

Bamboo as a Construction Material: Prospects and Challenges

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ABSTRACT

Bamboo is a naturally available, fast growing and renewable resource. Bamboo plants are found all over the world in tropical and non-tropical regions. Asia Pacific region is specifically rich in bamboo biodiversity. Due to high energy demand of existing construction materials and scarcity of other naturally available materials like wood, bamboo is a good alternative for construction. This paper reviews the mechanical properties and use of bamboo in construction. The tensile strength of different bamboo species varies in the range 70–210 MPa, compressive strength 20–65 MPa, elastic modulus 2500–17500 MPa, and modulus of rupture 50–200 MPa. Bamboo is a versatile material and can be used in construction in various ways. Bamboo can be engineered to specific need in construction such as laminated and scrimber bamboo. Engineered bamboo are used for various housing purposes such as roofing and flooring. Bamboo culms are often used directly without any alteration as structural members such as beams and columns. Bamboo can also be used as reinforcement in concrete as a replacement to steel. The shear and flexural behavior of bamboo reinforced concrete (BRC) beams is significantly better than plain concrete beams. Bamboo fibers reinforced concrete (BFRC) is a good alternative to existing synthetic fibers reinforced concrete such as glass and steel fibers. Development of standardized testing procedures and structural specifications utilizing existing and future research findings will pave the way towards an extensive use of bamboo in construction industry.

Keywords: bamboo, engineered bamboo, bamboo reinforced concrete, bamboo fibers reinforced concrete, bamboo construction, laminated bamboo

INTRODUCTION

Shelter from extreme weathers and for privacy is a basic requirement for all human beings. Historical evidence show that our ancestors have used different materials and techniques for this purpose such as stones, wood, bricks, steel, concrete, etc. However, with the passage of time, these materials are getting scarce and they also have high energy demands. There is a need for alternative renewable resources which are financially feasible, structurally strong and durable, and environmentally sustainable. One such material used is bamboo [1]. Bamboo is a naturally available, fast growing and renewable resource. It is an eco-friendly and cheaper material [2]. The

use of bamboo is not new, but it has been used throughout history in buildings [3]. Bamboo has a large variety, having almost 1300 species and are found all around the world apart from Antarctica and Europe. The growth of bamboo plant is very rapid as compared to other wood types. It has a typical harvesting period of 3 to 4 years and can grow as long as 36 m in only 6 months [4]. Some of the bamboo species can survive in extreme hot regions, while some species can tolerate extreme cold weathers as well [5, 6].

The culm (stem) of bamboo are round elongated and hollow in shape. Culm is divided by nodes in longitudinal direction. They are usually hard and slippery at the outer periphery of the culm. The fibers of bamboo tree are mainly

cellulose fibers [7] that grow in the longitudinal direction of culm [8]. A typical bamboo plant and bamboo culm is shown in Figure 1.

Availability of bamboo

Bamboo is a naturally occurring plant farmed globally [9]. For many years bamboo has played an important role in tropical countries lifestyle [10]. However, they are farmed in all tropical, subtropical and mild regions as shown in Figure 2 [11]. Bamboo accounts for 0.8% of total forest area of the world, covering 31.5 million hectare land [12]. Africa has a relatively low number of species (only five) of wooden bamboo. Comparatively, America has a higher biodiversity of wooden bamboo where about 430 different species of wooden bamboo spread across the South, Central and North America as given in Table 1 [13].

Asia pacific region has the richest biodiversity of wooden bamboo as compared to all other regions. A total of about 1012 species of wooden bamboo are known to be found in this region

with china alone having 626 species as given in Table 2 [14].

