A Review on Processing Techniques and Building Methods of Engineered Bamboo

Francis Cayanan, John Robert D. Gabriel, Carlito H. Pantalunan, Orlean G. Dela Cruz, and Irene R. Roque

Abstract The unstoppable growth of civilization and the unending process of the Industrial Revolution led people to search for high-strength materials that are strong enough to build skyscraper infrastructures and different venues, leaving the traditional Bamboo behind the innovations. Moving faster towards a more futuristic environment, we feel the negative impacts of harmful chemicals, non-eco-friendly materials, and pollution-emitting activities worldwide. That is why, Engineers, Architects, Builders, Scientists, and Researchers revisit the materials and methods that will lessen the greenhouse gas and carbon emissions we produce. Bamboo has several advantages and provides both strength and aesthetic value. Even though it was evident that there is still a long way to the perfection of Engineered Bamboo (EB) application in many construction fields, especially in structural engineering, the tireless effort being exerted by the researchers interested in its development is considered contributing and substantial. This paper will describe and summarize the current and related information on using engineered Bamboo as a construction material.

Keywords Engineered bamboo · Bamboo · Structural bamboo · Building method

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1 Introduction

The majority of modern construction materials require a lot of energy and environmental harm to make. They must be mined, processed, heated, or given various chemical treatments [1]. Greater than one-fourth of primary resource extraction, around 20% of CO_2 emissions, and 35% or so of the world's electrical use are all related to manufacturing. Reducing the materials used in construction (or using reasonably priced low-carbon substitutes) could lower building costs and reduce emissions during manufacturing [2]. Although timber is a low-cost building material, deforestation and rising urbanization have exhausted tropical resources. Timber forests need 30 to 50 years, with European oak requiring up to 80 years [3]. The projection is that oil, bauxite, iron, and copper will become scarce within this century, and soon after, there will be a shortage of tropical hardwood [4]. Due to rapid urbanization's growing demand for sustainable building materials, Bamboo has gained more attention and has been developed for use in modern construction [3].

Bamboo's mechanical strength, usability attributes, and anatomical features stabilize and develop in 3–5 years, making it appropriate for various uses [5]. According to test results, Bamboo may replace wood in structural applications from a load-carrying perspective because its strength and stiffness are comparable [6]. However, despite having natural qualities relatively similar to wood, Bamboo's original geometrical shape makes it challenging to use in modern construction [7]. Additionally, because Bamboo has an irregular cross-section and is not perfectly straight, it has problems with squeaky joints and thermal bridges [6]. Reduced variability of the natural material is the goal of Engineered Bamboo (EB) [8]. It represents bamboo products processed primarily to create a uniform, straight-edged building components from rounded, asymmetrical culms. It is a terminology that refers to a wide variety of reconstituted composite products made by cutting the complete element into smaller pieces, known as furnishing, and then fusing them together to make composite panels or shaped lumber stock using modern adhesives used in the wood industry [9]. Engineered bamboo products have the advantage of allowing for the creation of standard sections for members and connections and the reduction of variability within a single member [8].

Analysts anticipate that the bamboo market will increase between 2022 and 2030, at a Compound Annual Growth Rate (CAGR) of 4.5% after being valued at USD 59.30 billion in 2021, as stated by Grand View Research. This paper investigates the literature published regarding the improvements of EB as a building material through its manufacturing processes and construction methods. Furthermore, related applications, challenges to standardization, and future studies recommendations are to be discussed.

