Use of Bamboo in Constructions

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Abstract The application of bamboo in construction is briefly introduced in this chapter. The basic mechanical properties of bamboo under different loading directions are given. The compression and tensile stress–strain models in the bamboo fiber direction are reported. In terms of round bamboo, engineered bamboo, and hybrid bamboo structures, bamboo structures are introduced with various construction examples. The carbon emission of bamboo construction was also discussed, compared with other mainstream construction forms. These research results and construction practices validate that bamboo is a promising natural source that can be used as a sustainable construction material.

Keywords Bamboo structure · Bamboo construction · Round bamboo · Engineered bamboo

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1 Bamboo as a Construction Material

The use of bamboo in construction is prevalent in many bamboo-rich regions and has been practiced for centuries. The coordinate system of different bamboo products used for construction is given in Fig. 1. Various studies [1, 2] indicate that bamboo is one of the most effective natural materials that can be used as a sustainable construction material with high performance in terms of high strength-to-density ratio, good thermal insulation performance, and easy-to-manufacture. Such material has been successfully used for modern residential buildings, bridges, wind blades, and urban water pipelines in recent twenty years worldwide.

The nature of it dominates the mechanical properties of bamboo as a unidirectional fiber-reinforced composite material. Researches [3–7] have been conducted on different bamboo products' strength and modulus properties under different loading directions. According to the authors' recent study [7], Moso bamboo strips' average tension strength along its fiber direction (1-direction) is about 130 MPa, with a stand deviation (St. D) of 16 MPa. The average compressive strength of Moso bamboo strips along fiber direction (1-direction) is about 57 MPa, with St. D of 5 MPa. The modulus value is around 10 GPa. Strength values perpendicular to the fiber direction (2-direction) are about 6 MPa (St. D 1 MPa) for tension and 14 MPa (St. D 1 MPa) for compression. As shown in Fig. 2, the simplified segmental linear models can be derived for all bamboo products, as given in Fig. 1. As illustrated in this figure, seven parameters are used to describe the model, including values of f_{t1}, E_{t1}, f_{c1}, and $E_{c1,}$ as given above. ε_{tu} is the ultimate tension strain, 12,000 $\mu\varepsilon$ for round bamboo, bamboo strips, and unidirectional bamboo panels. It is 7800 $\mu\varepsilon$ for multidirectional laminated bamboo panels. ε_{c0} is the compression strain at maximum stress, which is 23255 $\mu\varepsilon$ for unidirectional bamboo products, and 10,000 $\mu\varepsilon$ for multidirectional