Treatment and preservation of bamboo

Bamboo have high sugar and starch content and is suspected to termite and fungal attack which defect the bamboo structure. Bamboo also has a high moisture content and hence it shrinks upon drying. Various physical and chemical techniques are used for the treatment of bamboo [4] to avoid these issues. Bamboo are most commonly soaked in water for a certain amount of time (usually 3–4 weeks) to remove the starch content in bamboo culms [15–17]. Low starch content make bamboo more resistance to fungus and termite attack [18]. Another technique used for preservation of bamboo against attack of microorganism is by heating it to about 150 °C. Although using this treatment reduces its mechanical strength and its elasticity, it provides better resistance against termites and fungus due to evaporation of water during heating. Various preservatives can also be



Figure 1. (a) Typical green bamboo plant, (b) Typical hard bamboo culm used for structural applications

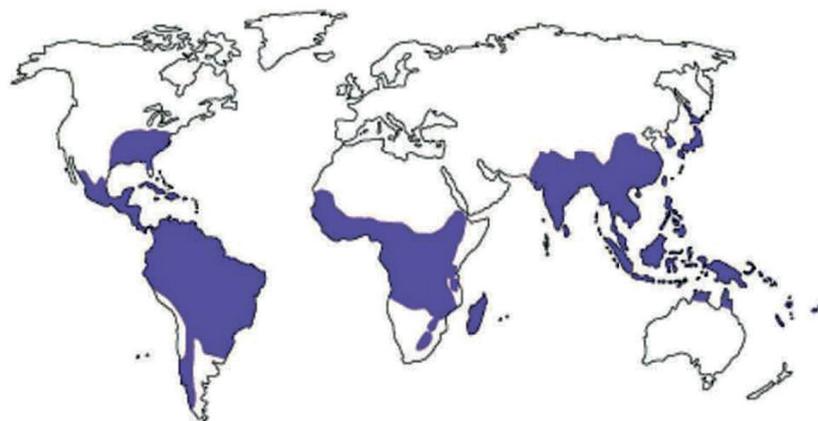


Figure 2. Availability of bamboo throughout the world [11]

Table 1. Biodiversity of bamboo in North, Central and South America [13]

Country	No. of naturally occurring species	Country	No. of naturally occurring species	Country	No. of naturally occurring species
Brazil	134	Argentina	12	Uruguay	5
Venezuela	68	Guatemala	12	Suriname	4
Colombia	56	Honduras	8	Belize	3
Ecuador	41	El Salvador	7	Bahamas	1
Costa Rica	36	Haiti	7	Dominica	1
Peru	35	Nicaragua	7	French Guiana	1
Mexico	32	Trinidad and Tobago	7	Guadeloupe	1
Bolivia	20	Dominican Republic	6	Jamaica	1
Panama	19	Paraguay	6	Martinique	1
Chile	14	Guyana	5	United States	1
Cuba	13	Puerto Rico	5	Virgin Islands	1

applied to prevent the bamboo against fungal and insect attack. Most common chemical techniques include dipping in boric acid, soaking with Noah and injection of creosote oil [19] etc. However, the use of chemical methods has some environmental and safety issues and must be used very carefully. One of the common method used for bamboo preservation is boiling of culm in a dilute solution of NaCO₃ or caustic soda for 30–60 minutes [20]. It aids in removing of starch present in culms which improve its fungal resistance. In this technique the culms of bamboo are painted with lime in slaked form which upon drying, converts to CaCO₃. It enhances the culm resistance against moisture and acid. To ensure good durability of bamboo structure, it must be kept as dry as possible, it must not be kept in direct contact with the ground, and it must be subjected to good air circulation [21].

Bamboo standards and codes

The first step in bamboo standards was taken by ISO (International Organization for Standardization). In 2004, ISO developed three standards for bamboo designated as ISO-2004a, 2004b and 2004c. These standards were derived from timber standards of ISO. ISO 2004a designated as ISO 22156, cover the specifications for structural design of bamboo including full culm, half culm and laminated bamboo structures [23]. ISO 2004b and 2004c designated as ISO 22157, specified different tests for determining mechanical properties of bamboo including moisture content, density, tensile, compressive, shear and flexural strength [24]. With increasing popularity of bamboo construction, countries which are rich in local bamboo resources started standardizing bamboo [25–29]. The existing standards and codes for bamboo specifications are summarized in Table 3 [22].

