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# A Comprehensive Review on the Development of Bamboo Scrimber

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**ABSTRACT:** Bamboo scrimber regarded as a facet of an engineered bamboo has progressively been researched as a material of utmost significance for structural purposes. Bamboo fiber-oriented composite created from crushed bamboo fiber and depicted as bamboo scrimber, has attracted significant consideration from researchers and manufacturers owing to its outstanding mechanical design and features. Bamboo scrimber is described as bamboo fiber with adhesives organized in parallel under a press. The whole idea of bamboo scrimber is founded on a consolidated wood, where wood splinters are bond together. The need for a sustainable product and rises of industries, has emphasized the significance of bamboo products due to its biodegradability. Therefore, bamboo is used to generate engineered bamboo composites to yield variabilities in form and material properties. The overview of bamboo scrimber, centered on available literature is widely explored on the history and present technology of bamboo scrimber. The facets of its production including heat treatment, densities, defibering times, etc., from outcomes and experimental exploration results are discussed on its functioning.

**KEYWORDS:** Bamboo Scrimber; engineered bamboo; fiber-based composite; renewable raw material

## I. INTRODUCTION

Over the past decades, scientific and technological research has moved toward renewable raw materials and processes that are comparatively environmentally welcoming and sustainable [1]. Lately, with cumulative resource demands in the current industrialized world, the request for structural timber products for building materials has boosted. An enormous decrease in quality logs from natural forests has caused constraints to wood-based industries globally.

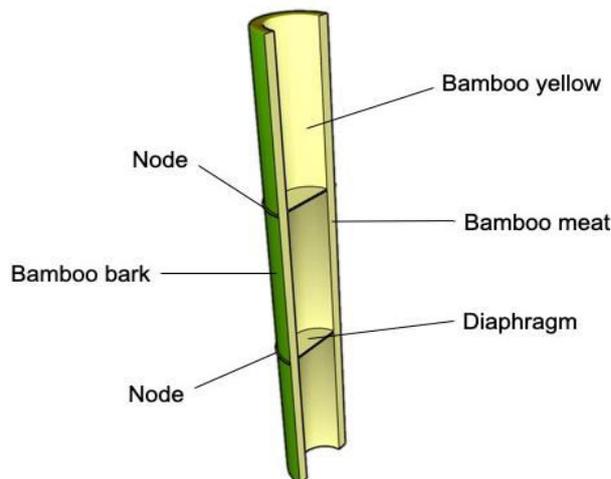
However, as the capacity and quality of wood resources from the forest have been dropped, it is becoming gradually essential to study chances for new building materials instead of traditional utilizations of wood. In addition to related ecological features such as renewability, biodegradability, and carbon sequestration, bamboo has exceptional mechanical properties comparable to wood and a faster growth rate. For that reason, it is taken as a promising raw material replacement for wood [2]–[4].

Bamboo is regarded as one of the quickest renewable plants with a maturity cycle of 3–4 years[5]; it grows as quickly, up to numerous centimeters per day, and has outstanding mechanical properties [6]–[8]. Bamboo is being grown as a plantation notwithstanding natural happening in many countries such as China and India, which paybacks local farmers to advance their lives by treating it into various products [9]. Bamboo is classified as a biological material with considerable significance, including sustainability and biodegradability [10], [11], appropriate processing with regard to physical, chemical, and mechanical treatments of bamboo culm can produce materials for various forms of appliances, natural fiber, activated carbon, and granulated fuel [12].

The bamboo fibers, identified by their slender form—long, taped at both ends, and occasionally, forked, also vary within the culm wall declining in density from the outer wall to the inner wall. The variations in geometric and mechanical properties limit the full culm bamboo construction despite more than 1200 bamboo species all over the globe. The main geometric descriptions of bamboo culms are their nodes, internodes, and nodal diaphragms, as shown in (Figure 1). Table 1 shows Native bamboo species showing culms from China, Columbia, and Mexico [13].

**Table 1:** Common Native species of bamboo culms [13]

Species	Origin	Age (years)	Number of culms
Phyllostachyspubescens (Moso)	Jiangsu, P. R China	3 - 4	84
Guaduaangustifoliakunth (Guadua)	Valle del Cauca, Columbia	2 - 5	30
Bambusaoldhamii (Oldhamii)	Veracruz, Mexico	3 - 5	121



**Figure 1:** Basic geometric features of a bamboo culm

Furthermore, it is problematic to make connections and joints for round units and tubes, which cannot be utilized in its application [14]. With the rising industry and the need for sustainable building products, bamboo is used to generate engineered bamboo composites to regulate the shape and reduce the variability of material properties [15]. Although there are over 1200 species worldwide, full culm bamboo construction is limited by the disparity in geometric and mechanical features. The trouble in making connections and joints suitable for round (and variable) sections is also unreasonable for mainstream construction; nevertheless, increasing research displays a growing industry and demand for sustainable building products. Studies differ from the use of full culm bamboo in construction and scaffolding [16]–[21] to engineered bamboo composites [22]–[30]. Engineered bamboo composites are of specific interest due to the standardization of shape and the relatively low irregularity in material properties [31].

The connection in raw bamboo buildings has always been a major difficulty and problem in the application of bamboo. The raw bamboo is hollow and thin-walled, which makes it confronted with the problems of inconvenient connection and poor reliability in the construction process, which seriously hinders the development of raw bamboo buildings [32], [33].

Bamboo scrimber, as a latest kind of engineered bamboo composite, is encompassed with crumpled bamboo fiber bundles saturated in resin and hard-pressed into a dense block [34]. This four-sided structural member has outstanding features such as a high bamboo exploitation ratio (over 80%), suitable grain pattern, comparable hardness, and color with hardwood, which makes it competitive with commonly used building and furniture resources [35]–[40].

A large trend of research works has been directed to the fabrication of bamboo scrimber initially, then research work considering properties and heat treatment was suggested with the improvement of fabrication maturity. Recently,

mildew proof, machining, and application-related issues are being considered by more and more researchers. In this paper, the state-of-the-art knowledge on the progress, processing, and resulting functioning of bamboo scrimber is shaped to establish studies on bamboo scrimber for further development.

## II. THE DISCOVERY AND THE PROGRESS OF BAMBOO SCRIMBER

Bamboo is widely dispersed in the developing countries of Africa, Asia, and Latin America, while many advanced countries in Europe and North America, including Japan and Australia, are significant consumer countries of bamboo products. Henceforth, bamboo scrimber is significantly getting much attention worldwide with its peculiar discovery.

Recently, the lower-value trees of the natural forests have been fully exploited to create wood products because of their availability and cost-efficiency. As the common log size is diminishing and wood quality is decreasing, large lumber members needed for commercial construction schemes are becoming less available and more costly. “Scrimber,” formerly proposed by Coleman, has been molded where low-quality wood was flattened and split into strands [41]. Afterward, the strands are glued and compacted to beams, overcoming the anisotropy of natural lumber and retaining the natural wood texture and the distinctive fiber orientation. Bamboo scrimber, also known as bamboo zephyr board in Japan and reconstructed limber in China, surfaced at the start of the 1980s by using small-diameter bamboo culms to make a recreated structural material [42], [43]. Initially, bamboo scrimber was founded in a laboratory in Nanjing Forestry University, China, in the year 1987, where high-strength bamboo scrimber was fruitfully prepared from bitter bamboo [44].

Subsequently, wild miscellaneous bamboo with unexploited value was utilized to create bamboo scrimber in the Chinese Academy of Forestry in 1989. Subsequently, wild miscellaneous bamboo with unexploited value was utilized to create bamboo scrimber in the Chinese Academy of Forestry in 1989 [7]. In the early days of the 1990s, a softening technology was adopted by Nanjing Forestry University, and bamboo scrimber without eliminating the bamboo outer skin was developed, and in the late 1990s, the industrial production of bamboo scrimber was actualized, which should be ascribed to the Anji enterprises in Zhejiang [45]. They invented and produced bamboo scrimber using cold-pressing equipment. The manufacturing technology level and automation level of the bamboo scrimber industry were not high when compared to wood-based panels. The bamboo’s outer skin and that of the inner were removed through the planning technique or splitting procedure, and the utilization rate of bamboo was about 50–60%. After more than ten years’ works, the Research Institute of wood industry in the Chinese Academy of Forestry advanced a new generation of bamboo-based fiber composite, which scrimber is considered as one by utilizing small-diameter scattered bamboo as raw material [34], [35], [46]–[48]. Long bamboo fiber bundles are detached straight from bamboo culm by means of the novel mechanical procedure deprived of eradicating the bamboo outer skin and inner skin. This technology is suitable for large-diameter Moso bamboo as well as small-diameter hybrid bamboo. The exploitation proportion of bamboo improved to more than 90%, yielding to the reduction of cost of the manufacture of bamboo scrimber [7].