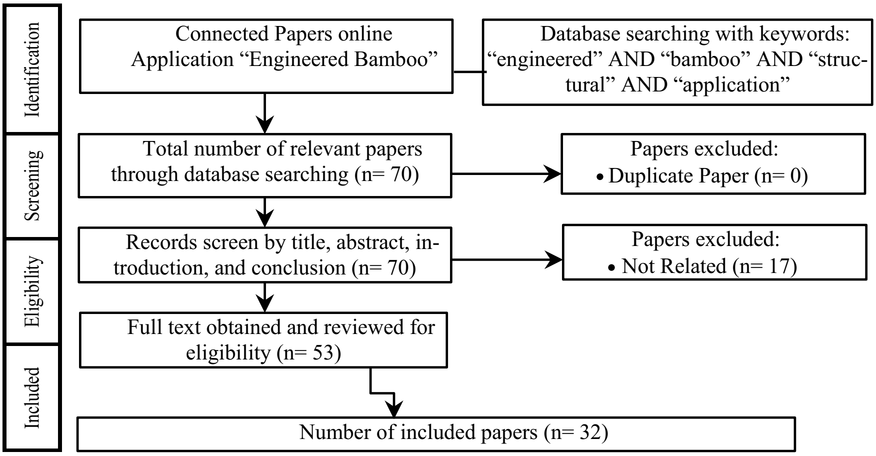

Fig. 1 Systematic method for selecting relevant literature

2 Methodology

The keywords used to find an article or journal are engineered, Bamboo, structural, and application. To determine the full potential of Bamboo as an innovative construction material.

The researcher uses the online application "Connected Papers" to answer the above-stated research questions. First, after reading the abstract to filter the papers directly connected to the topic, documents were searched using different online sources. Secondly, Fig. 1 shows the Systematic related literature selection process. Lastly, Fig. 2 shows the Topic Modelling of all related literature using Orange Data Mining Software, which shows the most used words from all the documents.

3 Discussion

3.1 Bamboo Physical and Mechanical Properties

Bamboo has different mechanical properties in the transverse, longitudinal, and radial directions because it is an anisotropic material. A large grass with hollowed culms and horizontal fibers oriented within lignin arrays split by solid diaphragms (nodes) makes up the raw material for bamboo. The bamboo fibers, vary within the wall of the culm, becoming less dense as they advance within, and the thickness, likewise, decreases from the bottom to the top [10]. Depending on its age, bamboo can be utilized for a variety of purposes, including: (a) eating (less than thirty days), (b) It takes six to nine months, to make a basket, (c) Making bamboo boards or laminations

Fig. 2 Topic modelling from selected related kinds of literature

Table 1 Properties of bamboo, wood, concrete, and steel

Property	Bamboo [12]	Wood [13]	Concrete	Steel
Density (kg/m^3)	620	–	2240–2400	7800–8000
Compressive strength (MPa)	51–56	43	20–40	≈172
Tensile strength (MPa)	150–264	89	2–5	350–420
Young's modulus (GPa)	11.219–	11	14–41	200
Poisson's ratio	–	–	0.20–0.21	0.25

takes two to three years, (d) Three to five years, for Construction use, (e) Bamboo rapidly loses strength from 6 to 12 years old (if not harvested). It's interesting that it can compete with steel in terms of tensile strength while outperforming wood, brick, and concrete in terms of compressive strength [11]. Some of the mechanical and physical features of bamboo, wood (spruce), steel, and concrete are included in Table 1.

3.2 Structural Grade Bamboo Species

Although there are more than 1200 species of Bamboo around the globe, the variety in geometric and mechanical qualities restricts the use of complete culm bamboo construction [10]. Table 2 shows the bamboo species with Structural Grade under the "Heavy Construction" category selected from an article by Stéphane Schröder.

Table 2 Structural grade bamboo species

Species	ML	MD	CW	Species	ML	MD	CW
B. balcooa	25	15	v.thk	D. peculiaris	18	15	Thick
B. bambos	30	18	v.thk	D. sikkimensis	18	13	Thick
B. polymorpha	25	15	Thick	D. sinicus	30	30	Thick
B. spinosa	25	12	Thick	D. xishuangbannaensis	28	22	Thin
B. valida	16	12	Thin	D. yunnanicus	25	18	Thin
D. asper	30	20	Thick	Gi. levis	20	13	Thin
D. barbatus	18	15	Thick	Gi. pruriens	15	12	Thin
D. brandisii	33	20	Thick	Gi. scortechinii	20	12	Thin
D. copelandii	30	25	Thin	Gu. aculeata	25	18	Thick
D. dianxiensis	28	18	Thick	Gu. amplexifolia	20	10	Solid
D. giganteus	30	30	Thick	Gu. angustifolia	25	15	Thin
D. hamiltonii	23	18	Thick	Gu. chacoensis	20	15	Thin
D. hookeri	20	15	Thick	Gu. superba	20	15	Thick
D. jianshuiensis	18	12	Thin	P. edulis	23	18	Thin
D. latiflorus	25	20	Thick				