Table 2. Biodiversity of bamboo in Asia Pacific region [14]

Countries	No. of naturally occurring species	Countries	No. of naturally occurring species
Australia	3	Myanmar	75
Bangladesh	18	Nepal	25
Bhutan	21	North Korea	2
Brunei	6	Pakistan	3
Cambodia	4	Papa New Guinea	22
China	626	Philippines	26
Hong Kong	9	Russia (Sakhalin and Kuril Islands)	1
India	102	Singapore	3
Indonesia	56	South Korea	6
Japan	84	Sri Lanka	11
Laos	13	Thailand	36
Malaysia	50	Vietnam	69
Total			1012

Mechanical properties of bamboo

The fibers of bamboo grow in longitudinal direction of culms. Understandably, the axial strength of bamboo in the direction of fibers is much higher as compared to lateral directions. Bamboo has generally shown ductile behavior with acceptable compressive and tensile strengths [30]. Bamboo culm shows uniform strength at all positions in longitudinal and lateral directions [31]. The strength of bamboo is effected by the type of bamboo used and method of thermal treatment [32]. Bamboo can be considered as transverse isotropic material. It has a significant axial strength in the direction of fibers. Tensile strength is almost double as compressive strength in the direction parallel to grains. The shearing strength in direction perpendicular to grains is comparable higher than the parallel direction [33].

The mechanical properties of bamboo are greatly affected by the moisture content present in bamboo. Bamboo is an hygroscopic material which absorbs water from environment [34]. The moisture content can be determined by water

absorption test as specified by ISO [24]. Moisture content can vary by species and also by the location of bamboo node i.e. top, middle or bottom. Average value of moisture content found in bamboo is between 15–30% [35]. The mechanical properties of bamboo namely tension, compression and shear properties degrade with high moisture content while the behavior at failure become more ductile [36]. Bamboo should be preferably air dried before use as air dried bamboo shows good strength as compared to oven dried bamboo [37, 38]. The important mechanical properties of bamboo are summarized in Table 4 [39–47]. The average tensile strength of bamboo along the fibers varies between 70–210 MPa for different species. Although the tensile strength of bamboo is less than steel, it is significantly better than aluminum and wood. The tensile and crushing strength varies at different location of bamboo culm and the source from bamboo is obtained. The average compressive strength varies between 20–65 MPa. The elastic modulus of bamboo generally varies between 2500 to 17500 MPa and modulus of rupture varies between 50 to 200 MPa.

Table 3. Existing bamboo standards and codes [22]

Country	Code	Standard
China	-	JG/T 199: Testing method for physical and mechanical properties of bamboo used in building (PRC MoC, 2007)
Colombia	Reglamento Colombiano de Construcción Sismoresistente – chapter G12 Estructuras de Guadua (Guadua structures) (ICONTEC, 2010)	NTC 5407: Uniones de Estructuras con Guadua angustifolia Kunth (Structural unions with Guadua angustifolia Kunth) (ICONTEC, 2006) NTC 5525: Métodos de Ensayo para Determinar las Propiedades Físicas y Mecánicas de la Guadua angustifolia Kunth (Methods and tests to determine the physical and mechanical properties of Guadua angustifolia Kunth) (ICONTEC, 2007)
Ecuador	Norma Ecuatoriana de la Construcción – chapter 17 Utilización de la Guadua Angustifolia Kunth en la Construcción (Use of Guadua angustifolia Kunth in construction) (INEN, 2011)	INEN 42: Bamboo Cana Guadua (bamboo cane Guadua) (INEN, 1976)
India	National Building Code of India, section 3 Timber and bamboo: 3B (BIS, 2010)	IS 6874: Method of tests for round bamboos (BIS, 2008) IS 15912: Structural design using bamboo – code of practice (BIS, 2012)
Peru	Reglamento Nacional de Edificaciones, Section III. Code E100 – Diseño Construcción con Bamboo (ICG 2012)	
USA	-	ASTM D5456: Standard specification for evaluation of structural composite lumber products (ASTM, 2013)
International	-	ISO 22156: Bamboo – structural design (ISO, 2004a) ISO 22157–1 Bamboo – determination of physical and mechanical properties – part 1: requirements (ISO, 2004b) ISO 22157–2: Bamboo – determination of physical and mechanical properties – part 2: laboratory manual (ISO, 2004c)

Table 4. Range of mechanical properties of bamboo

Mechanical property	Range
Tensile strength (MPa)	70–210
Compressive strength (MPa)	20–65
Elastic modulus (MPa)	2500–17500

Structural use of bamboo

Bamboo is a partially versatile material and can be used in different ways in construction. The bamboo culm can be used as a structural element due to its architectural demand or it can be altered in different ways according to need. It has socio-economic benefits as it is durable and available cheaply [11]. Bamboo can prove to be a viable alternative to existing construction materials and can be used in organic shaped structures [48]. The various forms of bamboo used in construction are discussed in the subsequent sections.