## III. CURRENT SCIENTIFIC TRENDS OF BAMBOO SCRIMBER

Worldwide attention is now attracted to bamboo scrimber since its discovery and the initial progress of its life cycle and production. China has significant quantity and quality bamboo raw materials and is regarded to be at the forefront of research applications of bamboo scrimber. Literature comparison between the Chinese National Knowledge Infrastructure (CNKI) and Web of Science revealed that more studies are reported in the database of CNKI than in the Web of Science. (Figure 2) shows literature statistics between CNKI and the Web of Science [49].

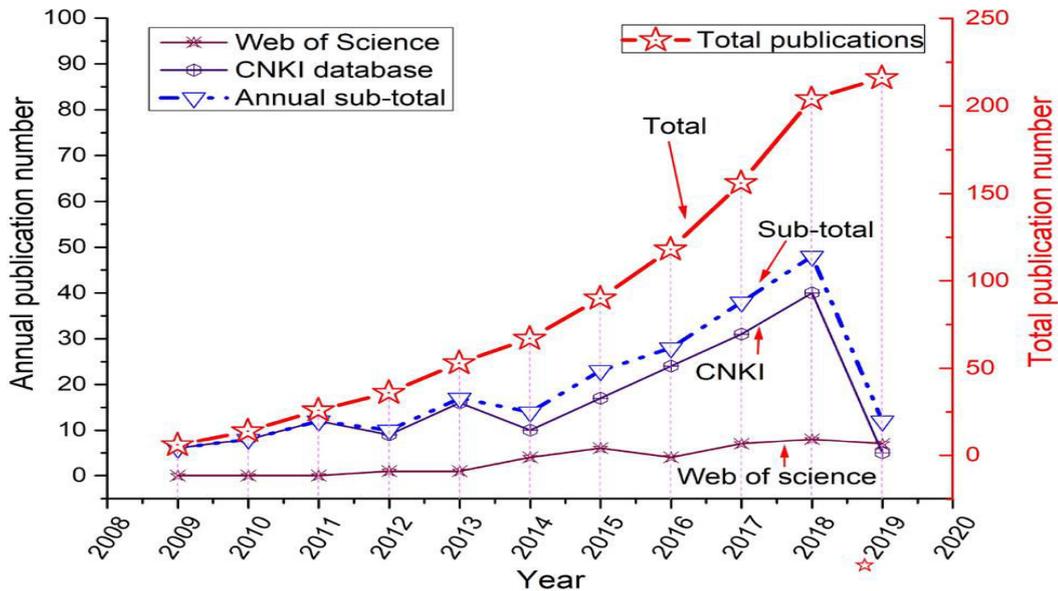


Figure 2: Bamboo scrimber literature statistics based on CNKI and Web of Science [49]

Even though a rise of research publications could be found in the last 3-5 years of the research, particularly in CNKI, yet slow growth movement can be noticed in the curve of the Web of Science. This indicates that the scientific world’s attention is driven to Bamboo scrimber. As shown in (Figure 3), the majority of papers are published in Chinese journals, whilst over 20% of the literature is academic dissertations containing detailed research about bamboo scrimber. Initially, researches were directed to the fabrication of bamboo scrimber, then researches regarding the properties and heat treatment were proposed with the improvement of maturity. Recently, mildew proof, machining, and application issues are studied by more researchers and scholars. (Figure 3) shows the large scope to which researchers are now focusing on facets of bamboo scrimber [49].

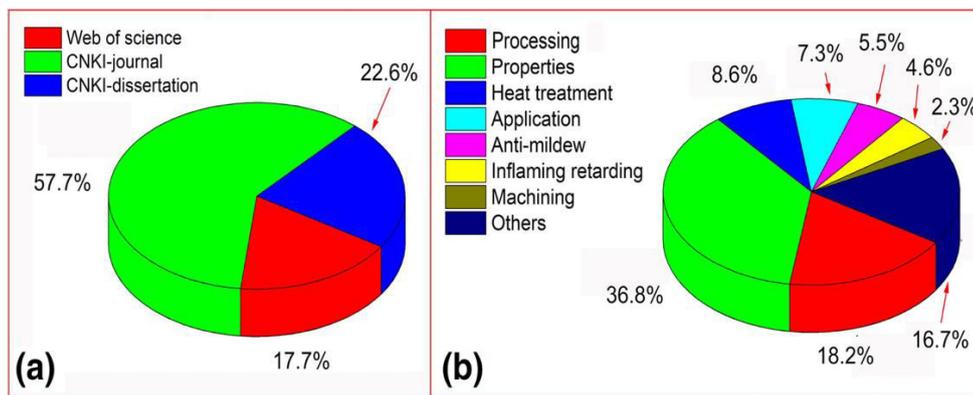


Figure 3: Literature resource and research focus of bamboo scrimber [49]

#### IV. DEVELOPMENT PROCEDURE OF BAMBOO SCRIMBER

Formerly, in the laboratory test stage, the focal production processes of bamboo scrimber involved truncation and splitting, softening, eliminating the bamboo outer skin, defibering, drying, sizing, assembly, and hot-pressing. With the endless progress of technology, some steps have been omitted in the process of large-scale manufacture of bamboo scrimber, where truncation and splitting, defibering, drying, dipping, assembly, cold-pressing, and heat curing or hot-pressing are the main procedures [7] as shown in (Figure 4). However, conventional preprocessing includes a chain of processes that can be categorized into four stages, i.e., bamboo fiber preparation, heat treatment and resin dipping, compression curing, and post-processing [49].

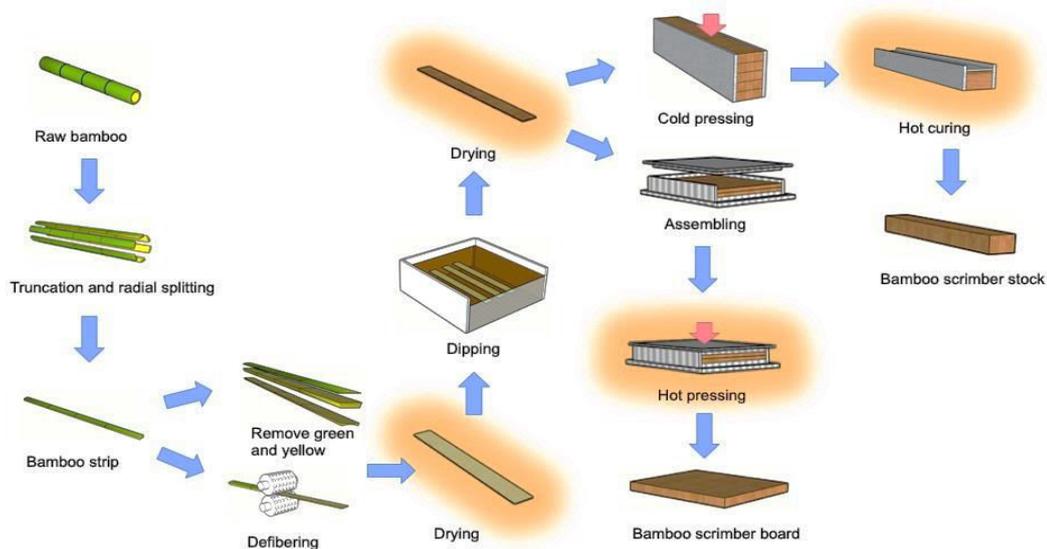


Figure 4: Process flow diagram of bamboo scrimber

#### 4.1 Bamboo Fiber preparation

The number of splitting pieces is regulated by the diameter of bamboo right after the bamboo is cut short, conferring to the dimension of the press. Bamboo culms 4–5 years old are commonly adopted for the productions of bamboo scrimber. The larger the diameter of bamboo, the additional the splitting pieces are, while the width of bamboo strips splitting from the bamboo with dissimilar diameters is unchanged. They are cut into segments as the length of segments can be as long as 1.4 m. Knots inside the bamboo segment can be detached by a long rod cutter [49].