*ML—Maximum length (in meters); *MD—Maximum diameter (in centimeters); *CW—Culm wall; B—Bambusa; D—Dendrocalamus; Gi—Gigantochloa; Gu—Guadua; P—Phyllostachys; v—very; thk—thick

3.3 Common Types of Engineered Bamboo

Bamboo is gaining popularity in contemporary buildings and bridge structures as part of the sustainable development trend [7]. Bamboo boards, reconstituted densified bamboo, and laminated bamboo are the three main categories of EB products [9].

Glue Laminated Bamboo (Glubam). The "thin layer bamboo strips" are laminated into mats using Glubam or ply bamboo sheets, which use the original method of plywood production [7]. A "strip" is a split that has been solidified into a rectangular cross-section after being dried out. After the outer and inner culm wall layers are removed, it is only three(3) to ten(10) millimeters thick in the circumferential(radial) direction and up to twenty-five(25) millimeters wide in the tangential direction [9]. In the main fiber direction, according to a recent study, Glubam has an average compression value of 51 MPa and a tension strength of 82 MPa, while, a 10,400 MPa Elastic Modulus is recorded. Also, it was found that Glubam has a parallel to the grain mean shear strength of about 7.2 MPa, a Modulus of Rupture of 9400 MPa, and a mean static bending strength of 99 MPa according to the results of the bending test [7]. An insightful study used the well-known Hankinson's equation to try to estimate the off-axis tensional strength of Glubam with a longitudinal and transverse fiber ratio of 4 to 1. Yet, the model continually overpredicts the results

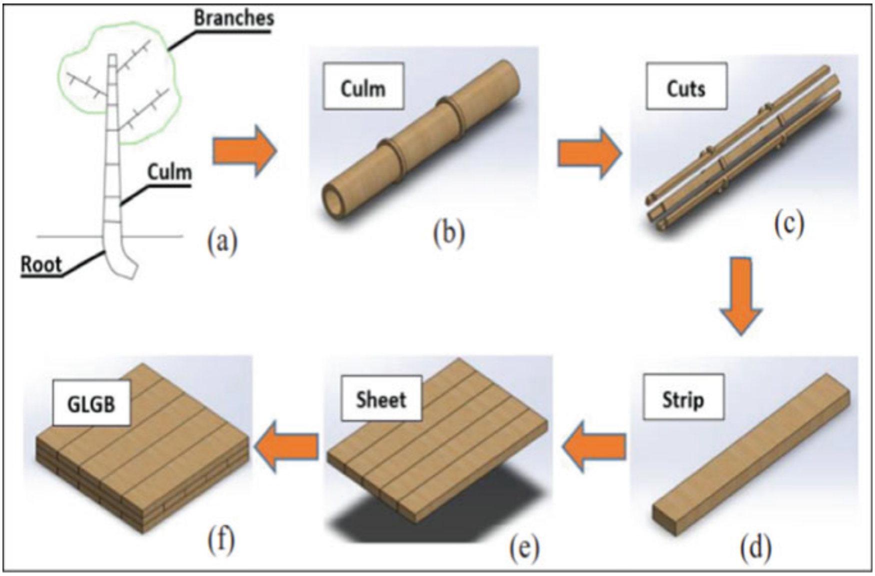

Fig. 3 Process of glued laminated (Guadua) bamboo [16]

regardless of the variations of the characteristic coefficient "n" proving that the original version of Hankinson's equation cannot correctly predict the strength of the material [14]. Typically, organized bamboo strips in a way called 4:1 sheets, with 80% of the strips oriented longitudinally and 20% oriented transversely. Bamboo curtains typically have 15 layers or fewer, with a 2 mm thickness between each layer [15]. Figure 3 shows the Glubam production process [16].

