APPLICATIONS OF ENGINEERED BAMBOO PRODUCTS IN THE CONTEXT OF BANGLADESH

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ABSTRACT

Construction industry is increasingly leaning towards regenerative and renewable materials to foster sustainability. Bamboo grows widely in the tropical and sub-tropical parts of the world and has been used as a construction material since the inception of human civilization. Owing to its faster harvesting rate and superior mechanical properties, bamboo could be a viable option to be used in diverse structural applications. Low environmental impact of bamboo has been evaluated as "factor 20" by means of life-cycle analysis in house construction, implying that the impact of bamboo on the environment is 20 times less than that of bricks and concrete. Advancement in technologies has evolved innovative use of materials with time, such as introduction of engineered bamboo products, where bamboo culms are cut to planks and glued together delivering a product with minimal variation in material properties and favourable sizes to suit various applications. Engineered bamboo products could range in various types and dimensions offering sustainable alternatives of concrete and steel to be used as floors, beams and walls in buildings and bridge structures. While the use of engineered bamboo products has been greatly appreciated in many parts of the world including Africa, Latin America and parts of south-east Asia including China, Indonesia, Philippines for structural purposes, in Bangladesh such attempt is still missing. Although, Bangladesh is a sub-tropical country, yet bamboo is grown round the year in rural home plantations and in forests. Current research discusses the potential of engineered bamboo for building construction drawing the experiences from world sphere. The production processes of various types of engineered bamboo products are described along with the strength comparison between bamboo products and other construction materials. The comparison shows engineered bamboo products offer high potential to be used in the building construction. Consequent discussion on the bamboo scenario of Bangladesh reveals that bamboo has been utilised, to a considerable extent, as a construction material in its natural form. Lastly, the mechanical properties of local bamboo species in Bangladesh were compared with the commonly used species for engineered bamboo production round the world. This reveals that the local bamboos possess the potential to manufacture homegrown engineered bamboo products.

Keywords: *Bamboo Scrimber; Building Structures; Engineered Bamboo; Engineered Bamboo Production; Glubam; Laminated Bamboo Lumber; Renewable Materials; Sustainability*

1. INTRODUCTION

The construction sector is one of the largest contributors of carbon emissions, producing about 40% of the total carbon emissions (McNeil et al., 2016; Zhou et al., 2018). The common materials used in building construction are steel and concrete, which uses extensive energy to be produced. Although, adopting various sustainable steps the production of carbon emissions could be lessened yet elimination of the carbon emissions is very difficult. Starting from designers, engineers, to policymakers all are embracing towards the construction material which offers higher sustainability and reduce adverse impacts on the environment.

On the other hand, with increasing demand for development and housing the developing nations are forced to overutilize the natural resources such as stones, sands for concrete production, also burning various fossil fuels to produce the construction materials (Ghavami, 2008). Bangladesh has fewer timber resources compared to the European and American countries, and thereby the use of concrete, RCC, tin, welded- hot rolled or cold formed steel are in a mass. However, usage of these materials poses serious issues to the environment. In contrast, challenges of using natural materials are the variability and lack of research.

While the urban and semi-urban areas are rapidly evolving in terms of infrastructural development, the rural life of Bangladesh is quite simple. The rural communities rely mostly on the natural raw materials such as bamboo to construct housings and other infrastructures, and household products (Alamgir et al., 2007; Motiur et al., 2006; Rana et al., 2010).

To attain sustainability for infrastructural development, researchers around the world have been investigating various approach. These approaches include increased use of natural raw materials (Nazmul et al., 2023), incorporation of recycled materials in construction (Mirmomeni et al., 2022), construction using mass timber (i.e. CLT, GLT) (Anwar-Us-Saadat et al., 2022; X. Li et al., 2021; Subhani et al., 2022) are a few of the research orientations deeply explored.