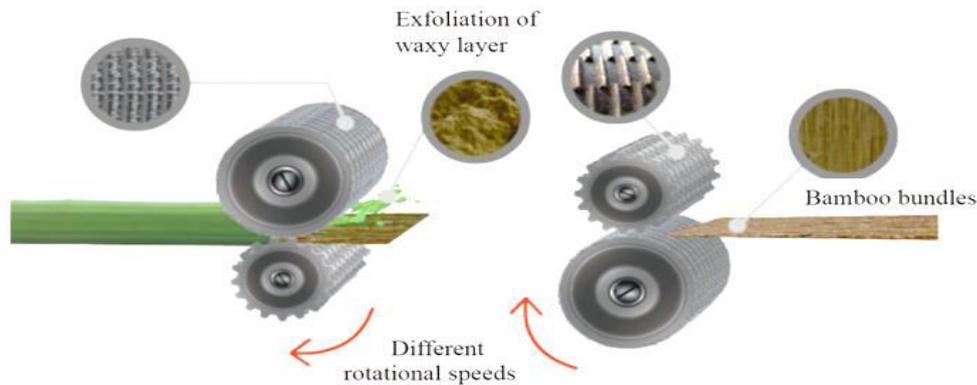
The bamboo intercellular layer could be detached with the lye treatment, which aided the defibering progression [50]. Though, excessive alkalinity considerably affects the physical and chemical properties of bamboo as well as the mechanical properties of bamboo scrimber. An improved softening effect could be gotten if bamboo was boiled in 3% with NaOH or Na<sub>2</sub>CO<sub>3</sub> solution. The use of chemical reagents amplified the cost and pollution; thus, the softening process was castoff in actual making.

The bamboo timber can be extra apportioned into three layers, and the outer layer where vascular bundles are dense is called bamboo green [51], [52]. This layer holds an evident amount of hydrophobic substances such as SiO<sub>2</sub>, fatty substances, and wax, which greatly affect glue abilities and wettability [53], [54]. Furthermore, the bamboo outer skin and inner skin have a pronounced effect on the mechanical properties and dimensional stability of bamboo scrimber [34]. Generally, the outer layer should be removed for the fabrication of bamboo scrimber as reported in the literature since its advancement in the 1990s [55]–[58]. Some machines, which are adopted for crack-free flattening, can be used for the removal of bamboo green from an approximate cylinder bamboo segment [59].

#### 4.2 Defibering

Defibering of bamboo is one of the necessary processes in the preparation of the bamboo unit to yield a high-quality bamboo scrimber. The early way of defibering was predominantly handmade, resulting in low effectiveness and required great labor concentration [60]. This process was removed due to the mechanical injuries causing bamboo whilst hammering, and a roll-in approach was embraced to organize bamboo bundles. It is harder to use the roll-in technique directly to attain ideal bamboo bundles, which makes it necessary to soften the bamboo before rolling. With the continuous technology development in equipment, it is no longer essential to soften the bamboo when making the bamboo scrimber. A multi-function machine will be a supplement for bamboo strip defibering [61], recently developed bamboo machines can combine the roles of defibering, removing bamboo knots, and bamboo green. The capacity of this machine is 800–900 kg/h, and the utilization rate increased from 60–65% to more than 75% [62]. With the progressively close collaboration between scientific research institutes and enterprises, the Wood Industry Institute of China, the Chinese Academy of Forestry jointly with the associated enterprises developed a novel fluffer machine (Figure 5)[7], [57]. The rollers of the novel machine were comprised of several special-shaped gears with intervals

between the teeth to make linear-shaped cracks, and the dynamic rollers arrange uniform convex pocks to generate dotted cracks on the bamboo [63]. The external skin and the internal skin were separated after the mechanical conduct.



**Figure 5:** Schematic diagram of the novel fluffer machine developed by the Chinese Academy of Forestry [7]

#### 4.3 Heat Treatment and resin Dipping

The moisture content (MC) of the bamboo after the defibering is exceeded at the fiber saturation point, and it only requires the bamboo bundles to be dried below 10% to create a chance for resins to sets in. Heat treatment of bamboo strips is highly recommended since employing high-temperature heat treatment can decrease the hygroscopicity of bamboo bundles to enhance their mildew-proof and anticorrosive possessions. Two available thermal treatments, namely saturated steam treatment (SST) and hot dry air treatment (HDAT), can be adopted for the bamboo bundles [34], [64], [65]. A typical heat treatment process is described [66]: bamboo bundles dried to less than 10% moisture content → packed into the carbonization furnace in layers → raised to 150 °C at a 10–20 °C/h heating rate → steam treatment starts, and then steaming treatment is continued to 170 °C for 0.5 h → steaming treatment raised to 180–210 °C for about 3 h → starting to cool down, using saturated steam atomization for 3 h to regulate the bamboo bundles → adjust water content to 4–6%, the temperature is lowered to 100 °C, and the kiln is closed for 0.5 h → open kiln and take out bamboo bundles when the temperature is below 90 °C. The heat treatment time can be increased or reduced appropriately to meet different strength and corrosion endurance requirements.

Another way to determine the bonding performance of bamboo scrimber is through the dipping process. Both the phenolic resin and the impregnation volume is controlled by the solid constituents of the resin. In real production, the impregnation is designed according to the requirements of bamboo scrimber's performance and usage. With regards to dipping treatment, bamboo bundles with a truncation of 300 mm are submerged in a phenolic resin and then dried at a low temperature until the water content was about 8% [67]. A dipping period of 20–25 min is appropriate. Extreme dipping time will make more water assimilated into bamboo, reduce the glue content in bamboo, and lead to the reduction in bonding strength [68]. A practical curing temperature of phenolic resin dipping should be around 135 °C, and it is challenging for the resin to solidify if the temperature is lesser than this value [68]. After the resin dipping is complete, the bamboo bundles should be dried. It is declared that the bamboo scrimber made from bamboo bundles processed at 180 °C hot dry air treatment merged with 18% PF resin loading exhibited suitable characteristics [34].

#### 4.4 Compression Curing

When drying the resin-impregnated bamboo bundles to 12–15% MC, they are directly shaped at extreme pressure of 70–80 MPa. Afterward, the mold is locked and sent to the curing channel for resin curing. The cold-pressing process is largely used for producing the square-edged bamboo scrimber with a thickness of 15–18 cm. The regularly adapted size for the square stock corresponds to 193 × 10.5 × 15.0 cm or 200 × 14.5 × 15.0 cm [69]. The conventional heat transmission technology by contacting is used to fabricate the slab at a certain temperature for hot-pressing. The unit pressure is 4–6 MPa, far lower than that used for the cold-pressing method.

Both technologies have merits and demerits. Cold-pressing and heat curing have comparatively great production efficiency and low energy consumption. Though, owing to the need for high pressure, bamboo bundles are simply crushed by machinery, resulting in lower mechanical characteristics. Furthermore, the density of bamboo scrimber using cold-pressing technology could reach 1.2 g/cm<sup>3</sup>. At such high density, there is a likelihood that the resin does not remain on the surface of the bamboo bundles, which results in starved joints and additionally reduces the binding potency [7]

While the hot-pressing technique has made up the shortage of cold-pressing to some extent, there are also two problems. On the one hand, the slab requires artificial paving, resulting in large hesitancy in the density of boards.

## V. POST-PROCESSING AND QUALITY INSPECTION

The compressed bamboo scrimber at this stage is cut into small pieces to pass through the maintaining process, which is very necessary for arriving at the desired outcome of the bamboo scrimber. Usually, the maintenance time for cold processing is about 4-5 days after cooling and demolding, while the hot pressing needs to be cooled to 55-60 °C after curing and then stored for 4-5 days after being taken out [70].