Laminated Bamboo Lumber (LBL). One of the most innovative composite materials is created by binding thin and flat bamboo culms next to each other [18]. The bamboo plant's stem, or "culm," is made up of several segments (internodes) that are spaced apart by diaphragms (nodes) [9]. Because LBL possesses the mechanical properties of bamboo yet can be made with well-defined shapes, similar to the available commercial wood products, it has drawn the interest of both academics and practitioners in particular [6]. Brittle tensile failure, which begins at the tensional face of the beam, is what causes LBL beams to fail. Moreover, stress concentrations in areas where defects are present can affect its tensile strength [18]. Figure 4 shows the LBL production process [17].

Reconstituted Densified Bamboo—(Scrimber). Bamboo Scrimber (BS), often referred to as parallel-strand bamboo or strand-woven bamboo, is created from crushed fibers which have been pressed into a solid mass after being soaked with resin [10]. Cold molded, hot cure, and high-temperature pressing are the three primary forming processes [19]. Fiber Bundles are the pieces of crushed culm walls that can be gathered and used to make reconstituted lumber. In the scrimber process,

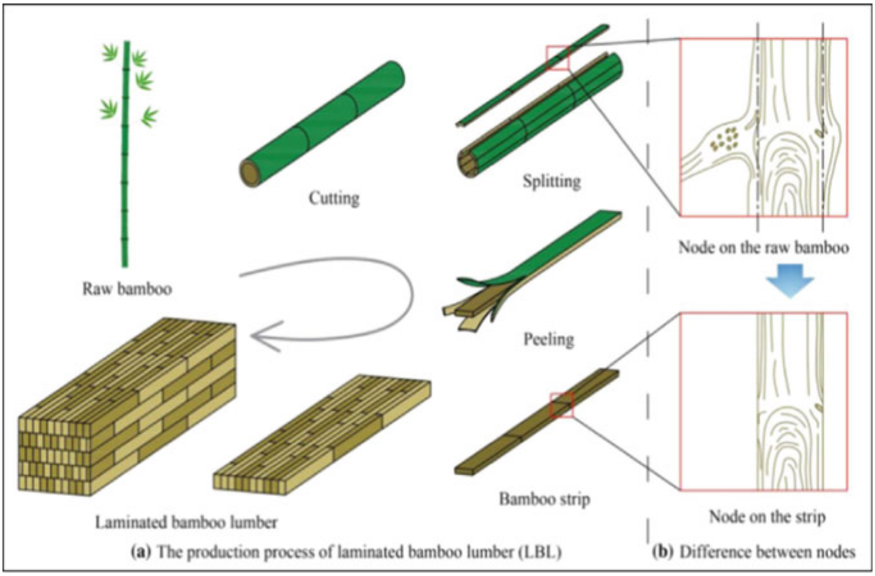

Fig. 4 Laminated bamboo lumber (LBL) [17]

these are made by roughly splitting the culm wall with chopper-rolling, crushing it through a series of closely spaced rollers, and brooming (for elements with smaller diameter) [9]. The unprocessed culm of bamboo was turned into EB scrimber, a laminated (with resin which is thermosetting) or crushed product with a density of 800–1200 kg/m^3 [20]. A separate experiment found that the bending specimen resin did not experience compression failures, but the bamboo scrim material did. This outcome might have been influenced by the resin's tendency to be more rigid than Bamboo when fully cured, even at 4% resin loading [19]. Figure 5 illustrates the BS manufacturing process [21], while, Fig. 6 presents the detailed process of mechanically rolled bamboo fibers [22].