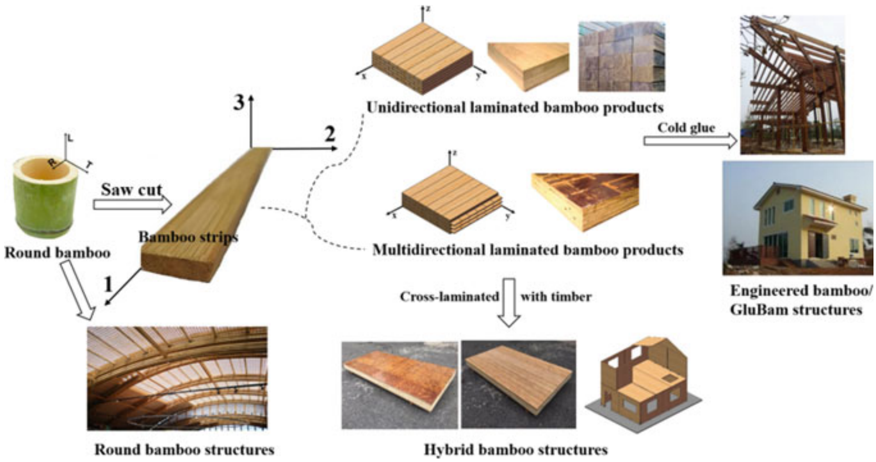

Fig. 1 The coordinate system of different bamboo products and bamboo structures

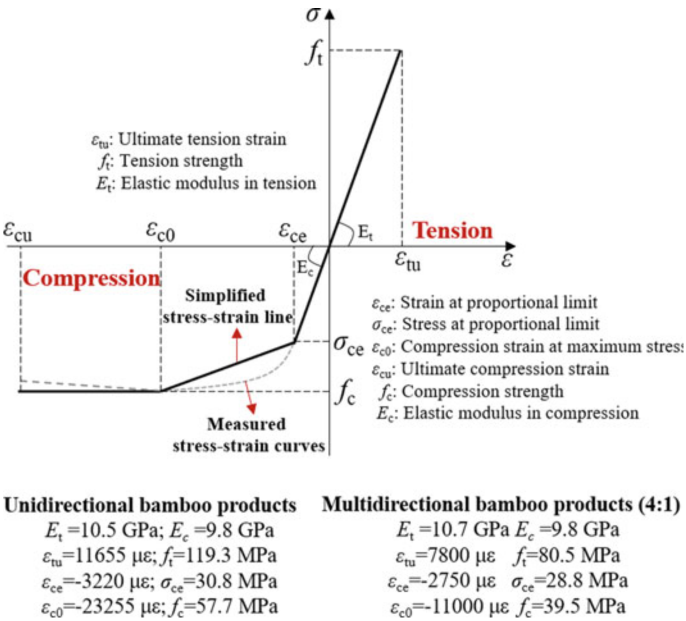

Fig. 2 Stress–strain model of bamboo products

bamboo panels. The ultimate compressive strain ε_{cu} is about 30,000–35,000 $\mu\varepsilon$ for all bamboo products. Parameter σ_{ce} is the measured stress at the proportional limit state, 30.8 and 28.8 MPa for thick and multidirectional bamboo. Strain ε_{ce} corresponding to the proportional limit stress is 3220 and 2750 $\mu\varepsilon$ for unidirectional and multidirectional bamboo products, respectively. The performance of bamboo structures with stresses on their main-fiber direction can be estimated with this stress–strain model.

Specifically, for bamboo used in residential construction, three types of structural forms are widely used nowadays: round bamboo structures, engineered bamboo structures, and hybrid bamboo structures with conventional construction materials as concrete, steel, and timber.

2 Round Bamboo Structures

Bamboo has been indispensable in human life, and its history being used as building and bridge structural materials can be traced back as long as wood. Its natural properties are pretty comparable to those of wood. Today, people in many countries still keep the habits of living in traditional round bamboo buildings, such as Bahareque bamboo houses in Colombia (Fig. 3a), Quincha bamboo houses in Ecuador (Fig. 3b), Sidama bamboo houses in Ethiopia (Fig. 3c) and Gan-Lan bamboo houses in China (Fig. 3d) [8]. Most traditional round bamboo houses were designed and constructed without

a. Bahareque bamboo house in Colombia

b. Quincha bamboo house in Ecuador

c. Sidama bamboo house in Ethiopia

d. Ganlan bamboo house in China

Fig. 3 Traditional round bamboo houses around the world (Photo source: Fig. 3d provided by Huang Wenkun, others provided by INBAR) [8]

the participation of architects and engineers. Local people built them according to the experience passed down from their ancestors [8].

However, due to the irregular geometrical shape and anisotropic material properties, the bamboo culms are challenging to be widely used as an industrial building material in modern construction. It is urgent that the people need modern construction technologies to consolidate the inheritance of traditional skills. Since the 1970s, modern round bamboo structures with architects' participation in design and construction have developed unprecedentedly. A group of excellent architects from Colombia solved the bearing capacity problem of hollow round bamboo joints by pouring cement mortar into bamboo poles and anchoring them with metal connections. It makes bamboo used to build larger public buildings (Fig. 4) and brings a new chapter in developing modern round bamboo structures. In Asia, where it is suitable for bamboo growth, many excellent round bamboo structures (Fig. 5) also have emerged in the past two decades.

In some cases, modern prefabricated technologies are also used for the construction of round bamboo structures. One trial project was the application of round bamboo culms with engineered bamboo panels in shear walls. Due to prefabrication and assembly construction requirements, the walls must be made into standard units and then transported to the construction site to form the structure through simple connectors. The outer framing is made of GluBam and then nailed with the

a. A teaching building in Colombia. (photo by Wang Ge)

b. Jenny Garzon Bridge in Colombia. (photo by Liu Kewei)

c. A Hotel in Panama. (Photo by Simón Veléz Architects)

d. Nomadic Art Museum in Mexico. (Photo by Simón Veléz Architects)

Fig. 4 Modern round bamboo structures in Latin American countries [8]

sheathing panels. The round bamboo columns as inner studs are connected with the sheathing through U-hoop connectors and connected to the framing through L-shape connectors. A demonstration house using this type of bamboo shear walls was built in Hunan, as shown in Fig. 6. With the promotion of modern technology, the round bamboo structure has promising development potential.

3 Engineered Bamboo Structures

In recent 20 years, engineered bamboo products have gradually gained commercial importance. In many countries, engineered bamboo products are used in commercial projects for decoration purposes, like indoor or outdoor flooring, wallboard, ceiling, etc. However, engineered bamboo is mainly used in China for its structural uses, where some local pioneer architects started to apply them in different projects.