Before the product leaves the factory, series of quality tests are required to be performed (e.g., density, moisture content, formaldehyde emission, ground proximity decay, and anti-mildew). Excluding few specific standards (e.g., bamboo scrimber flooring standard), the standards associated with bamboo scrimber are frequently according to wood standards. The following outlines the China national standards that are typically referred to in regards to the fabrication and inspection of bamboo scrimber; Scheme for determination of the density of wood (GB/ T1933-2009); Scheme for determination of the moisture content of wood (GB/T1931-2009); Scheme for determination of the water absorption of wood (GB/T1934.1-2009); Scheme for determination of the swelling of wood (GB/ T1934.2-2009); Test approaches of evaluating the properties of wood-based panels and surface decorated wood-based panels (GB /T 176572013); Indoor decorating and redecorating materials limit of formaldehyde emission of wood-based panels and finishing products(GB 18580-2017); Durability of wood—Part 1: Scheme for laboratory test of natural decay resistance(GB /T13942. 12009); Durability of wood—Part 2: Scheme for field test of natural durability (GB/T 13942.2- 2009); Thermally-modified wood (GB/T 31747-2015); Field test technique for evaluation of wood preservatives by ground proximity decay (GB/T 29900-2013); Bamboo scrimber flooring (GB/T 30364-2013); Determination of phenol emission from wooden materials and their redecorated products— Small chamber method (GB/T 31762-2015); Test scheme for anti-mildew agents in controlling wood mold and stain fungi (GB/T 18261-2013) [49]

## VI. PERFORMANCE FEATURES OF BAMBOO SCRIMBER

Bamboo scrimber possesses the natural ligneous feeling of wood with xylem vessel-shaped fine grooves on the surface (Figure 6a). Some of the surface textures are straight strip-shaped (Figure 6b), some are mountain molded (Figure 6c), and some possess a small pattern of vortexes (Figure 6d), natural and fluent, rich in change. This scrimber material impression is similar to wood, warm, and smooth.



**Figure 6:**The surface of bamboo scrimber with different textures (a wood grain; b strip-shaped; c mountain-shaped; d pattern of vortexes) [7]

Manufacturers can apply the wood processing equipment and technology to process the bamboo scrimber because of its benefit of processing suitability. The structure of furniture prepared from bamboo scrimber could combine with the traditional furniture tenon, and the modern connection structure could also be actualized.

Many scientists have developed an interest in examining bamboo scrimber both for manufacturing technology and mechanical properties. He et al. [71] investigated the mechanical performance of bamboo scrimber prepared from Moso bamboo (*Phyllostachys pubescens*) treated with heat oil. NaresworoNugroho et al. [42], [43] selected zephyr strand from Moso bamboo (*Phyllostachys pubescens* Mazel) and made a structural composite board. Accelerated aging method



and aging resistance influence the performance of bamboo scrimber has also been examined [72]. Bamboo Scrimber’s mechanical and physical properties have been researched by Ahmad et al.[73]. The mechanical properties and physical properties of bamboo scrimber made from Asian bamboo (*Dendrocalamus asper* Backer) were also examined [74].

**Table 2:** Comparison of density and the mechanical properties of bamboo scrimber and other materials [75]

	$\rho$ kg/m <sup>3</sup>	$f_{ts}$ /MPa	$E_{ts}$ /MPa	$f_{th}$ /MPa	$E_{th}$ /MPa	$f_{cs}$ /MPa	$E_{cs}$ /MPa	$f_{ch}$ /MPa	$E_{ch}$ /MPa	$f_b$ /MPa	$E_b$ /GPa	$\tau_{ss}$ /MPa
BS <sup>a</sup>	1254	156.2	15649	3.88	4012	100.9	14160	52.8	4313	144.3	9.919	26.7
BS <sup>b</sup>	1163	120	-	3	-	86	-	37	-	119	13	15
LB <sup>c</sup>	686	90	-	2	-	77	-	22	-	77-83	11-13	16
GLG <sup>d</sup>	741	143.1	18345	3.2	-	62	32271	5.3	455	122.4	13.26	9.5
GB <sup>e</sup>	700	83	10344	-	-	42	-	-	-	99	9.407	16
RB <sup>f</sup>	666	153	-	-	-	53	-	-	-	135	9	16
LG <sup>g</sup>	555-625	91.7	11860	-	-	38.3	13070	5.3	1250	90	11.03	-
SS <sup>h</sup>	383	59	-	-	-	36	-	-	-	67	8	-
DFL <sup>j</sup>	520	49	-	-	-	57	-	-	-	68	13	-
LBR <sup>k</sup>										92.6	7999	
LBT <sup>l</sup>										101.1	9177	

Note: **a.**Bamboo Scrimber [75]; **b.** Bamboo scrimber [76]; **c.** Laminated bamboo [76]; **d.** Glued Laminated *Guaduaangustifolia*Kunth – tangential[77]; **e.** GluBam[15], [78]; **f.** Raw Bamboo *Phyllostachyspubescens*[79]; **g.** *Larixgmelini*[80]; **h.** Sitka spruce [34], [81]; **j.** Douglas-fir LVL [82], [83]; **k.** Laminated bamboo lumber under the radial bending direction (LBR) [80]; **l.** Laminated bamboo lumber under the tangential bending direction (LBT) [80];  $f_{ts}$  and  $E_{ts}$  are the strength and elastic modulus for the specimens under tensile parallel to grain respectively;  $f_{th}$  and  $E_{th}$  are the strength, and elastic modulus for the specimens under tensile perpendicular to grain;  $f_{cs}$  and  $E_{cs}$  are the strength and elastic modulus for the specimens under compression parallel to grain respectively;  $f_{ch}$ , and  $E_{ch}$  are the strength and elastic modulus for the specimens under compression perpendicular to the grain.  $f_b$  and  $E_b$  are the strength and elastic modulus for the test specimens under bending;  $\tau_{ss}$  is the shear strength for the test specimens.

(Table 2) shows the test outcomes for all bamboo scrimber specimens and results for materials

obtained from other literature. As can be seen from Table 2,  $f_{th}$  and  $E_{th}$  have the largest discreteness amid the values for the strength and elastic modulus for bamboo scrimber. With the exception of  $E_b$ , all other test values are for bamboo scrimber [76] produced centered on the new method are greater than the test values for bamboo scrimber produced by the conventional method

The elastic modulus for the bamboo scrimber specimens under tensile parallel to the grain is shown to be larger than that for GB and LG, however smaller than that for GLG. The elastic modulus for the bamboo scrimber under compression parallel to the grain is likewise smaller than that for GLG but larger than that for LG. Excluding the two elastic modulus values stated above, all other values for bamboo scrimber specimens are bigger than the related values for other materials listed in (Table 2). This means that the bamboo scrimber material produced based on the new method stated above has very good mechanical properties and could be utilized in the construction area [75].

Furthermore, certain specific researches have been conducted with regards to the mechanical performance of bamboo scrimber being tested under tensile and compressive performance during heating temperatures ranging from 20 to 270 ° C. The outcome from (Figure 7) shows that tensile stress-strain relationships of a bamboo scrimber parallel to grain at higher temperatures were linear from the start of loading to failure, and the tensile strength and modulus reduced with rising temperature from 20 to 270 ° C, except at 200 ° C, whereas in the perpendicular to grain direction,

the tensile stress-strain relations exhibited nonlinear performance, and the ultimate strengths were tiny. Consequently, it was witnessed that the modulus decreased to zero from 20 to 180 °C [84].

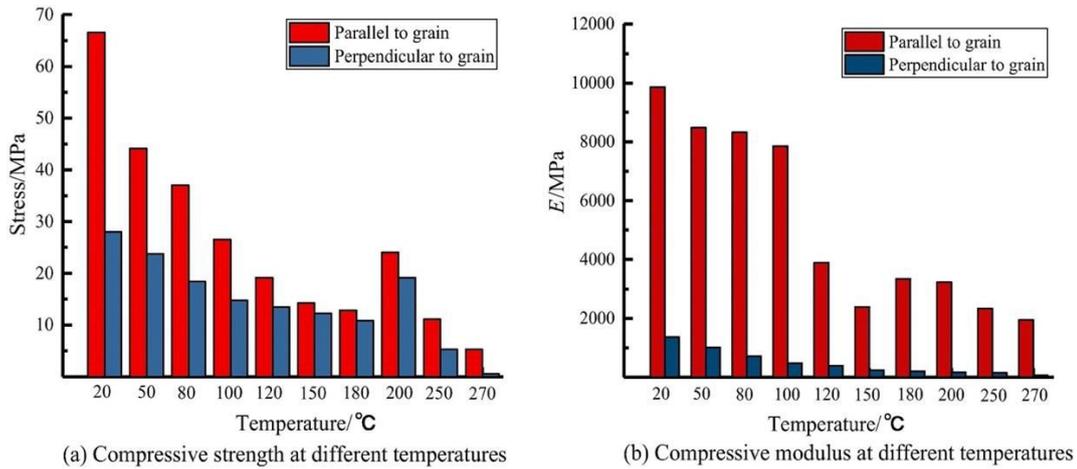


Figure 7: Tensile strength and modulus at different temperatures, a tensile strength; b tensile modulus [84]

Li et al. [75] Compared two series of the test under compression, both parallel to grain and perpendicular to the grain, as shown in (Figure 8). Plots for strain-stress curves for the tests were analyzed where each specimen experienced elastic and elastic-plastic stages. According to the final state for the specimens under compression parallel to the grain, four typical failure modes could be classified as shown in (Figure 9).