3.4 Adhesives

Any organic material, whether natural or artificial, containing a viscous liquid or non-crystalline is referred to as resin. Natural resins are often transparent or translucent organic materials with a yellowish-to-brown appearance that is combustible and fusible. A broad category of synthetic products with some physical features of natural resins but different chemical compositions are referred to as synthetic resins. Plastics and synthetic resins cannot be distinguished with certainty. Glubam sheets are made using phenol–formaldehyde, just like plywood in North America [15]. An experiment showing superior technical properties for the bamboo scrimber made from

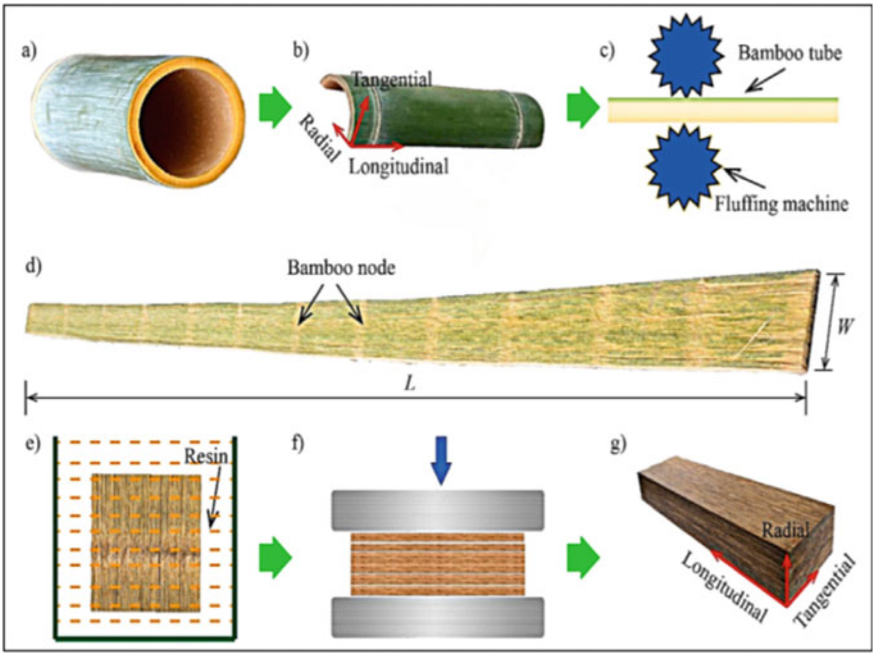

Fig. 5 Manufacturing process from full-culm rolled Bamboo to BS [21]

processed bamboo bundles (180 °C), combined dry air treatment and 18% PF resin loading, yielded favorable results. The binding performance of the bamboo scrimber slightly increased with greater PF resin loading, whether or not it underwent heat treatment [19]. Moreover, another notable result showed that other than the modulus of bending, which was not greatly impacted by density, practically all parameters enhanced with higher resin amounts and densities [23]. Table 3 contains the resins used by the recent studies.

3.5 *Existing Structural Elements or Structures Made of EB*

At Nanjing Forestry University, a three-story office building with LBL was constructed in 2017 as depicted in Fig. 7a [28]. Second, in Fig. 7b, from one study, the industry is adopting a new trend of creating new bamboo products to broaden the present application from surfaces to structures [3]. Lastly, Fig. 7c proves that due to the unique flexibility of the material slats and laminated planks, curved bamboo arcs preserve the original performance of Bamboo, making them an excellent choice for structural columns or posts for tiny house frames that can carry a specific amount of weight.