Increasingly popular for its aesthetics and sustainability, the mass timber buildings typically include members (GLT, GLULAM) or panels (CLT) made from timber planks joined by means of glue or dowels. Like that concept the Engineered Bamboo (EB) was developed adjoining split bamboo strands or plates using adhesives. Since inception, this sustainable product has been extensively researched to establish its use in construction (D. Kumar & Mandal, 2022; Sharma et al., 2015).

Compared to the timber counterparts Bamboo is quick to grow, reaching full height of 15 – 30m within a period of 2 – 4 months (Xiao et al., 2013). Bamboo stalks generally attain maturity within 8 years, making it highly renewable (Mahdavi et al., 2011). Whereas Sitka spruce a popular raw material for CLT or GLT production generally has a 35 – 45 years rotation period for commercial use in Great Britain (Moore, 2011). Thus, production and use of EB owing to it sustainability are suitable for the countries where bamboo is grown naturally (Rittironk & Elnieiri, 2008).

However, till date no research has been found to explore the potential of EB application in aspect of Bangladesh, this paper will try to explore that. The paper initiates with a brief discussion on the history usage, production, and characteristics of the various EB products available around the world. Then the paper will adjoin the current state of literature about the bamboo species available in Bangladesh, current usages, and mechanical properties.

2. ENGINEERED BAMBOO

2.1 Brief history and definition

Bamboo has been widely used in construction for hundreds of years. An archaeological discovery in Ecuador discovered bamboo made house dated back to 9500 years (Hidalgo, 1992). Bamboo is taxonomically classified as a grass and grown in the tropical, subtropical, and even in the temperate regions which receive ample rainfall. According to current count by the Royal Botanic Gardens in Kew, there are about 1821 species of bamboo species around the world, but the woody bamboos are favourable to use for construction purposes (Guadua Bamboo, 2023a).

The use of bamboo in traditional construction has been dominated by experiences by the local artisans. It is often challenging to standardize the application of bamboo in structures (Sharma et al., 2015), mainly due to the wide variety of species grown around the world and those vary in respective geometry and properties. Further challenges to build modern structures from bamboo stem arise due to the shape of the plant. Bamboo has a circular to elliptical shaped cross-section with hollow-core and periodic nodes along its length. A schematic of the bamboo plant is shown in Figure 1. Typically, the bamboo plant has a larger diameter at the base of the stem which eventually decreases ascending towards the top of the plant. Due to this irregular shape establishing standard connections is also difficult.

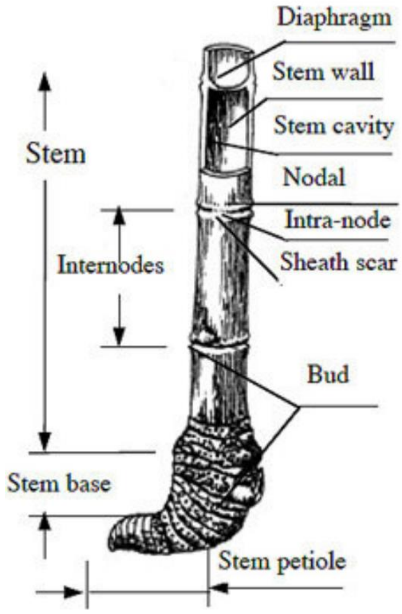


Figure 1: Schematic of bamboo stem (Guadua Bamboo, 2023b)

To overcome these issues, the concept of engineered bamboo was developed. Engineered bamboo products are typically produced using by joining bamboo strips or bamboo fibres using glue. The products can be shaped to typical geometric shapes such as square and rectangular cross-sections making it easier to be used in the construction.