Full/half culm bamboo

Full culm of bamboo can be used as a whole element for architectural demand, scaffolding, resorts construction, etc. This type of use is more common in regions where bamboo is available locally. Full or halved bamboos are connected together and used in columns, walls, roof purlins and poles etc. as shown in Figure 3. Connections in such type of bamboo use are challenging due to the hollow shape of bamboo culm. Usually culms are tied together at the end with the aid of ropes. Other methods adopted for connections are use of hose clamps, concrete infill and bolts. The use of hose clamps or concrete infill highly improve the performance of connections [49].

Engineered bamboo

Engineered bamboo refers to use of bamboo which is processed and altered before use in construction. Such use is adopted for flooring, sheeting, wall panels and other uses. Most common type of engineered bamboo used in construction is laminated bamboo. In laminated bamboo, the bamboo culms are first pressed and flattened to form laminated strip layers of uniform size [50] as shown in Figure 4 [51]. Those laminated strips are glued together in layers to form laminated bamboo boards as shown in Figure 5 [52].

The laminated bamboo sheets are mostly used in similar applications as wooden plywood, though its properties differ in certain ways. The laminated bamboo section shows orthotropic behavior, with compressive strength in grain direction much greater than the other two transverse directions [53].

Another modern engineered product of bamboo is bamboo scrimber. The bamboo strips are crushed and rolled to form bamboo fibers bundles. These bundles are treated with adhesives and highly compressed in hot temperature to form a very compacted material known as bamboo scrimber as shown in Figure 5 [52].

Density of commercially available engineered scrimber varies between 800–1200 kg/m³. Density affects the mechanical properties and water absorption capacity of the bamboo scrimber [54]. Scrimber prepared from bamboo bundles which is air dried at high temperature and treated with phenol formaldehyde (PF) resin showed improved moisture absorption. It also showed resistance to swelling, which makes it lucrative for uses such as decorating and furniture [55].



Figure 3. Use of bamboo culm (a) full bamboo culm as structural elements, (b) half/full culm as roofing

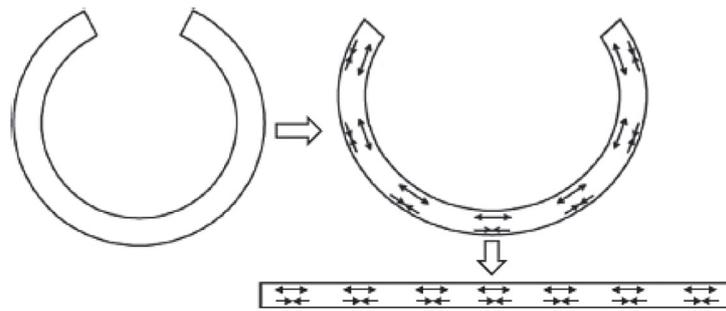


Figure 4. Bamboo culm flattening for laminated bamboo [51]



Figure 5. (a) Layers of bamboo glued tighter to form laminated bamboo, (b) Bamboo strips compressed together to form bamboo scrimber

Bamboo scrimber and laminated bamboo shows superior behavior to existing timber [56].

Other products formed by alternating the bamboo culms include veneers, fireboards and mat board etc. Bamboo mat board, corrugated sheet and veneer composites can also be good alternatives to current wood construction [57]. The properties of existing engineered bamboo products are summarized in the Table 5.

