Bangalore, India) and phenol formaldehyde (PF) resin (1:1.8 by weight ratio) (synthesized in laboratory).

Manufacturing the bamboo strand lumber

First, the bamboo length was measured, and marking was done on the top, middle, and bottom portion of the bamboo with four feet one-inch length. After marking the portions, cross-cutting of bamboo was performed to cut the bamboo culms into the desired length on 4’ 1”. After cross-cutting the bamboo, the outer nodes were removed. Then splitting was performed to split the bamboo culms into the desired width of 10 mm to 15 mm. To obtain a smooth surface for the bamboo strips, the internal node was removed.

The outer green skin of the bamboo was scraped off. This process eliminates decontamination and improves the appearance of the strips. The skin removal process can be done either by a machine (Chin Yung Bamboo & Wood Co., Ltd. No. 97, Min TSU RD., Lukang Chen Chang Hua Hsien, Taiwan (P.C.:50542)) or manually. When scraping the skin, it is important to apply force evenly along the culm surface to ensure a uniform colour.

The hydrothermal treatment of bamboo strips was done before crushing them. After this treatment, the bamboo strips became soft and easy to crush and the fibres would not break during crushing. Hydrothermal treatment can be accomplished by following two methods: boiling or steam heating.

In the boiling method, bamboo strips were kept in a closed tank filled with water. The level of water was kept above the level of strips, and then the tank was heated. The advantage of this method is that preservatives can be added in boiling water while steam heating; preservation cannot be added during treatment. Another good advantage of boiling is that it retains the natural colour of the strips.

Bamboo is a natural material that disintegrates with time. It is susceptible to attack by insects and fungi and must be treated to prevent degradation of the material. There are several methods of treating bamboo, which are grouped into the traditional or non-chemical and the chemical methods. Borax is supplied as odourless, colourless, transparent crystals or white granules or powder. Here borax and boric acid were used as a bamboo preservative, which were added into boiling water. Borax melts at 65 °C. Thus, it dissolves into boiling water. The bamboo strips were cooked for approximately 45 min in the solution. The following steps were carried out:

1. Crushing of strips: Crushing was performed mannually by hammering to disintegrate fibres from the bamboo.
2. Drying of crushed bamboo strands: The operation of drying refers to the removal of water from materials by converting them into water vapour by the supply of heat. In technical terms, it is the heat and mass transfer process. The purpose of drying of crushed bamboo strands is to reduce the moisture content to a range suitable for gluing. Strips contain more than 30% moisture, and if the drying is not completed, then crushed bamboo strands cannot absorb a sufficient amount of resin. Generally, the suitable moisture content for gluing is 6 to 8%. Therefore, the strips were dried up to 6 to 8% moisture content in an industrial furnace at 50 °C to 60 °C temperature for a period of 24 h.
3. Preparation of phenol formaldehyde (1:1.8) resin: In bamboo strand lumber, single stage a conventional phenol formaldehyde resin with 1:1.8 weight ratios was used. For making 10 kg of PF resin, the following amount of phenol, formaldehyde, caustic, and water were used. The phenol formaldehyde resin was manufactured by reacting phenol and formaldehyde in the ratio of 1:1.8 weight ratios in the presence of an alkali catalyst in the reaction kettle. The resin flow time through a B4 cup was 15 s at 90 °C with the total dry solid content being 48% to 52% and a water tolerance of 1:16.

The caustic solution was prepared by adding 264 g of caustic into 528-g water, and this solution was cooled to room temperature. 3300 gm liquid or molten phenol was charged into resin kettle followed by 5940 gm formalin (37% formaldehyde). After loading the formalin immediately, the condenser was started. Then, the caustic solution was added into the kettle. The temperature inside the kettle automatically increased because of exothermic reaction. When the temperature stopped increasing, the heated oil circulated to heat the kettle until the temperature inside the kettle reached 60 °C. Then the hot oil circulation was stopped and the cold water was circulated, because of exothermic reaction the temperature inside the kettle automatically increased up to 90 °C. The temperature was maintained inside the kettle up to 85 ± 2 °C until precipitate was formed in water and the flow time in the B4 cup reached 14 to 16 s. Then, the cooling was started and continued until the temperature inside the kettle attains the room temperature, and the resin was unloaded. The properties of the resin are given in Table 1.

Table 1. Properties of Resin

S. No.	Particulars	Results
1	Flow time of resin in B4 flow cup (at 90 °C)	14 to 16 s
2	Flow time of resin in B4 flow cup (at room temp.)	20 to 22 s
3	Water tolerance	1:16
4	Practical solid content	48.23%

Resin Application

Resin was applied by dipping the crushed bamboo strands into diluted resin for making bamboo strand lumber. Conventional PF resin was used and the same amount of water (1:1) was added into resin to reduce its viscocity. Then, crushed bamboo strands were dipped into the resin for 5 to 10 min.