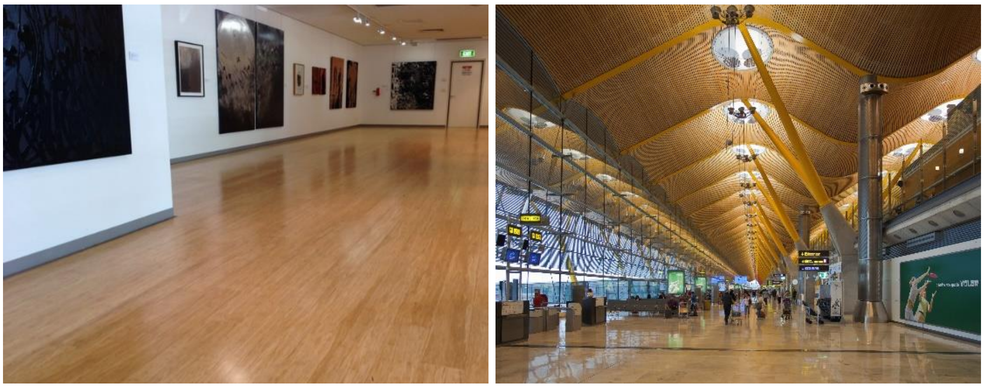
Engineered bamboo eradicates the issues arise from the variability of geometric shape and properties of the plant at its natural state. Again, having a rectangular shape, the connection systems available for timber and associated products could also be potentially utilized to join bamboo members.

It is difficult to exactly determine the date of development of engineered bamboo, but initial production of bamboo boards could be found in China during 1970s (Ganapathy et al., 1999). Throughout 1980-90s workshops, conferences, publications were emerged on detailing the production processes of bamboo made boards. Since then, owing to the sustainability offered by bamboo, various products were developed, and research related to the production and manufacturing of bamboo-based products has been significantly increased. Recent research on laminated bamboo lumber, reveal since 2000s the number of published research articles on the topic of engineered bamboo rapidly growing (Dauletbek et al., 2022) .

Currently, China is the largest producer of engineered bamboo, and the products are mainly exported to the US and Japan. Bamboo made panels have been extensively used for the flooring and architectural application in the building industry around the world, mainly in the temperate regions. Figure 2a shows a typical bamboo panel used in floor construction. An iconic use of bamboo panels in ceiling construction could be seen in case of Barajas International Airport in Madrid. There, about 200,000 m^2 of bamboo panels were utilized to construct the ceiling (Figure 2b).

The structural construction using engineered bamboo products is often hindered due to the lack of appropriate design standards accepted by the builders, structural engineers and designers. Thus, researchers around the world have been working to employ the beneficials properties of EB as a structural material. These works include material properties testing (Verma et al., 2014), member testing, constitutive modelling of material properties (Goonewardena et al., 2022), and on the manufacturing process of EB (D. Kumar & Mandal, 2022; Mahdavi et al., 2011).

In 2017, Chen et al. (2020) reported the construction of a 3–storied office building in Nanjing Forestry University in Nanjing, China where the laminated bamboo lumber panels were used.



(a) (b)

Figure 2: Application of bamboo panels (a) flooring (Flooring, 2023) and (b) ceiling of Bajaras International Airport, Madrid, Spain (Wikipedia, 2013)

Recently a 3-storied office building was constructed fully using the bamboo made members (Su et al., 2021). The building was reported to be constructed in Ganzhou, China. The total area covered by the building was 1100 m^2 and the highest point of the building was at 12.8 m. The beams and columns were made by laminated bamboo lumber (LBL) which were joined using bolt and steel plate connections. The structure was designed using load combinations from Chinese standards and modelled using SAP2000 software. The

Figure 3 shows the external and internal images of the building.

In addition, Xiao et al. (2010) reported about the construction of laminated bamboo made bridges in China. There were multiple bridges constructed. The first one was 1.5 m by 5.0 m pedestrian bridge built in 2006. In 2008 another bridge was designed and build to carry trucks in addition to the pedestrian traffic. Later bridge was 3.5 m in width and 22.8 m in length. Both bridges were built using girders made from bamboo laminates.

(a) (b)

Figure 3: Three – storied office building constructed using LBL members (a) structural system of the roof and (b) front view (Photo courtesy: Su et al. (2021))

2.2 Manufacturing process and classification

Typical manufacturing process of engineered bamboo follows few broad steps, firstly, derivation of strips or fibres from the bamboo culm, secondly processing of strips to have a shape, then preservation of the strips, followed by resin or glue impregnation and lastly, stack arrangement and compression. For most of the EB products the first step remains same. Depending on the final product, the raw curved strips are processed as either planned, crushed, or sliced to have a desired shape. Figure 4 shows a typical schematic diagram of the steps to obtain bamboo strips.