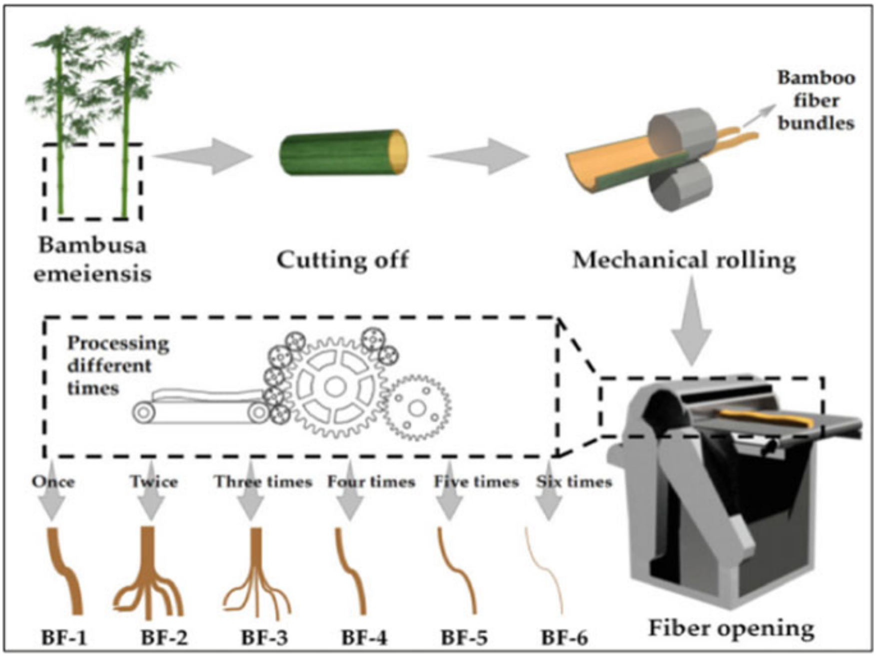

Fig. 6 Process for preparing mechanically bamboo fibers [22]

Table 3 Resins used in recent studies

Resin	Refs.	
PF	Yu et al. [19]	Note: PF—Phenol Formaldehyde; UF—Urea–Formaldehyde; E—Epoxy; I—Isocyanate; PRF—Phenol-Resorcinol Formal dehyde
UF	Correal et al. [24]	
E	Verma and Chariar[25], Verma et al. [26]	
I	Sinha et al. [27]	
PRF	Sinha et al. [27]	

3.6 Standardization

Construction stakeholders' coordinated participation is necessary for standardization, which they do by collectively promoting and accelerating the process. International coding and standards would promote structural and engineered Bamboo as a sustainable building material globally [3]. Table 4 compiles the Material Testing standard used and the description of each.

Fig. 7 Existing structural elements or structures made of EB

Table 4 Material testing used by some recent studies

Material testing used	Description	Refs.
ASTM D-1037	Standard test method for evaluating properties of wood-base fiber and particle panel materials	[19, 23]
ASTM D143-94	Standard test methods for small clear specimens of timber	[7]
ASTM D198	Standard test methods of static tests of lumber in structural	[18]
ASTM D2334	Short-beam strength testing of polymer matrix Composite materials	[19, 23]
GB/T 30,364–2013	Bamboo scrimber flooring	[29]
GB/T 50,329–2012	Standard for test methods of timber structures	[18]

It can be observed from the description that most of the studies about Bamboo use the relevant codes primarily intended for Timber or Wood and that the engineered bamboo composites currently need to be described by standards or codes [20].

4 Challenges and Limitations

The challenges from the reviewed materials are summarized in Table 5. Addressing the issues listed in Table 5 is important for the future development of the engineered bamboo and the discipline as a whole. The insights shown in this Table 5 will lead us in the appropriate path for improving the quality and dependability of using engineered bamboo as construction material. These recommendations, drawn from previous experiments' lessons, have an opportunity to provide significant and accurate information that will substantially aid in the ongoing advancement of the engineered bamboo studies.

Table 5 List of future research recommendations

Refs.	Challenges and limitations
[30]	Processing-related changes to Bamboo's characteristics and those of its numerous derivative materials in structural applications
[10]	Full-scale specimens testing
[15]	Possibility of combining bamboo with different materials like wood, steel, and FRP
[19]	Dimensional stability while preserving the bamboo bundles' mechanical qualities
[31]	Applying lateral pressure to layers to better understand how it affects the strength characteristics
[14]	Failure characteristics of Glubam; Glubam with various fiber ratios and complex stress states
[32]	Thermal treatment effects

5 Conclusions

The market can accept engineered Bamboo as a competitive product. Bamboo has several advantages and provides strength and aesthetic value compared to other materials. Although developing a thorough codification of structural bamboo products may be necessary soon, the process will be slow and useless without coordinated cooperation from relevant parties. The engineering quantification of mechanical properties will determine future structural applications. Through experimentation and analysis, academic research should seek to inform how industry leaders and policy-makers can work to lay the groundwork for standardization. Even though it was evident that there is still a long way to the perfection of EB application in many construction fields, especially in structural engineering, the tireless effort being exerted by the researchers interested in its development is considered contributing and substantial.