As shown in Fig. 7a, architect Li Daode created a youth hostel through digital design method and generation logic in Niubeishan Mountain in Sichuan Province. The rolling roof of the hostel is echoing with the mountains in front of it and clouds behind it, utilizing bamboo scrimber made from *Dendrocalamus affinis*, which is a new engineered bamboo material that emerged in the Chinese market. Architect Cao

a. OBI Great Hall in Java, Indonesia. (photo by Andry Widyowijatnoko)

b. Naman Retreat in Vietnam. (photo by Cai Wei)

c. Eco-Children's Activities and Education Center, Thailand.

d. INBAR Pavilion at 2019 Beijing International Horticultural Expo, China. (photo by Wang Xudong)

Fig. 5 Modern round bamboo structures in Asian countries. The project of Fig. 5c won the Second Prize of the International Bamboo and Rattan Products Design Competition organized by INBAR at the 2010 Shanghai World Expo, provided by Olav Bruin [8]

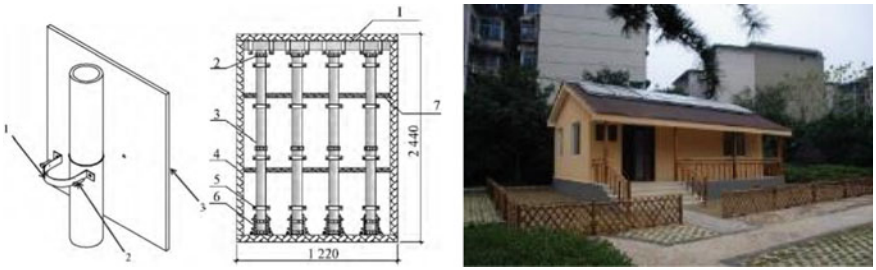

Fig. 6 Prefabricated round bamboo house with its shear wall

Xiaoxin used artistic rammed earth concrete as a new "soil" and bamboo scrimber as a new "wood" to translate the old traditional construction mode to express his respect to the ancients' wisdom in the construction of Zhaojun Museum (Fig. 7b). (1) In the renovation and expansion project of the Zen Center of Baoguo Temple (Fig. 7c), Architects Liang Jingyu and Ye Siyu tried to find light and small members

a. Youth Hostel in Niubeishan Mountain, Sichuan, China.

b. Zhaojun Museum, Huhhot, Inner Mongolia, China.

c. Zen Center of Baoguo Temple in Lezhi, Sichuan, China.

d. Outdoor Heteromorphic Bamboo Landscape of Shanghai Qinsen Group.

Fig.7 Application cases for structural uses of engineered bamboo. (Photos source: Fig. 7a provided by Hongyazhuyuan Science and Technology Company of China; Fig. 7b provided by China Construction Technology Group Co., Ltd and photo by Zhang Guangyuan; Fig. 7c provided by Approach Architecture Studio; Fig. 7d provided by Ganzhou Sentai Bamboo & Wood Co., Ltd.) [8]

to form a spatial grid structure of a large-span roof of the Zen Hall on the sites of the Sui Dynasty (581–618 A.D) buildings. Bamboo scrimber material was chosen and processed into 2 by 4 cm cross-section rods, solving the problem that this site can only rely on human transportation and small equipment. (2) The outdoor heteromorphic bamboo landscape of Shanghai Qinsen Group at the 2019 Beijing International Horticultural Exposition brought the application of glued laminated bamboo in the outdoor landscape into full play (Fig. 7d). The whole design shows the respect of the beauty of nature, with the inspiration of the curl and undulating three-dimensional space structure of wood shavings [8].

For those projects introduced as above, most applications belong to public buildings. Bamboo is also an excellent material for residential houses. A mature and reliable structure system is one of the critical issues for scaling it up. Lightweight GluBam frame structure is one of the most successful structural applications, and more than 20 lightweight GluBam buildings were built up to now (Fig. 8). Like lightweight wood-frame construction, the lightweight GluBam structure comprises the primary structural framing members and sheathing. It can be constructed following the platform-frame construction. The floor system is composed of joists

Fig. 8 Lightweight GluBam frame constructions

covered with sub-flooring to form a working surface upon which exterior walls and interior partition can be quickly erected. The shear walls are connected to the foundation or the lower story walls through the floor system by anchor connections. The roof system, normally prefabricated trusses, is connected to the shear walls' top beam by metal connections.