The third step of preservation is performed to increase longevity of the final product, eradicating the sugar and wax from the bamboo. Boiling or caramelization procedure are undertaken to preserve the strip. Resins are used to hold all the strips or fibres together in the respective final shape. Commonly used resins include phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, polyvinyl acetate, melamine-urea-formaldehyde, polyurethane, emulsion polymer-isocyanate and epoxy (Dauletbek et al., 2022). After the strips are soaked in the resin, they are stacked for the pressing process. The compression applied on the stacked strips or mats could be performed in a cold or a hot temperature.

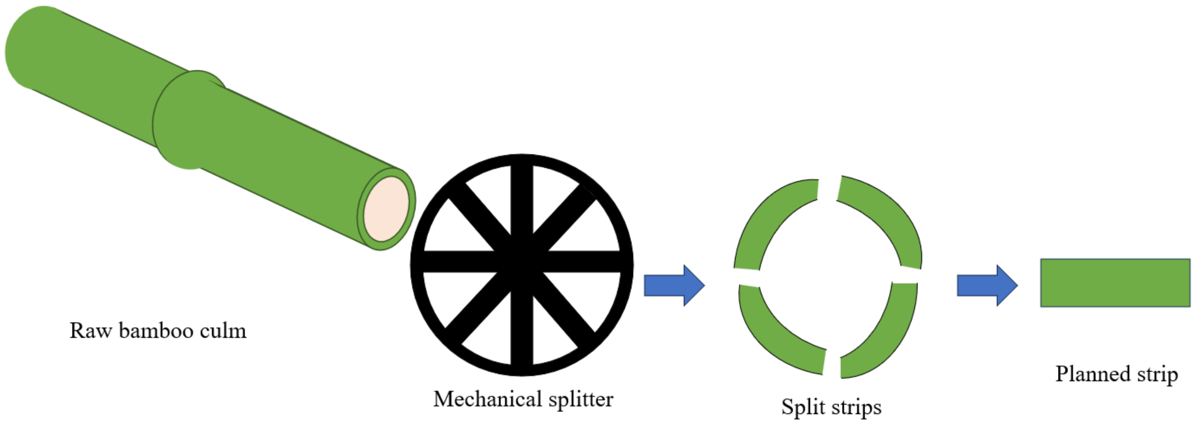


Figure 4: Steps to obtain planned strip for engineered bamboo production

Engineered bamboo includes various types of products within the cohort, such as layered laminated bamboo composites (LLBC), laminated bamboo boards (LLB), bamboo scrimber (BSC), glued laminated bamboo (Glubam), parallel strand bamboo (PSB) laminates and laminated bamboo lumber (LBL) (D. Kumar & Mandal, 2022). On the forthcoming section few of these products will be discussed while the respective images are given in the Figure 6 and Figure 6.

2.2.1 Laminated bamboo lumber (LBL)

To produce LBL, the bamboo culm is initially passed through the splitter machine to disintegrate into curved strips, which are then scrapped and planned to provide a rectangular shape. Next, the strips are fed with resin (commonly Phenol formaldehyde) followed by stacking of the strips and pressing. Depending on the method of strip layering, the final product is classified as flatwise or edgewise LBL.

2.2.2 Bamboo Scrimber (BSC)

Bamboo scrimbers are also called strand woven bamboo or parallel strand bamboo (PSB). These are produced by compressing the stacks of bamboo fibres into a beam section by compression. Initially the bamboo culm is split into strips then, the strips are crushed before submerging into resin followed by compression of the combined stack into a rectangular cross-section. This process has been found to be highly efficient in terms of material utilization (Sharma & van der Vegte, 2020).