References

1. Low impact building: housing using renewable materials. Wiley, vol 1 (2013)
2. Chrysanidis T, Mousama D, Tzatzo E, Alamanis N, Zachos D (2022) Study of the effect of a seismic zone to the construction cost of a five-story reinforced concrete building. Sustainability (Switzerland) 14(16). https://doi.org/10.3390/su141610076
3. Gatóo A, Sharma B, Bock M, Mulligan H, Ramage MH (2014) Sustainable structures: bamboo standards and building codes. Proc Inst Civ Engineers: Eng Sustain 167(5):189–196. https://doi.org/10.1680/ensu.14.00009
4. Burroughs S, Růžička J (2019) The use of natural materials for construction projects-social aspects of sustainable building: case studies from Australia and Europe. IOP Conf Ser Earth Environ Sci 290(1). https://doi.org/10.1088/1755-1315/290/1/012009
5. Lee CH, Chung MJ, Lin CH, Yang TH (2012) Effects of layered structure on the physical and mechanical properties of laminated moso bamboo (Phyllosachys edulis) flooring. Constr Build Mater 28(1):31–35. https://doi.org/10.1016/j.conbuildmat.2011.08.038

6. Mahdavi M, Clouston PL, Arwade SR (2011) Development of laminated bamboo lumber: review of processing, performance, and economical considerations. J Mater Civ Eng 23(7):1036–1042. https://doi.org/10.1061/(asce)mt.1943-5533.0000253
7. Xiao Y, Yang RZ, Shan B (2013) Production, environmental impact and mechanical properties of glubam. Constr Build Mater 44:765–773. https://doi.org/10.1016/j.conbuildmat.2013.03.087
8. Sharma B, Gatoo A, Bock M, Mulligan H, Ramage M (2015) Engineered bamboo: state of the art. Proc Inst Civ Engineers: Constr Mater 168(2):57–67. https://doi.org/10.1680/coma.14.00020
9. Liu X et al (2016) Engineered bamboo nomenclature
10. Sharma B, Gatóo A, Bock M, Ramage M (2015) Engineered bamboo for structural applications. Constr Build Mater 81:66–73. https://doi.org/10.1016/j.conbuildmat.2015.01.077
11. Raj D, Agarwal B (2014) Bamboo as a building material and its processing methods. J Civ Eng Environ Technol 1(3): 56–61. https://www.krishisanskriti.org/vol_image/03Jul201502074415.pdf
12. Masdar A, Siswosukarto S, Suryani D (2020) Implementation of connection system of wooden plate and wooden clamp on joint model of bamboo truss structures. Int J GEOMATE 17(59): 15–20. https://doi.org/10.21660/2019.59.4589
13. Gutu T (2013) A study on the mechanical strength properties of bamboo to enhance its diversification on its utilization. Int J Innov Technol Exploring Eng (IJITEE) 5:314–319
14. Yang RZ, Xiao Y, Lam F (2014) Failure analysis of typical glubam with bidirectional fibers by off-axis tension tests. Constr Build Mater 58:9–15. https://doi.org/10.1016/j.conbuildmat.2014.02.014
15. Xiao Y (2016) Engineered bamboo. In: Nonconventional and vernacular construction materials, Elsevier, pp 433–452. https://doi.org/10.1016/b978-0-08-100038-0.00015-9
16. Castaneda H, Bjarnadottir S (2016) Analysis of the bolted connection of a bamboo composite i-shaped beam subjected to bending. Procedia Eng 145(December):796–803. https://doi.org/10.1016/j.proeng.2016.04.104