The lightweight GluBam frame structures have good lateral resistant behavior. The shear walls perpendicular to the lateral force can transfer the load to the horizontal diaphragms (floor or roof). The horizontal diaphragms distribute it to the shear walls parallel to the lateral force; finally, the shear walls transfer the force to the foundation. The lightweight GluBam shear wall is the main component to resist lateral loads. Figure 9 describes the fabrication process and its structural elements and connection system. Wall framing includes studs, top, and bottom beams. The vertical studs are supported on a bottom beam and support the top beam. Studs usually consist of 40 × 90 mm or 40 × 140 mm and are commonly spaced 305 or 405 mm on center. The stud spacing can be changed from 300 to 610 mm, depending on the load. The ply-bamboo panels are usually used as wall sheathing. The connection system consists of a panel-frame connection, frame-frame connection, and hold-down connection, which are the dominant factors determining the GluBam shear wall's lateral performance [9]. The high resistance of lightweight GluBam frame construction is provided when sheathing panels are adequately nailed to the framing members. Existing studies [10] indicate that lightweight GluBam shear walls have a high bearing capacity but limited ductile performance than wood-frame shear walls when using the same panel-frame connectors.

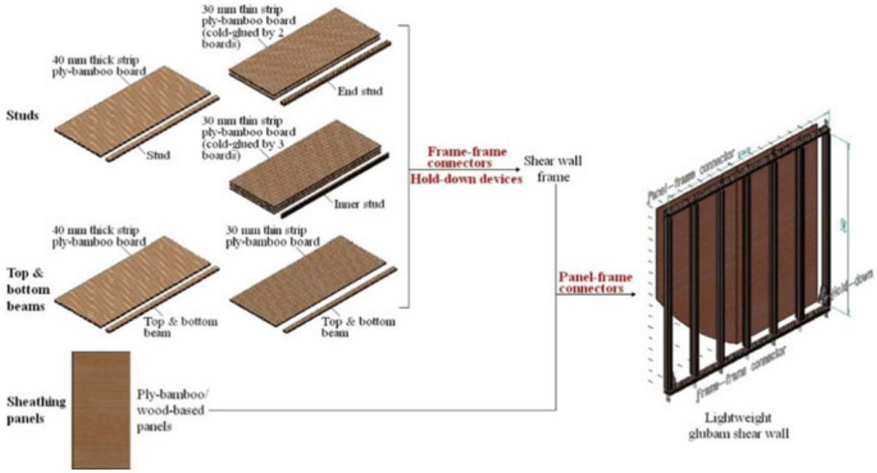

Fig. 9 The fabrication process of the GluBam shear wall

The lightweight GluBam structure floor consists of sills, girders, joists or floor trusses, and sub-flooring. The joists usually are spaced 305, 405, or 610 mm on centers and are supported by the foundation and the center girder. The size of the girders is determined by load calculation and detailing requirements. Sub-flooring or flooring sheathing is applied over the framing to provide a working platform, and the common sheathing material is a 15 mm thin strip ply-bamboo panel, as shown in Fig. 10. The roof system (Fig. 11) is typically made with prefabricated GluBam trusses as engineered trusses can reduce on-site labor and provide greater flexibility in interior walls' layout. Large-span GluBam trusses can be made up to 24 m long, as shown in Fig. 12.

4 Hybrid Bamboo Construction

High strength and modulus values of bamboo products on its main-fiber (x) direction support the application of bamboo materials, mainly as tension elements for hybrid bamboo structures such as bamboo-reinforced concrete structures. Due to the lack of steel for construction during World War I, hundreds of bamboo-reinforced concrete buildings were built in China, mainly in Canton. Some of them are still in service up to now as public buildings. However, due to biomaterials' durability limitations, applying bamboo reinforced concrete is mainly limited in research practices. Inspired by the recent development of cross-laminated timber (CLT), cross-laminated bamboo and timber (CLBT) was developed [11]. The CLBT is made by glue laminating under pressure the layers of laminated bamboo panels, and standard timber lumbers (SPF or fast-growing species in China). The orientation of the elements can be predetermined to satisfy design requirements. The CLBT construction is similar

Fig. 10 Processing and installation of lightweight GluBam shear wall and floor diaphragm