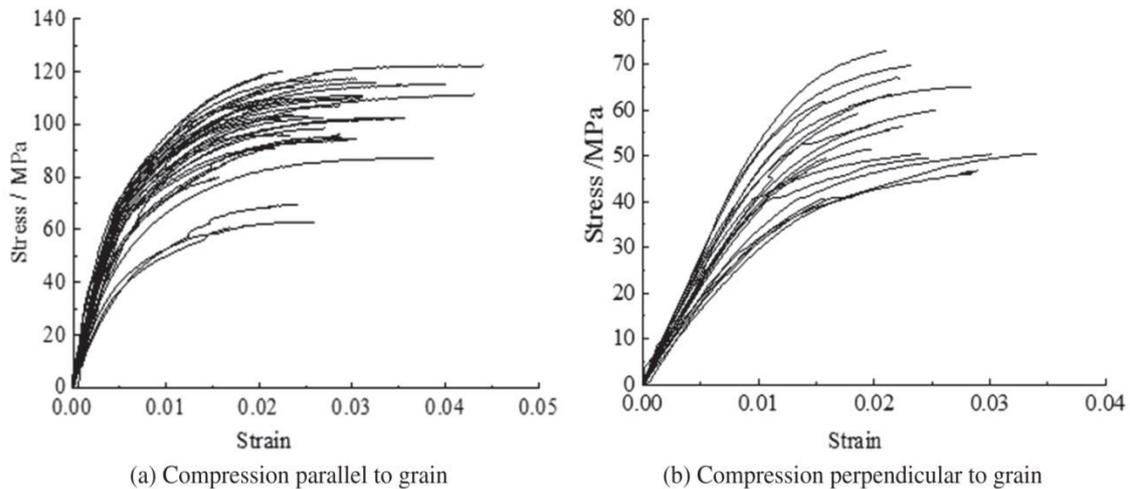


Figure 8: Stress and strain curves for compression specimen [75]



Figure 9: Typical failure modes for axial compression specimens[75]

Shangguan et al. [85] tested the compressive strength of bamboo scrimber at different grain angle directions. They proposed a new approach to describe the failure stresses of bamboo scrimber with a 2D model, as shown in (Figure 10), which comparatively have much less error between projected values and measured ones. Shangguan et al. [86] also established that the average critical strength and proportional limit strength decreased from 133.4 to 25.7 MPa and 113.9 to 14.9 MPa from 0 to 90°, which signified that the maximum stress concept could forecast compressive strength. Xu et al. [84] asserted that compressive stress-strain curves of bamboo scrimber subjected to higher temperatures were divided into a linear branch and a nonlinear branch beyond the proportional limit for both grain directions.

A new type of bamboo scrimber beam strengthened by fiber-reinforced polymer composite sheets embedded in the internal tensile region was presented by Wei et al. [40], which examined the flexural performance of the bamboo scrimber beams with a four-point bending test. The outcomes indicated that the flexural load-carrying ability and the flexural rigidity of the strengthened beam increased. Chang et al. [87] determined that the influence of distinctive aging treatments on the bending functioning of carbonized bamboo scrimber is non-negligible. The average reduction rates on the MOE and modulus of rupture (MOR) of the samples after aging were correspondingly 47.48 and 34.98%.

Zhong et al. [38] devised a reinforced bamboo scrimber composite beam merging the bamboo-section and the reinforcement part and discovered the failure modes, ultimate load, and cross-section stiffness of the beams were drastically correlated to the diameter of reinforcement as well as the heat treatment of bamboo bundle. Bamboo scrimber with holes in different sizes at dissimilar positions were surveyed by Zhao et al. [88]. The results showed that drilling holes caused a reduction in the bending properties, and the larger size of drilling holes triggers the lower bending properties. The positions for drilling holes produce the change of the stress distribution and then reduces the bending properties.

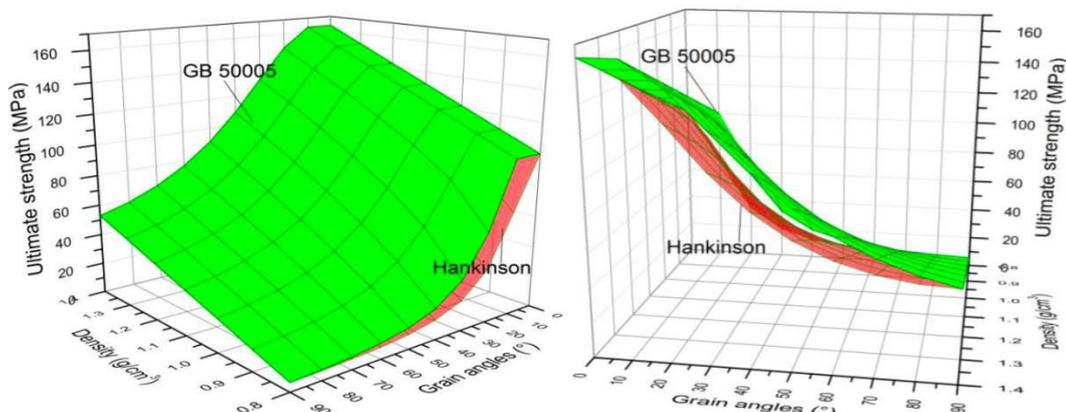
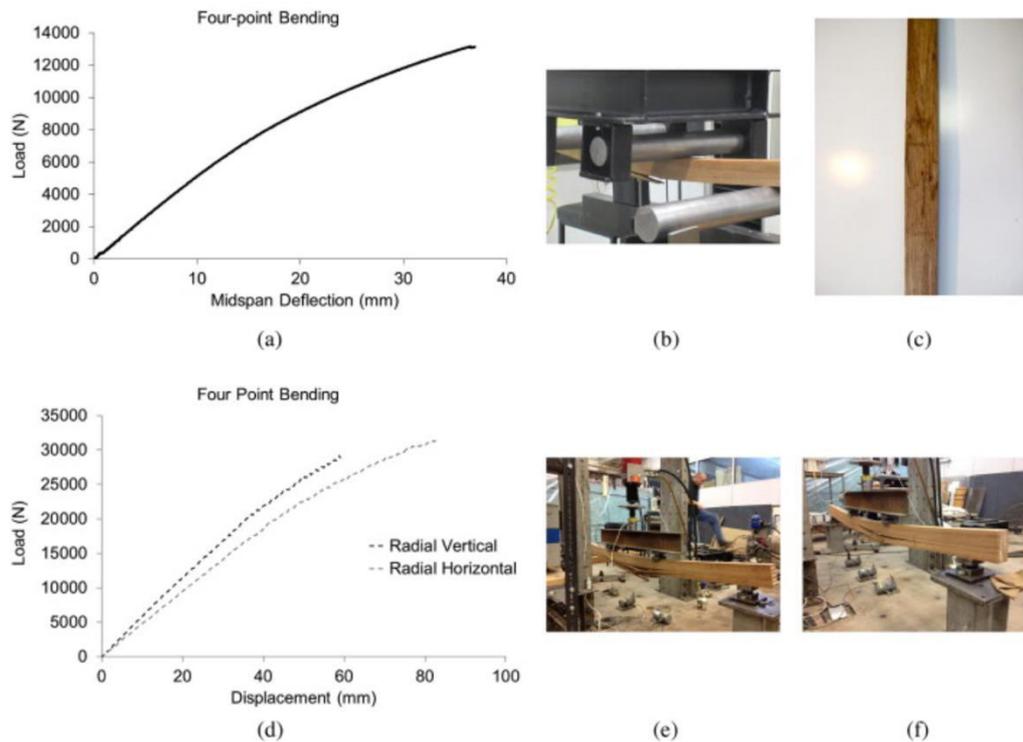


Figure 10: 2D models of ultimate strength for various grain angles and different densities Figure [85]

**6.1 Bending**

Bending outcomes for the bamboo scrimber shown in (Figure 11a) implies that a large displacement was attained in the specimen before failure, which occurred at the tension faces of the specimens at the mid-span. Likewise, the laminated bamboo failures happened near mid-span, while these were characterized as longitudinal shear failures (i.e., VQ/I failures) within the depth of the beam for both the edgewise and flatwise oriented specimens (Figure 11b). The contrast of the two orientations signifies that while reaching similar maximum loads, the flatwise orientation had an amplified modulus of elasticity with a gain of approximately 18% over the edgewise orientation [76].