2.2.3 Glued laminated bamboo (Glubam)

Glued laminated bamboo is in short called Glubam. The term was first proposed in the works of Xiao et.al (2007). Keeping to the similarity with its timber counterpart Glulam, the name was invented. Glubam production process follows 2-step lamination process, firstly creating bamboo boards using thin bamboo strips as LBL, then combining those into a deeper rectangular board as Glubam. The Glubam produces a strong composite and currently being used in residential construction in China.

(a) (b)

Figure 5: EB products (a) flatwise LBL & (b) bamboo scrimber (Moso International B.V., 2023).)

(a) (b)

Figure 6: Engineered bamboo products (a) Glulam I-section beam and (b) edgewis LBL (Hiyo Bamboo, 2023)

2.3 Strength comparison of various products

Table 1 shows the strength comparison of various engineered bamboo products with other structural materials obtained from the available research. It is observed that the bamboo products are strongest in case of parallel grain tensile strength. The tensile strength was higher compared to concrete and comparable to Douglas fir. Among the bamboo products, bamboo scrimber demonstrates the maximum strength compared to LBL and glubam.

Likewise in terms of compressive strength bamboo scrimber was found to be stronger too. While in certain cases the bamboo products were showed strengths higher than that of douglus fir, concrete and Moso bamboo. In shear and modulus of rupture (MOR), most of the engineered bamboo products show strength within a similar range.

Key factors contributing to the strength of engineered bamboo products are the bamboo species, moisture, adhesive or matrix used, treatment methods and bamboo defects, number and arrangement of nodes (D. Kumar & Mandal, 2022). Except the bamboo species all other factors could be adjusted during the production process. The manufacturing of the engineered bamboo is mainly done using the product which is locally available. The literature also reports around the world bamboo species as, *phyllostachys, dendrocalamus, bambusa, guadua, moso* and *gigantochloa*. Thus, while exploring the possibility of engineered bamboo production it is significant to select an appropriate bamboo species which will have higher strength.

Table 1: Mechanical properties of various engineered bamboo products in comparison with other structural materials

Group	Material	Remarks	Parallel grain tensile strength (MPa) f_{yLt}	Parallel grain compressive strength (MPa) f_{yLc}	Parallel grain shear strength (MPa) f_{yLv}	Flexural Modulus (MPa) MOE	Modulus of Rupture (MPa) MOR
Engineered Bamboo	Laminated bamboo lumber						
	Sharma et al. (2015)		82-144	63-64	9-16	7000-17000	39-145
	Dauletbek et al. (2022)		90-124	30 – 73	7 – 18	8320-10912	64 – 128
	Glubam						
	Xiao et al. (2008)		82	51	-	10400	99
	Sinha et al. (2014)	BGB*	-	60	~ 16	22600	42 – 70
	Xiao (2019)		85	73	17	11200	120
	Tang et al. (2019)		83	49	16	9800	-
	Bamboo Scrimber						
	A. Kumar et al. (2016)		145	116	17	18650	167
	Huang et al. (2019)		228 – 365	71 – 199	-	13500-32300	179 -398
	H. Li et al. (2020)		156	101	27	9919	144
	Dauletbek et al. (2022)		120	86	15	13000	119
Other structural materials	Concrete (M20 to M80 grade)		3 – 5	20-80	-	22000-44000	3 – 6
	Douglus fir - (Forest Products Laboratory, 2021)		108	50	8	13400	85
	Moso Bamboo (Phyllostachys pubescens)		153	53	16	-	135

*In this research the product tested was named as Bamboo Glulam Beams - BGB

3. USE OF BAMBOO IN BANGLADESH

In Bangladesh, about 33 different types of bamboo species are found till date with the plantations covering about 5000 sq kms area country wide (Mahzuz et al., 2013; Rahman et al., 2017). Being a subtropical country, plantations of bamboos could be in both rural and forest areas of Bangladesh (see Figure 7). In a rural setting, the spread of bamboo plantations is typically found all around the country. However, the forests producing bamboos are typically from the Eastern areas of the country. Previous research reported that 80% of the bamboo supplies are from rural sources and rest are obtained from the forests (Rahman et al., 2017). Bamboo products are widely used for various trades around the country, predominantly around the rural areas in Bangladesh. Bamboo is primarily used in non-structural applications but some structural uses are also noticeable. It worth noting that the structural applications are not code compliant as there is no design code for bamboo in Bangladesh.