Fig. 11 Roof system in lightweight GluBam structure

Fig. 12 Large span GluBam truss

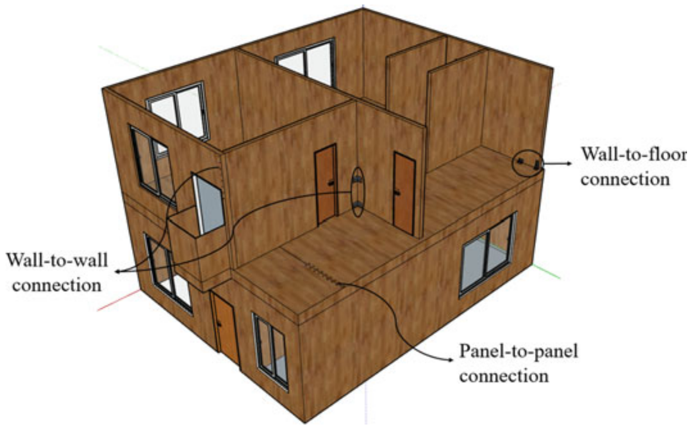

Fig. 13 Typical CLBT structures

to the lightweight frame structure; the difference is that the panel components are used instead of the framing members in lightweight GluBam structures, as shown in Fig. 13. The CLBT structure can be divided into prefabricated panel components; the horizontal floor (or roof) panels rest directly on top of vertical wall panels through simple metal connections. The CLBT structure system can be used in 3–4 story buildings or even high-rise structures. Due to the significant in-plane shear stiffness of the CLBT panel, the energy dissipation of structural components is provided by the anchorage connectors between the panel and the foundation (or floor) and the connection between adjacent panels. Therefore, the performance of these two types of connections determines the overall behavior of the CLBT structure.

Another successful application of engineered bamboo with other construction materials is the hybrid bamboo-steel space truss [12, 13], as shown in Fig. 14. The hybrid space truss system specially designed comprises two primary materials, glue-laminated bamboo and steel. The GluBam chords are mainly used for the upper compressive chords and web chords, while the steel pipes are mainly used for the bottom tensile chords. Compared with traditional steel space trusses, the hybrid space

Fig. 14 Hybrid bamboo-steel truss

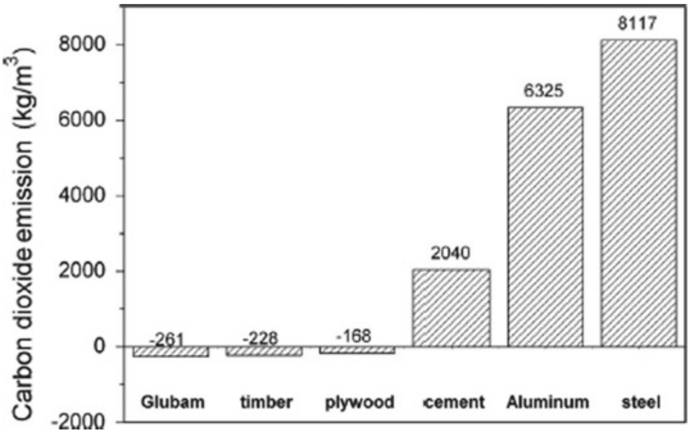

Fig. 15 Carbon dioxide emission of GluBam and comparable construction materials [3]

truss system is developed with the concept of achieving possible maximum carrying capacity and lighter self-weight together.

5 Carbon Emission of Bamboo Construction

As a structural material, its influence on the environment is crucial in today's trend towards a sustainable construction industry. The low carbon emission of bamboo products has been widely recognized, making it very attractive in today's move towards a sustainable society. Numerous studies have shown that bamboo forests are more superior to other forests in capturing CO_2. The histogram shown in Fig. 15 compares Glubam with other construction materials, including timber, plywood, cement, aluminum, and steel, in carbon emission [3]. Cement, aluminum, and steel discharge much more carbon dioxide than the other materials. In comparison, GluBam is carbon emission negative and outperforms timber and plywood.

6 Conclusion

The development in scientific research and engineering practices on bamboo materials and constructions has been noticed in the recent 30 years. The promising potentials of bamboo materials used in the construction industry can be observed clearly based on the accumulated research goals and construction examples. The structural bamboo can be modeled as a unidirectional reinforced bio-composite material. High tension and compression strength values can be noticed for it. However, relatively low modulus values, around 10 GPa, can be noticed for bamboo. Thus, the design of bamboo structures is typically governed by deformation limitations. The hybrid timber/steel-bamboo structure is an effective solution for optimizing bamboo material usages in construction. The carbon emission of bamboo construction, using GluBam structures as an example, is discussed and compared with timber, plywood, cement, aluminum, and steel structures. Superior carbon emission performances can be noticed for bamboo construction. More research on standardization and industrial-grade methods is suggested for the vast application of this environmentally friendly material.

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