**Figure 11:**Four-point bending (a) results and (b) specimen failure for bamboo scrimber. Laminated bamboo (c) results and specimen failures for (d) radial horizontal and (e) radial vertical orientations [76]

**VII. FACTORS AFFECTING THE PERFORMANCE OF BAMBOO SCRIMBER**

**7.1 Bamboo species and Bamboo internode**

The differences in bamboo properties considerably affect its mechanical or chemical processing measures and the functioning of the end products [89]. There is a record of 75 genera with 1250 bamboo species around the world, coupled with other anatomical structures and mechanical differences from species [90]. Currently, 75 genera with 1250 bamboo species are demographically placed around the world, and bamboo properties involving anatomical structure and physical-mechanical properties are considerably different from species. Xie et al. [91] produced bamboo scrimber from five bamboo species and discovered that the slighter fiber lumen diameter of bamboo aided to lower water absorption of bamboo scrimber, and thicker fiber wall aided to lower MOR.

Qi et al. [92] discovered that bamboo fiber mats with nodes had bigger horizontal shear strength, whilst fiber mats without nodes had greater tensile strength.

**7.2 Defibering times**

Bamboo might be separated into some basic tissues containing vascular bundles, ducts, and fibers. With intensifying the defibering times, more dotted and linear-shaped cracks are formed in the culm wall and the diameters of bamboo bundles decline. This surges the specific surface area of bamboo bundles, which makes it more effective for adhesives to penetrate and enhance the bonding capacity. Improved compression strength is observed from bamboo scrimber developed from the bamboo bundles defibered seven times (type 1). Likewise, dimensional stability and

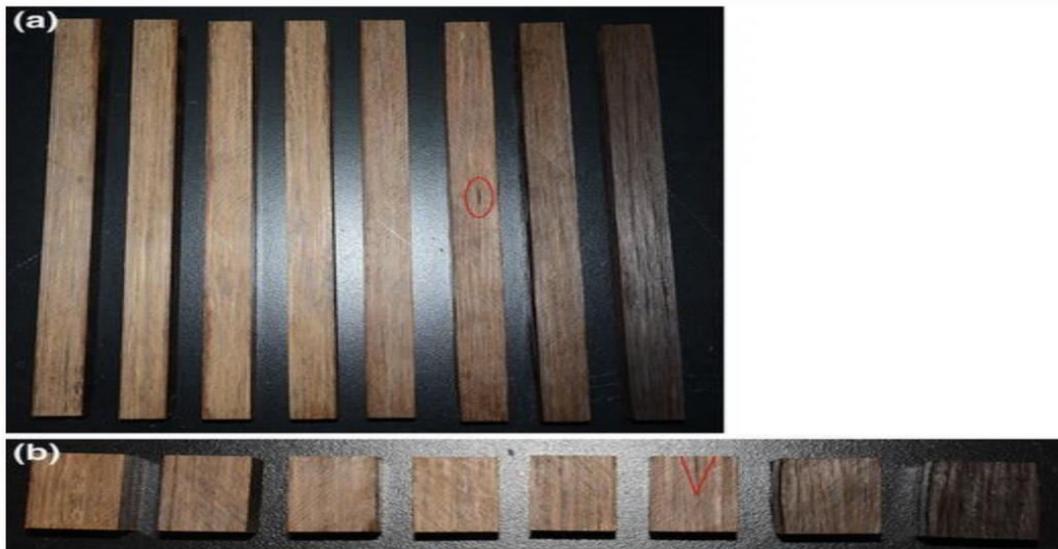


Young’s modulus improved, compared with that from the bundles defibered for five times (type 2) [46]. However, type 1 displays lower tensile strength since the surge in the defibering process leads to the further broking of bamboo fibers. The study by Nugroho and Ando [42] used diverse numbers of bamboo clumps that passed through the rollers to get different sizes of bamboo zephyr strands. The outcomes presented that bamboo scrimber had higher mechanical properties in the case of smaller strands. This was as a result of the smaller strands had more bundle sheaths per area than the bigger ones. Test results provided by Deng et al. [54] indicated that the color disparity of bamboo could exemplify defibering level.

**7.3 Heat Treatment, Moisture absorption and color changes**

A drying process is essential to control the MC of bamboo fiber mats following defibering. The results delivered by Jeang-Kwan and Jong-Bum presented that the mechanical properties decreased with increasing the MC of bamboo fiber mats [93]. When the moisture content was beyond 12%, MOR, MOE, and internal bond effectiveness decreased significantly.

Color variations of bamboo scrimber after heat treatment are shown in (Figure 12) and (Table 3). The original light color of samples revolved to be dark brown after heat treatment as wood [94], especially at temperatures of 200 and 230 °C. *L\** represents lightness stability [95], reduced significantly above 170 °C, demonstrating a tendency of bamboo scrimber surface to become darker. Increased and decreased values display a tendency of surface to become reddish and greenish for *a\** and yellowish and bluish for *b\**[95]. Surfaces of bamboo scrimber revolved to be greenish and bluish after heat treatment at 230 °C. The frequency of color change stood below 170 °C compared to that above 170 °C. The different temperatures due to change of color may be because of deprivation of lignin, a Gramineae lignin constituted of hybrid dehydrogenation polymer of coniferyl, sinapyl and *p*-coumaryl alcohols [96], on which chromophoric groups are found. Lignin is comparatively stable at room temperature but is easily oxidized with forming chromophoric groups at high temperatures [97], [98]. The  $\beta$ -O-4 linkages, main linkage kinds in lignin, are splitted significantly during steam eruption treatment (210 °C) [96], forming a free hydroxyl group. In the incidence of the auxochrome group (hydroxy, carboxyl, and ether bond), the color of bamboo scrimber grew dark [99]. The blue shift of methoxy (lignin) is an additional reason for the color change of bamboo. The peak of methoxy shifts to higher wavenumbers as temperature surges and wavelength comes down [100]. Visibility shows that the lesser the wavelength, the darker the color appears. Cracks shows on the exterior of both compression and bending testers once the temperature got to 170 °C. This may be a result of the curing of adhesive that caused stress concentration on sample surfaces.



**Figure 12:** Discoloration of the control and heat-treated bamboo scrimber samples. From left to right are the control samples and samples exposed to 50, 80, 110, 140, 170, 200, and 230 °C for 2 h. a Bending sample. b Compression samples [60].