Air Drying

Resin dipped crushed bamboo strands were kept in normal atmospheric condition for air drying by keeping the strips vertical with support in a container for 3 to 4 h to drain out excess resin from the strips.

Oven Drying

The gluing moisture content of the strips was maintained between 10 to 12% before pressing. After air drying, the strips were kept in an industrial furnace at 50 to 60 °C temperature until the moisture content of the strips reached 10 to 12%. Over-drying was avoided because over drying of the strips also leads to poor bonding of the lumber.

Assembling and Hot Pressing

After the strips attained the desired moisture content, the strips were cut into the required length. Then, the strips were assembled in such a way that all the strips were in the same alignment from both ends. Next, the strips were wrapped with biaxially oriented polypropylene (BOPP) film for lamination and both ends were tied firmly with thread. The width of the assembled strips was measured, and the same width in the hot press was set by adjusting the guider plates. The assembly was loaded into the hydraulic hot press (Hydraulic Hot Press; WMW AG/Machine trading Messe-Allee 10a, 04158 Leipzig, Germany). In this press, one hydraulic cylinder was placed at the base house that could move up and down. The gap between the two platens was 19 mm and was set by moving up the bottom cylinder. This gap was set after loading the assembly. The thickness of the lumber depends on this gap. Another two hydraulic cylinders were placed inside houses, which give lateral pressure. The bottom and top cylinder of the hydraulic hot press only gave the contact pressure to the assembly, while the two lateral cylinders exerted the side pressure of 15 kg/cm^2. This pressure was transmitted through guider plates. The assembly was pressed by side pressure. The hydraulic hot press is designed for pressing bamboo strips at high pressure and temperature for the preparation of bamboo lumber. Other than bamboo, the hydraulic hot press machines can also be customized for pressing wood and other materials. The pressing parameters are given in Table 2.

Table 2. Pressing Parameter

Parameters	Range
Temperature	145 ± 5 °C
Gauge pressure	117 kg/cm^2
Specific pressure	15 kg/cm^2
Time	19 mm (thickness) + 3 min = 22 min

Trimming

Trimming was done to give proper size and shape to the lumber. It also removed defects present in the edges. This process involves cutting the four edges of the board to obtain a board of required size and perfect squareness.

Sanding

The process of sanding involves the removal of a small extent of the surface layer from a panel by using abrasive materials. Sanding is done for the following reasons.

- To produce a panel of required thickness having thickness uniformity within specified limits.
- To produce a clean, smooth surface finish suitable for subsequent polishing, painting, or overlaying.
- To clean up splits or remove handling dirt such as dust and finger marks.

In this study, these lumbers were sanded with a wide belt sander (Sanding Max, Kalyan Industries, Yamuna Nager, India). These operations have tables that are adjustable to the thickness of the panel to be sanded. It is the more common type of sanding machine in use today. These machines come in various combinations of one, two, four, and six belts. The wide belt sander has an added roller spaced behind the contact roller and a narrow resilient pad is inserted. The process for the manufacturing of bamboo strand lumber is depicted as a flow chart shown in Fig. 1.