Bamboo reinforced concrete

Bamboo fibers grow in longitudinal direction of culm which makes it axially strong in both tension and compression. Such behavior of bamboo makes it a viable alternative for traditional steel reinforcement. Bamboo culms are usually used in the form of strips or full culms and are first treated for termite using different solutions. The performance of bamboo reinforced concrete mainly depends upon the interlock between bamboo strips and concrete. Load carrying behavior of bamboo reinforced concrete beams is similar to RC beams. The use of adhesives can make bamboo reinforcement water resistant and use of hose clamps can prevent it against slipping [59].

Use of Sikadur 32-gel also enhances the bonding strength between bamboo and concrete and also improve flexural strength of bamboo reinforced beams [60].

Bamboo reinforcement is generally used in beams as main bars or stirrups. It can also be used in column as main bars or hoops [61]. Various researchers have worked on efficient use of bamboo in concrete as reinforcement. The behavior of BRC beams is generally far better than PCC beams. The shear and flexure behavior of BRC with 3.8% bamboo reinforcement becomes very similar to RCC beam with 1.23% steel reinforcement [62]. The performance of bamboo reinforcement can be enhanced using rebar as mechanical anchors [63] or by using hose clamps [64]. The behavior of BRC beam having 200 mm² bamboo reinforcement with hose clamps and steel reinforced beam (SRC) having 100.48 mm² steel reinforcement is shown in Figure 6. As shown from graph, the use of hose clamps has enhances the ultimate load capacity of BRC beams [64], but generally steel reinforced beams are much more stiffer and ductile than BRC beams [30].

Table 5. Properties of various engineered bamboo products [58]

Types of Bamboo Products	Density (kg/m ³)	Rupture modulus (Nmm ⁻²)	Elastic modulus (GPa)
Bamboo mat board (India)	766	51	3.7
Bamboo mat board (China)	850	93	NA
Bamboo curtain board (China)	850	121	12.5
Bamboo strip board (Vietnam)	815	124	9.6
Bamboo strip board (China)	780	113	NA
Bamboo parallel glulam (China)	850	167	11.5

Note: NA = not available

Bamboo reinforcement can also be used in slabs as it gives decent flexural and shear strength [65]. The use of bamboo reinforcement can also improve the ductility of shear wall. The shear strength and ductility of RC shear wall having bamboo reinforcement is significantly better than unreinforced shear wall. However, bamboo reinforcement must be prevented from any moisture, which can reduce its ultimate strength [66].

Bamboo fiber reinforced concrete

Fiber reinforced concrete has been used in the past utilizing different fibers. As concrete is weak in tension, fibers are generally provided in high tensile zones to strengthen concrete and reduce crack width [67, 68]. Synthetic fibers such as glass, steel, asbestos, carbon [69] and other polymers are generally used in fiber reinforced concrete, but with scarcity and high energy demands of synthetic fibers, the use of recycled aggregates [70] or naturally available fibers such as wood, coconut, hemp, sisal and rice husk and bamboo are encouraged in fiber reinforced concrete [71–76].

Bamboo fibers are environmentally efficient material [77] and can be used in fiber reinforced concrete. Bamboo fibers are usually obtained by crushing and grinding the bamboo culms into small fibers and then removing the moisture content by drying [78]. The length of bamboo fibers used in concrete varies from 10 mm to 67.5 mm [79–81]. Bamboo fibers do not improve the compressive strength of concrete. In fact they cause a decrease in compressive strength of concrete due to poor bond strength between aggregates and cement matrix as owing to the presence of bamboo fibers. Conversely, bamboo fibers significantly improve tensile strength of concrete [82]. The tensile behavior of BFRC with 0.26% fibers is compared with plain concrete in Figure 7 [82].

The addition of bamboo fibers slightly improve the flexural strength of concrete, but it enhances crack control and ductility [79, 82, 83]. Bamboo fibers can significantly improve the impact resistance of BFRC compared to plain concrete. When it is used in hybrid form with steel fibers, it can improve impact resistance up to 550% [80].