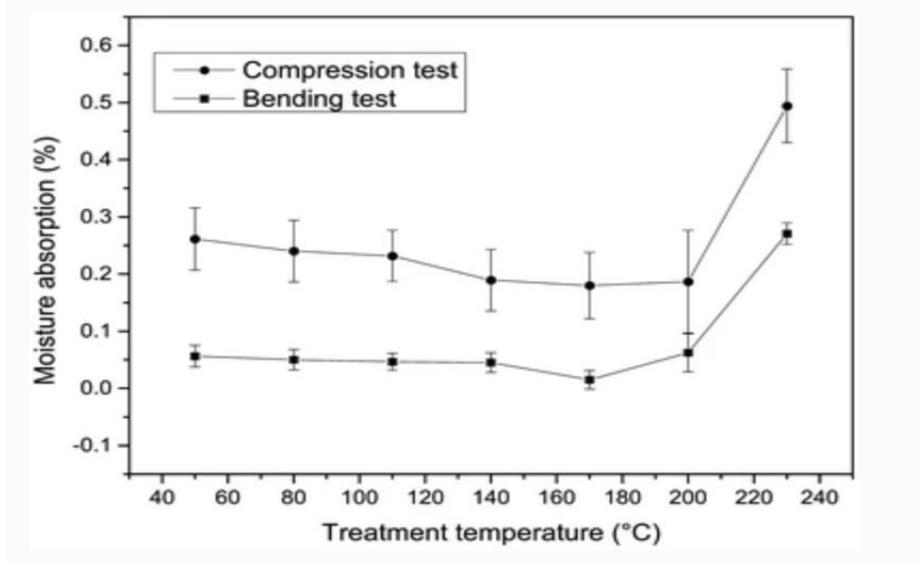


**Table 3:**Color changes of bamboo scrimber samples after heat treatment [60]

Temperature (°C)	L*	a*	b*
20	39.04 (0.45)	9.96 (0.21)	23.71 (1.04)
50	37.14 (0.65)	9.59 (0.49)	24.87 (0.74)
80	38.24 (0.49)	10.15 (0.32)	23.84 (0.50)
110	37.25 (0.083)	8.55 (0.091)	24.43 (0.14)
140	37.05 (0.41)	9.37 (0.31)	25.14 (0.34)
170	34.18 (0.19)	10.32 (0.49)	27.83 (0.52)
200	26.76 (0.64)	10.15 (1.54)	24.75 (1.42)
230	14.21 (0.27)	-0.54 (0.81)	20.57 (1.14)

(Values in parentheses denote standard deviation)

The moisture absorption dropped slightly when the temperature was below 170 °C and enlarged when the temperature exceeded 170 °C, as shown in (Figure 13). The contact angle of oil heat-treated bamboo (180 °C) increased after oil extraction, as are results of changes to the chemical components of bamboo [101]. At low temperatures, increased crystallinity [102], loss of hemicelluloses or fragile pentoses and hexoses, reduction of OH bonds, structural modifications, and chemical variations of hemicelluloses [94] can lead to dimensional stabilization and decrease hygroscopicity and swelling of bamboo. At 230 °C, moisture absorption increased maybe since the crystal structure of cellulose, where water is not easy to enter, was damaged [102]. Crystallinity reduces at the later stages of heat treatment due to depolymerization and degradation in both crystalline and non-crystalline regions [102]. And water entered the amorphous area, rising moisture absorption. Reduced density and obliteration of chemical structure may also show the details for increasing moisture absorption at tremendous temperatures. Moisture absorption of the compression sample was larger than that of the bending sample, probably since the specific surface area of the compression sample was larger than the bending sample.



**Figure 13:**Influence of temperature on moisture absorption [60]

#### 7.4 Dye treatment and Adhesives

The aim of broadening the usability of bamboo scrimber in the exterior environment has aroused the recognition and application of different colors through proper dyeing skills to the natural and carbonized color. In a study by Hu and Yu [103], bamboo fiber mats were treated with acid black. It was discovered that the dyeing procedure slightly reduced the MOR and MOE of bamboo scrimber but enhanced the water resistance. A comparable variation trend for mechanical properties and water resistance was revealed when Basic Brown G dye was utilized [104].

Nugroho and Ando [42] stated the outcomes for the thickness swelling of bamboo scrimber using diphenylmethane diisocyanate (MDI) resin. The TS values of bamboo scrimber enlarged with the increase in board density, which could be accredited to the greater spring-back of the condensed elements in boards of high density. Conflicting to Nugroho and Ando, Xie et al. [91] found that both the width and thickness swelling showed a decline with the fabricated density when phenolic resins were utilized. The alteration may originate from the different molecular weights of adhesives, which regulate the permeability of adhesives in bamboo.

As shown in (Table 4), a significant decline of thickness swelling (43.0%) and width swelling (53.8%) of Bamboo scrimber were studied as the resin dosage increased from 7 to 11% [105]. While the minimum thickness swelling was noticed at the resin dosage of 13%, no substantial change in thickness swelling was discovered between the resin dosage of 11 and 13%. The least width swelling (1.8%) was gotten at a resin dosage of 11%. The composite glued by phenol-formaldehyde (PF) resin has high water resistance because of the contacts between polar hydroxyl groups of PF and the hydrophilic fibers, as established by Yu et al. [106]. Additionally, the water pathway could be somewhat jammed by the cured PF resin as high pressure is applied during the fabrication.

**Table 4:** Physical-mechanical properties of bamboo scrimber concerning resin dosage [105]

RD/%	TS/%	WS/%	CS/MPa	HSS/MPa	MOR/MPa	MOE/GPa
7	21.9±1.0 <sup>a</sup>	3.8±0.4 <sup>a</sup>	82.4±3.0 <sup>a</sup>	10.0±3.0 <sup>a</sup>	193.3±48.5 <sup>a</sup>	23.8±2.6 <sup>a</sup>
9	13.6±1.0 <sup>b</sup>	2.4±0.3 <sup>b</sup>	94.6±8.5 <sup>a</sup>	13.0±2.5 <sup>ab</sup>	166.1±5.8 <sup>a</sup>	18.4±0.6 <sup>b</sup>
11	12.2±1.3 <sup>bc</sup>	1.8±0.14 <sup>c</sup>	100.0±4.1 <sup>b</sup>	16.2±0.4 <sup>b</sup>	187.2±10.5 <sup>a</sup>	23.4±1.9 <sup>a</sup>
13	10.7±1.4 <sup>c</sup>	2.1±0.1 <sup>bc</sup>	93.0±2.1 <sup>a</sup>	15.0±0.7 <sup>b</sup>	193.3±8.8 <sup>a</sup>	24.0±0.5 <sup>a</sup>
15	11.2±1.7 <sup>bc</sup>	2.2±0.2 <sup>bc</sup>	90.4±1.2 <sup>a</sup>	12.3±2.6 <sup>ab</sup>	188.0±15.0 <sup>a</sup>	22.0±2.6 <sup>ab</sup>

RD, TS, WS, CS, HSS, MOR and MOE and MOE are resin dosage, thickness swelling, width swelling, compressive strength, horizontal shear strength, modulus of rupture, and modulus of elasticity respectively. Values with the same letter in the same row are not significantly different  $p < 0.05$

Table 4 exemplifies that the MOR and MOE of bamboo scrimber presented fluctuating trends with growing resin dosage, ranging from 166.1 to 193.3 MPa and 18.4 to 24.0 GPa, respectively. The minimum MOR and MOE were detected at a resin dosage of 9%, while the maximum ones were uncovered in those with a resin dosage of 13%. According to the ANOVA analysis, there were no substantial differences in the MOR and MOE among resin dosages of 11 and 13%. At large, as a reinforcing phase, the fiber bundles make a major contribution to the bending performance of the composite, as stated by Meng et al. [107]. Hence, the MOR and MOE would not be remarkably influenced by the resin dosage. Expansively, the resin dosage of 11% was optimized to fabricate bamboo scrimber with different maturing bamboo culms.

#### 7.5 Fire retardant

As the construction materials, the flame retardancy of bamboo scrimber is very significant. According to research, there are presently two main approaches for refining the flame retardancy of bamboo scrimber, one is carbonization treatment, and the other is adding flame retardant material [49].

Carbonization treatment could reduce heat release rate (HRR) and mass-loss rate, decline total heat release, rise oxygen index, and interruption time to ignition (TTI). The peak of HRR was reduced by 36.6%, the time of reaching

peak HRR was delayed by 450 s, and TTI was boosted by five times [108]. The addition of fire retardants can be managed before resin dipping or after resin dipping. The utilization of flame retardant before gluing can advance the physical and mechanical properties of bamboo, but it will give rise to the amount of PF and extend the drying time and hot-pressing time.

The application of bamboo scrimber in building and decoration fields leaves thoughts for the chance of fire accident occurrence, which increases because bamboo material belongs to combustible material. The results from Fu et al. [7], adding Nanoparticles ( $\text{CaCO}_3$ ,  $\text{CaO}$ ,  $\text{MgCO}_3$ , and  $\text{MgO}$ ) with a diameter of 5–50nm, advanced the flame retardancy of bamboo-wood hybrid scrimber, agreed with the study reported by Du et al. [109] in which applying  $(\text{NH}_4)_2\text{HPO}_4$  fire retardant before gluing would upsurge part of the physical and mechanical properties of bamboo scrimber. Conversely, it would raise the manufacturing cost.