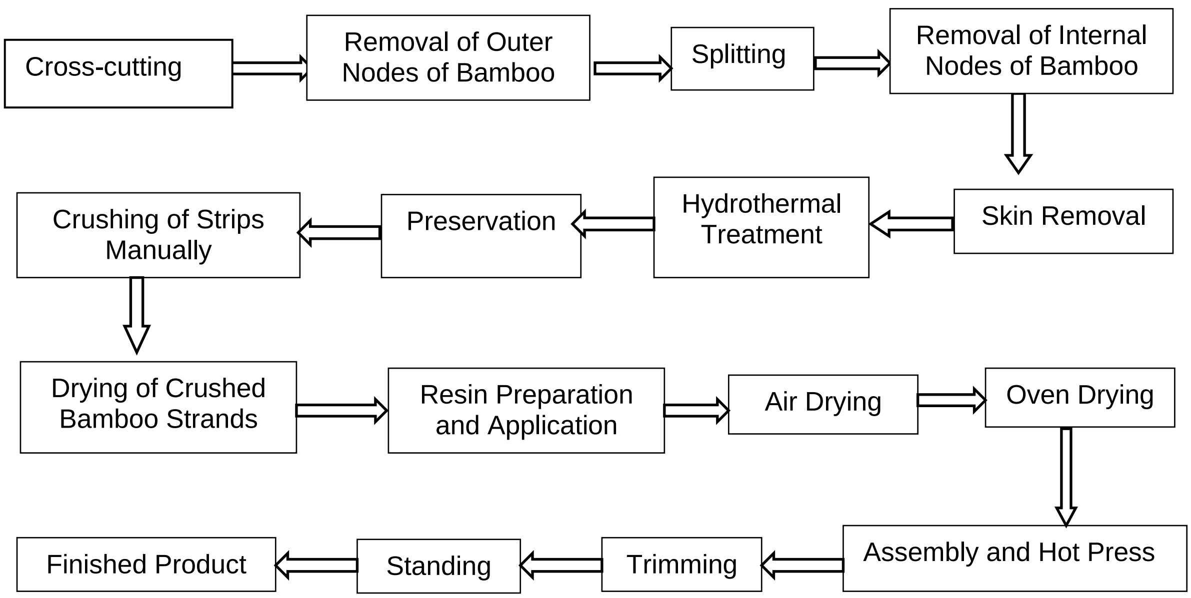

Fig. 1. Process flow chart for manufacturing of bamboo strand lumber

Table 3. Properties of Bamboo Strand Lumber With Respect to Laminated Veneer Lumber (LVL)

S.N.	Parameter	Laminated Veneer Lumber (IS 14616 1999)	BSL Value
1	Water absorption (%) 2 h 24 h	IS 3087 (2005) (Table 1 through ii)	 2.3 5.1
2	Density (kg/m^3)	500 to 900 kg/m^3	1156.9
3	Modulus of rupture (N/mm^2)	50 Minimum	215.2
4	Modulus of elasticity (N/mm^2)	7500 Minimum	23216
5	Moisture content (%)	5 to 15%	9.68
6	Compressive strength parallel to grain (N/mm^2)	35 Minimum	38.4
7	Screw withdrawal strength (N) a) Edge b) Face	 2300 Minimum 2700 Minimum	 1245 1985

Testing

The physical and mechanical properties *viz.*, water absorption (IS 2380 1977), density (IS 2380 1977), modulus of rupture in bending, modulus of elasticity in bending (IS 1708 1986), moisture content (IS 1734 1983), compressive strength parallel to the grain, and the screw withdrawal strength in face and edge (IS 1734 1983), were investigated.

RESULTS AND DISCUSSION

The results of the study showed that bamboo strand lumber can have comparable mechanical properties to laminated veneer lumber. Table 3 shows that the physical and mechanical properties *viz.* water absorption, density, moisture content, modulus of rupture in bending, modulus of elasticity in bending, compressive strength, and the screw withdrawal strength in face and edge. Compressive strength parallel to the grain value, modulus of rupture in bending, and modulus of elasticity in bending were on the higher side, but screw withdrawal strength was slightly lower compared to IS 14616 (1999). Particularly, screw withdrawal strength was 45% and 26.4% lower at edge and face, respectively, which may be due to inherent properties of bamboo, *i.e.*, weak adhesion of longitudinal fibers and non-availability of radial fibers. Water absorption properties for 2 hours and 24 hours for BSL 77% and 74.5% respectively were higher than the required values. This was attributed to the four-side compression of bamboo strands material in the hydraulic press during production besides excellent adhesion quality of phenolic resin with bamboo stands. On top of that, MOR and MOE were also higher, 300% and 400% respectively, which can be credited mainly to inherent material properties of bamboo. The results showed that the density of bamboo strand lumber is the prime factor responsible for achieving high values of MOR, MOE, and compressive strength parallel to the grain. The density of bamboo strand lumber was 1157 kg/m^3, which is 28.54% higher than the required value of LVL. This was achieved due to pressure in the hot press. The bottom and top cylinder of hydraulic hot press only gave the contact pressure to the assembly, while the two lateral cylinders exerted the volumetric pressure of 15 kg/cm^2. These properties show that bamboo lumber technology is resilient in nature and can provide sustainable raw material for the wood-based industries.

CONCLUSIONS

Bamboo strand lumber (BSL) manufactured from bamboo species is one of the fastest growing agroforestry plantation species (lignocellulosic fiber) in South East Asia and certain parts of Latin America. This material has huge potential for wood substitutes that may be produced without affecting natural forest systems and the environment. From Table 3, it can be said that screw withdrawal strength properties can be improved by developing a Bamboo Strand Groove making machine. All the mechanical properties have been improved except screw withdrawal strength (Table 3). Which has been reduced due to the process parameters for generating bamboo strand manually, hence, this process can be refined further with the help of developing Bamboo Groove making machines for making Bamboo strand.

1. After analysing the physical and mechanical properties of bamboo strand lumber, it can be concluded that bamboo strand lumber may be an ideal substitute of wood. It would be reasonable to conclude that it could be economically used as building material, as a replacement for timber. Thus, bamboo strand lumber can be used for flooring, furniture making, interior decoration, moulding, and constructional purposes.
2. Its improved mechanical properties in addition to its short harvesting age makes this bamboo lumber an innovative and sustainable building material in South East Asia that would lessen the stress due to recent demand in timber for developing LVL.
3. Research results summarized in this paper can be further used for the basis of structural design though some in-depth studies especially in the long-term. Relative standards and codes must be developed in order to ensure efficiency and safety of design.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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