17. Wang Z et al (2021) Bamboo node effect on the tensile properties of side press-laminated bamboo lumber. Wood Sci Technol 55(1):195–214. https://doi.org/10.1007/s00226-020-01251-9
18. Li H-T, Deeks AJ, Zhang Q-S, Wu G, Flexural performance of laminated bamboo lumber beams
19. Yu Y, Zhu R, Wu B, Hu Y, Yu W (2015) Fabrication, material properties, and application of bamboo scrimber. Wood Sci Technol 49(1):83–98. https://doi.org/10.1007/s00226-014-0683-7
20. Kumar A et al (2016) Engineered bamboo scrimber: Influence of density on the mechanical and water absorption properties. Constr Build Mater 127:815–827. https://doi.org/10.1016/j.conbuildmat.2016.10.069
21. Luo X, Wang X, Ren H, Zhang S, Zhong Y (2022) Long-term mechanical properties of bamboo scrimber. Constr Build Mater 338(February): 127659. https://doi.org/10.1016/j.conbuildmat.2022.127659
22. Zhao W, Zhang J, Zhang W, Wang J, Wang G (2022) Changes in the structural composition and moisture-adsorption properties of mechanically rolled bamboo fibers. Materials 15(10). https://doi.org/10.3390/ma15103463
23. Yu Y, Liu R, Huang Y, Meng F, Yu W (2017) Preparation, physical, mechanical, and interfacial morphological properties of engineered bamboo scrimber. Constr Build Mater 157:1032–1039. https://doi.org/10.1016/j.conbuildmat.2017.09.185
24. Correal JF, Echeverry JS, Ramírez F, Yamín LE (2014) Experimental evaluation of physical and mechanical properties of Glued Laminated Guadua angustifolia Kunth. Constr Build Mater 73:105–112. https://doi.org/10.1016/j.conbuildmat.2014.09.056
25. Verma CS, Chariar VM (2012) Development of layered laminate bamboo composite and their mechanical properties. Compos B Eng 43(3):1063–1069. https://doi.org/10.1016/j.compositesb.2011.11.065

26. Verma CS, Sharma NK, Chariar VM, Maheshwari S, Hada MK (2014) Comparative study of mechanical properties of bamboo laminae and their laminates with woods and wood based composites. Compos B Eng 60:523–530. https://doi.org/10.1016/j.compositesb.2013.12.061
27. Sinha A, Way D, Mlasko S (2014) Structural performance of glued laminated bamboo beams. J Struct Eng 140(1). https://doi.org/10.1061/(asce)st.1943-541x.0000807
28. Chen G, Yu Y, Li X, He B (2020) Mechanical behavior of laminated bamboo lumber for structural application: an experimental investigation. Eur J Wood Wood Prod 78(1):53–63. https://doi.org/10.1007/s00107-019-01486-9
29. He S, Xu J, xing Wu Z, Yu H, he Chen Y, gang Song J (2018) Effect of bamboo bundle knitting on enhancing properties of bamboo scrimber. Eur J Wood Wood Prod 76(3): 1071–1078. https://doi.org/10.1007/s00107-017-1263-y
30. Sharma B, Shah DU, Beaugrand J, Janeček ER, Scherman OA, Ramage MH (2018) Chemical composition of processed bamboo for structural applications. Cellulose 25(6):3255–3266. https://doi.org/10.1007/s10570-018-1789-0
31. Mahdavi M, Clouston PL, Arwade SR (2012) A low-technology approach toward fabrication of laminated bamboo lumber. Constr Build Mater 29:257–262. https://doi.org/10.1016/j.conbuildmat.2011.10.046
32. Sharma B, Gatóo A, Ramage MH (2015) Effect of processing methods on the mechanical properties of engineered bamboo. Constr Build Mater 83:95–101. https://doi.org/10.1016/j.conbuildmat.2015.02.048