### 7.6 Method of mat formation

The production of mats at the process of bamboo scrimber by hot-pressing is usually shaped manually. This process consequently gives low efficiency and also results in the abrupt unevenness of the density profile for bamboo scrimber. According to a study by He et al. [110], bamboo bundles were knitted to consecutive bamboo bundle veneer, which was afterward laminated and hot-pressed along the grain to manufacture knitted bamboo scrimber. The outcome exposed that the bamboo bundle knitting process could regress the thickness swelling and improve shear strength due to a more uniform structure and even density profile over the cross-section.

### 7.7 hot-pressing parameters and density

The test results provided by Kim et al. [111] specified that the internal bond strength of bamboo scrimber was vastly amplified with increasing temperature. Bamboo scrimber hot-pressed by 160 °C for 12 min and 180 °C for 10 min showed relatively higher wet-bending strength [112].

Referred by Kumar et al. [113], all the mechanical features of bamboo scrimber significantly differ in regards to the density of bamboo scrimber and likewise the fiber direction. A positive linear association was discovered concerning density and MOR (or MOE) regardless of measurements done parallel or perpendicular to the fiber path of the bamboo scrimber [114]. As the density enlarged from 1.02 to 1.3  $\text{g/cm}^3$ , the MOR of bamboo scrimber almost enlarged by 50%, from 271 to 398 MPa, and the MOE increased from 26.4 to 32.3 GPa [48]. The water absorption declined from 43.0 to 5.01% as the density increased from 0.8 to 1.2  $\text{g/cm}^3$  [91], which could be credited to the close orientation of bamboo lumens.

Furthermore, the rise of density had positive impacts on color and dimensional steadiness. In regards to service-performance and as well as cost-minimization considerations, 1.1  $\text{g/cm}^3$  was taken as the most appropriate density for general applications [115].

## VIII. ANTI-FUNGI ABILITY AND ANTI-MILDEW TREATMENT

Fungi resistance of bamboo scrimber against white-rot and brown degradation was evaluated, results showed that both brown-rot and white-rot infections are limited to the surface of the bamboo scrimber, and penetration into the interior is blocked [116], which signifies that bamboo scrimber has high resistance against bio-deterioration by white and brown-rot fungi.

Anti-mildew treatment for bamboo scrimber is critical for its efficiency and utilization, particularly for those used in an outdoor environment. This is because bamboo fiber contained in bamboo scrimber easily attracts mildew and causes failure. Physical and chemical modification approaches have been employed [62], [117], [118] to deal with this defect. A kind of the simple dip-coated Si–Al solution process which aids in avoiding the problems of complex craft, wastewater treatment, and draining of anti-mildew agents was proposed by Wu et al. [119], as shown in (Figure 14). The procedure is elaborated as follows,  $\text{Al}_2(\text{SO}_4)_3$  solution (2% w/w) was slowly added, dropwise, into the flask containing diluted sodium silicate solution (10% w/w) with vigorous stirring in a 50 °C water bath. After mixing,  $\text{H}_2\text{SO}_4$  was added to adjust the pH value between 10 and 11. The solution was uniformly stirred for another 2 h to prepare the Si–Al sol.

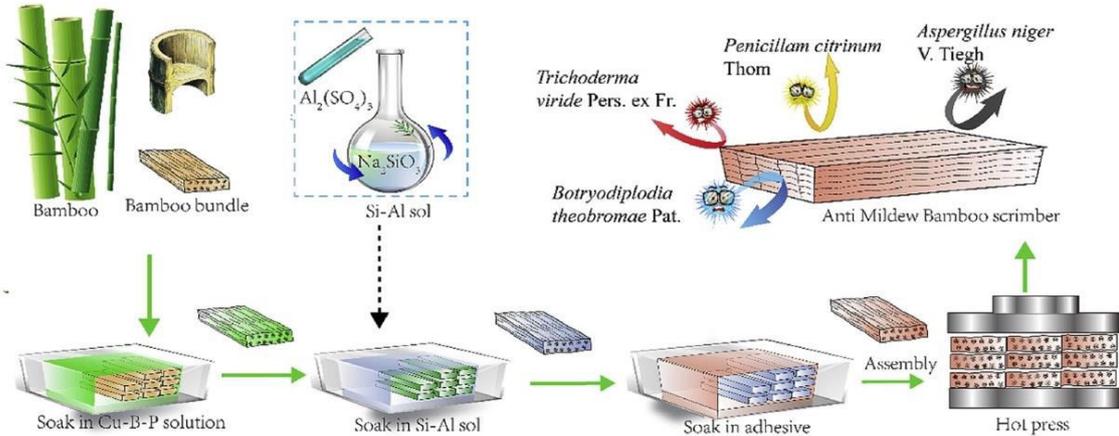


Figure 14: Preparation process of mildew resistant bamboo scrimber [119]

### IX. POST-TREATMENT OF PRODUCTS

An examination of the consequence of post-treatments was done by Li et al. [120]. The after-effects showed that the bamboo scrimber became darker after all treatment situations, specifically the oil treatment and infrared drying. The dimensional stability was relatively disturbed by the treatment conditions except for oil treatment. Zhu et al. [121] did a test on bamboo scrimber subjected to outdoor exposure for two years. The outcome projected the surface color values had a decreasing tendency, and a gradual decline was observed in MOR, MOE, as well as shear strength of bamboo scrimber.

### X. APPLICATIONS OF BAMBOO SCRIMBER

Prior to the current diverse utilization of bamboo scrimber, its target product market was primarily located on the indoor floor due to its natural and elegant texture of over 1.2 g/cm<sup>3</sup> density. Consequently, the consumer market is developing rapidly. Bamboo scrimber can achieve a texture and color similar to mahogany, which is a potential material for imitating mahogany, as shown in (Figure 15).

With the supplementary understanding of the performance of bamboo scrimber, its solicitation possibility has gradually extended to furniture manufacturing (Figure 16a), decoration (Figure 16b), and outdoor (Figure 16c). [7]. Aside from the floor and furniture applications, it has also been used as a structural material such as a wind turbine (Figure 16d). Wei et al. [122] built a residential house with bamboo in 2009 for the first time showing the possibility of its utilization.

Combining bamboo scrimber with other materials like steel [123] and carbon fiber reinforced plastic has also been adopted in many regards to boosting the strength and efficiency of products and artifacts [49], [124].



Figure 15: Application of bamboo scrimber to furniture [125].



**Figure 16:**The application of bamboo scrimber. a Doors and windows, b interior decoration, c outdoor materials, d wind turbine blade [7]

## XI. CONCLUSION

Increasing knowledge and discoveries of bamboo scrimber through research can be found in recent years (particularly in China) and has attracted many researchers in the international scope. Bamboo fiber-based composite created from crushed bamboo fiber, characterized as bamboo scrimber, has gained specific thoughtfulness from researchers and manufacturers on account of its outstanding mechanical features and design. The bamboo scrimber equipped with heat treatment and phenolic resin has certain outdoor resistance to mold and decay. Consequently, bamboo scrimber could be considered for outdoor use such as outdoor flooring, trestle, and pavilion to give full play to its merits of high strength and high abrasion resistance. This could advance the added value of bamboo scrimber products and relieve the concern about the shortage of building structural resources.

Currently, there is still a lot of vacuum for development in the production technology and equipment, such as the irregular mat formation in terms of hot-pressing and automation of the equipment used for cold-pressing. Also, many enterprises are inadequately managed and coordinated, manufacturing solely based on experience; hence the lack of precise and standardized process control ends in unstable and variable products, official codes and principles have not yet been developed. At this present time, more than 80% of enterprises in China are still using bamboo strips as the elementary material component, and an extra process is needed to eliminate the outer skin and inner skin of bamboo strips.

The poor procedure to remove the outer skin of bamboo strips can be resolved by the defibering method deliberated in this paper for the production of bamboo scrimber. An upgrade of the degree of mechanical automation of the cold-pressing and hot-pressing production line of bamboo scrimber is required. Likewise, developing automatic paving equipment for hot-pressing would also be necessary to improve labor productivity. Formulation of operation methods and technical rules and testing for product quality as well as strengthening the demonstration work of on-the-spot management would help the production line to make headway. Exertions of researchers and practitioners are seen in their work on this topic, and progress is ongoing to standardize codes.

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