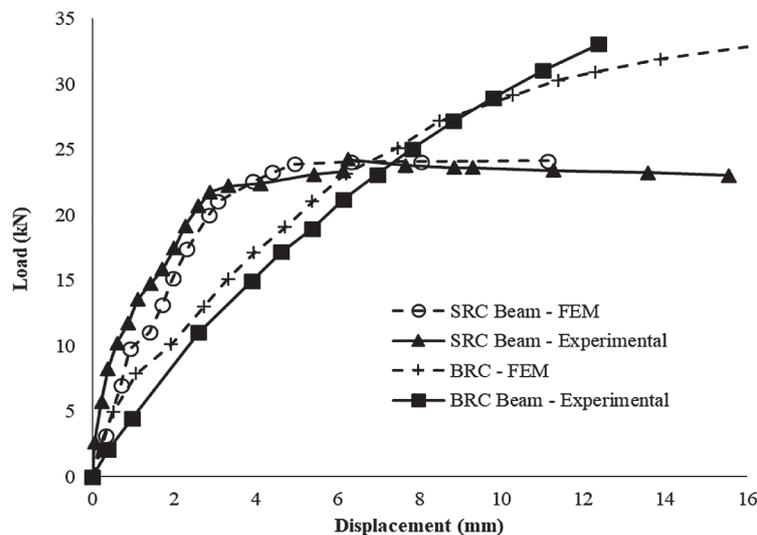


Figure 6. Load-deflection relations of BRC and SRC beams [64]

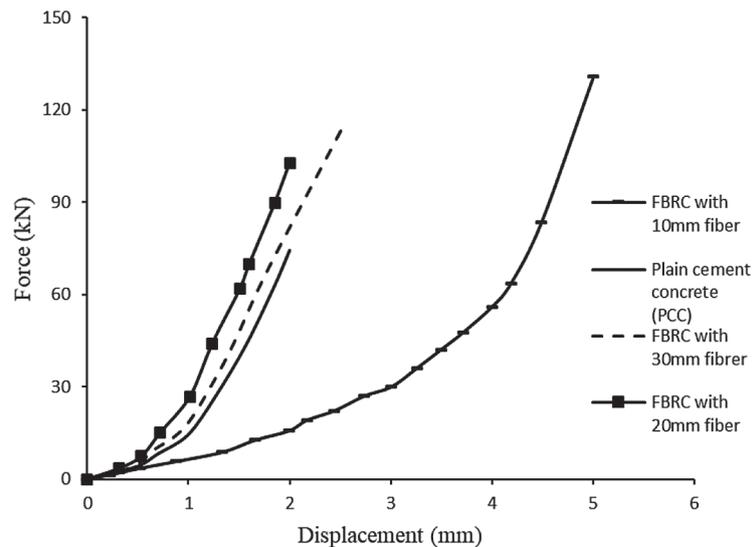


Figure 7. Load-displacement relations in split tensile tests for FRBC and PCC [82]

Drawbacks/Gaps in use of bamboo as construction material

Bamboo provides a great natural alternative to existing synthetic materials in construction industry. Though bamboo is available in most parts of the world, use of bamboo in construction is still dependent on the availability of bamboo in local conditions. Bamboo offers great versatility in its structural use, especially in reinforced and fiber reinforced concrete. Its performance mainly depends on interlocking force with concrete. Further studies need to be carried out to improve bamboo strips interlocking with concrete. Also proper numerical models need to be developed along with experimental studies to predict its behavior and dynamic loads.

structural properties. However, a lot needs to be done in standardizations and specifications to ensure consistent use of bamboo in construction industry.

- The tensile strength of bamboo is not as high as steel, but it is significant compared to wood and aluminum. Hence, it is an attractive alternative to use in construction.
- The properties of engineered bamboo are comparable to wood and can be used in construction as laminated and scrimber bamboo. Bamboo culms can also be used as structural elements such as beams and columns.
- Bamboo is gaining popularity for its use in concrete. It can be a viable replacement for conventional steel reinforcement though there is a need for further study in developing techniques for proper bond between concrete and bamboo reinforcement.

CONCLUSIONS

This study reviews various aspects of bamboo as a construction material. The main conclusions can be summarized as:

- Bamboo plant is farmed all over the world in tropical and non-tropical regions. It is specifically more common in Asia Pacific region.
- Bamboo is treated by different methods to reduce starch content before use. Air drying and chemical treatment are most common methods.
- ISO has developed standards and codes for bamboo as a construction material. ISO specified different tests for determining the mechanical properties of bamboo and its

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