(a) (b)

Figure 7: Typical bamboo plantations in (a) rural areas and (b) forests (Mukul & Rana, 2013)

Non-structural uses of bamboo include producing various household items such as baskets, toys, screeners, mats, fish traps, rickshaw hood, thinly weaved and densely weaved fences. Some of these items are presented in the Figure 8. Research on a bamboo-based market in eastern part of Bangladesh revealed that, 30% of the entrepreneurs earned their livelihood by selling non-structural bamboo products. (Mukul & Rana, 2013)

Most structural applications of bamboo utilize the culm directly in the structure. Structures built using bamboo could also be classified as permanent and temporary structures. The permanent structures include houses, shops, and bridges (see Figure 9), whereas the temporary structures could be pavilions, gates, concrete formwork, propping, stages and so on (see Figure 10). However, it is worth noting that, these structures are typically built based on the experiences of the craftsmen rather than supported by material testing and experimental program.

(a) (b) (c)

Figure 8: Various non-structural bamboo products used in Bangladesh (a) baskets, (b) fences, (c) fish trap and (d) screener (Mukul & Rana, 2013)

Figure 9: Walkway bridge over a waterway in Eastern Bangladesh (Wikipedia, 2013)

(a) (b)

Figure 10: Bamboo poles used for construction (a) propping (Mukul & Rana, 2013) and (b) temporary formworks (Riyad, 2023)

In 2007, a 2-storied building structure was constructed as Modern Education and Training Institute (METI school) in Rudrapur, Dinajpur, Bangladesh (Heringer, 2007), which won the prestigious Aga Khan Award for Architecture. The focus of this structural construction was to utilize traditional construction techniques and locally available material of clay and bamboo. Further to this structure, DESI Training School and Anandaloy (2018) were also constructed embodying similar concept (Heringer, 2018). It should be noted that bamboo culms were used in these constructions rather than engineered bamboo and the buildings were hailed for the innovative architectural concepts rather than structural engineering point of view.

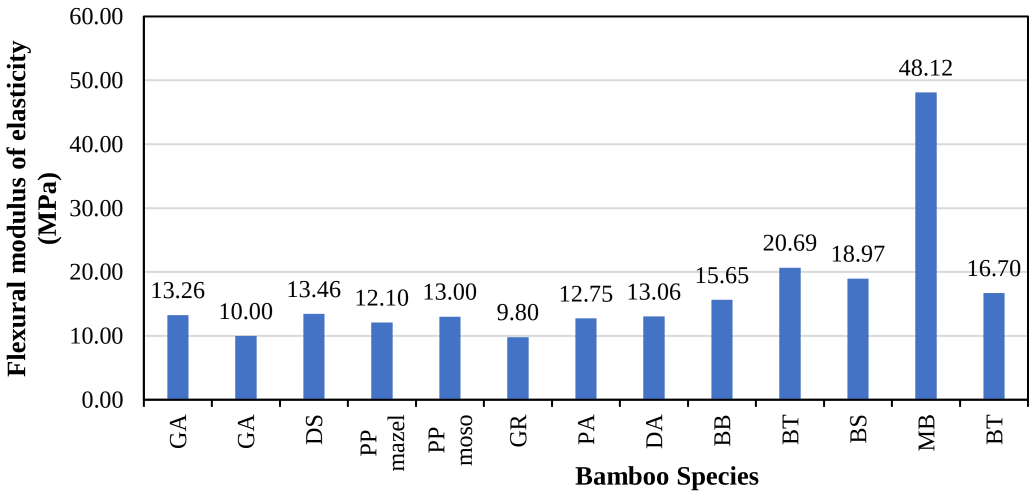
4. EXPERIMENTAL PROGRAMS ON BAMBOO SPECIES OF BANGLADESH

Limited numbers of literature are available on the mechanical properties test results on various bamboo species found in Bangladesh. Kamruzzaman et al. (2008) investigated the effects of age and height on mechanical properties of bamboo. This experimental program contained 4 different bamboo species found in southern Khulna region of the country. The bamboo specimens were tested under static bending test, which is also referred as 3-point bending test. The study revealed that the height and age of the sample did not have any significant effect on the flexural modulus of elasticity (MOE) and MOR. Another study was undertaken by Ahmad et al. (2020), which utilized raw bamboo culms to construct roof top mobile tower. This was an innovative use of bamboo in the aspect of Bangladesh found so far. The study tested *Bamboosa tulda* for tensile, compressive, and bending strength with 30 specimens for each load type. Based on the comprehensive test results, further design work was conducted. Apart from these, two more test programs were conducted by Mahzuz et.al (2013) on *Bamboosa tulda* strips and by Hoque et.al (2019). Though the later work did not specify the bamboo species used for the testing rather referred the samples as green and dried bamboo. In their research work, (Hoque et al., 2019) concluded the MOR found for the bamboo specimens was significantly low compared to the other reported studies. Table 2 reports the mechanical properties found in such species.

To compare the applicability of producing engineered bamboo products from bamboo species grown and used in Bangladesh, it is important to analyse the strength properties against the internationally available bamboo species. As reported in literature, 6 types of bamboo species were extensively used in different parts of the world to produce engineered bamboo products (D. Kumar & Mandal, 2022). Thus, in Figure 11 the flexural MOE were compared, which reveals the bamboo species found in Bangladesh demonstrates (BB, BT, BS, and MB) comparable strength to their international counterparts. However, it is worth noting that further comprehensive research on native species is required to establish the mechanical properties of bamboo to ensure proper material utilization prior to any structural applications or production of engineered bamboo.

Table 2: Mechanical properties of various bamboo species found in Bangladesh

Source	**Bamboo species**	**Tensile strength (MPa) f_{yLt}**	**Compressive strength (MPa) f_{yLc}**	**Flexural Modulus (MPa) MOE**	**Modulus of Rupture (MPa) MOR**
Kamruzzaman et.al (2008)	*Bamboosa balcoa*	-	-	15648	175
	Bamboosa tulda	-	-	20685	192
	Bamboosa salarkhanii	-	-	18970	212
	Melocanna baccifera	-	-	48122	237
Mahzuz et.al (2013)	*Bamboosa balcoa*	93	-	-	-
Hoque et.al (2019)	-	48 - 112	19 - 54	-	29 - 34
Ahmad et.al (2020)	*Bamboosa tulda*	56	42	16695	77



International species: GA – *Gigantochloa atroviolacea* – Java Black, DS – *Dendrocalamus strictus* – Calcutta Bamboo, PP mazel – *Phyllostachys pubescens* Mazel ex J.Houz. – Mazel, PP moso – *Phyllostachys edulis* – Moso bamboo, GR – *Gigantochloa robusta* – Robusta Bamboo, PA – *Phyllostachys angusta* – Stone bamboo, DA – *Dendrocalamus asper* – Indonesian clone; Bangladesh species: BB – *Bamboosa balcoa* – Borak, BT – *Bamboosa tulda* – Mirtinga, BS – *Bamboosa salarkhanii* – Korjoba, MB – *Melocanna baccifera* – Muli

Figure 11: Comparison of flexural modulus of elasticity of various bamboo species

5. CONCLUSIONS

The paper introduces various engineered bamboo products available in the global market and highlights their beneficial properties. Brief discussion was presented on the production process, but it is acknowledged that establishing engineered bamboo production facilities would require to train workers and depending on local material availability. The locally grown bamboo demonstrates comparable strength with the international breeds. Although, further experimental research is required to reliaze the potential of local bamboo species. Thus, it is highly feasible to manufacture engineered bamboo products in Bangladesh using local species, which not only will attain sustainability but also contribute to the economy of rural and impoverished communities.

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