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Sustainability in Beauty:
A Review and Extension of Bamboo Inspired Materials

Ting Tan[1*], Tian Xia[1], Hunter O'Folan[1], Justin Dao[1], Zachary Basch[1], Karl Johanson[1], Mieko Ozeki[2], Michelle Smith[2]

[1]*School of Engineering, the University of Vermont, VT, US*
[2]*Office of Sustainability, the University of Vermont, VT, US*

Abstract
Bamboo is a functionally graded grass composite in nature with extraordinary mechanical properties. This paper performed a review of studies on bamboo inspired materials. It started with the bamboo microstructural properties and mechanical characterizations. Then, a summary of the bamboo fiber reinforced polymeric composites was presented by introducing the fabrication process and the primary features. Subsequently, the study of bamboo inspired functionally graded materials were reviewed based on different applications. Finally, the authors introduced a hybrid energy harvesting system using a bamboo wind turbine and solar panels as an extension of bamboo inspired studies, which could also be a sustainable solution for renewable energy harvesting and utilization in different areas.

Keywords: Bamboo, Functionally Graded Materials, Sustainability, Renewable Energy

1. Introduction
Bamboo is a group of perennial grasses in the grass family Poaceae, subfamily Bambusoideae, tribe Bambuseae [1]. It grows in many tropical and temperature regions, and it is among the fastest-growing plants in the world [2]. An estimate classified bamboo into 75 genera and approximately 1500 species [1]. Moso (*Phyllostachys heterocycla pubescens*) is the most widely distributed bamboo for utilization known [1]. Bamboo consists of a culm above the ground and the rhizome system under the ground (Fig. 1a). The culm is made of structural nodes enclosing hollow regions in between. Besides supporting the structure of bamboo, there are also channels in culm to exchange water and nutrients with the bottom earth. There have been more than 1000 document uses of bamboo different areas, such as housing and transportation [3]. Some featured applications include the bamboo racing bicycles [4] and the famous Simón Vélez bamboo church in Columbia [5]. The ever growing interest in using bamboo for sustainable products has incubated a multi-billion dollar bamboo market globally [6].

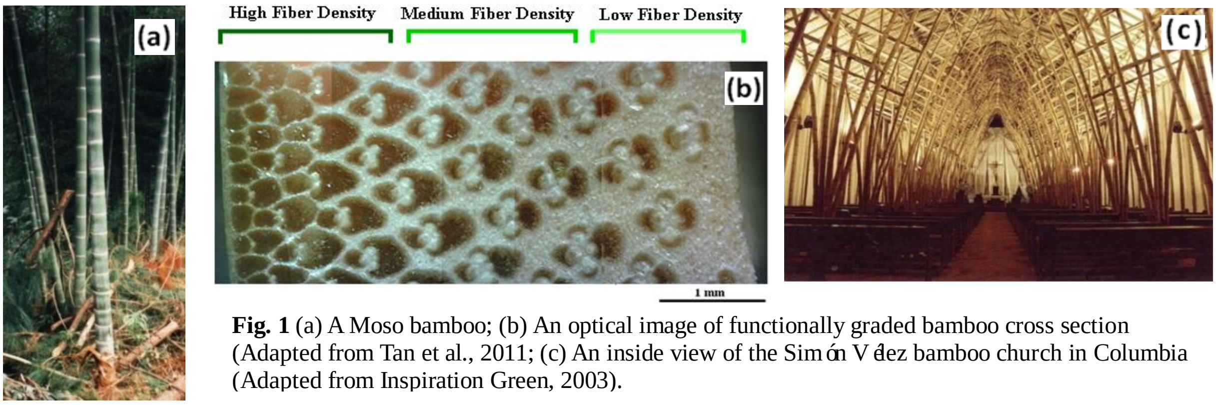


Fig. 1 (a) A Moso bamboo; (b) An optical image of functionally graded bamboo cross section (Adapted from Tan et al., 2011; (c) An inside view of the Simón Vélez bamboo church in Columbia (Adapted from Inspiration Green, 2003).

2. Bamboo properties
Bamboo, in its natural habitat working as a cantilever beam with fixed support in the earth, is a functionally graded composite in nature with remarkable mechanical properties. Prior researchers studied the microstructural features of bamboo cross section [7]. The culm includes approximately 40% cellulose fibers, 52% parenchyma tissue and 8% conduction tissue (vessels, sieve tubes, companion cells), which may vary with species and bamboo growth stages [1]. Sclerenchyma fibers are the principle supporting tissues within the vascular bundles of bamboo (Fig. 2a). The phloem vessels are used to transport sugars and nutrients; while the metaxylem vessels are used to transport water [8]. The ground tissue surrounding the vascular

* The corresponding author, email: ting.tan@uvm.edu.

bundles is parenchyma. It is shown that the ratio of the vascular bundles over the parenchyma decreasing from the outside to the inside surface (Fig. 1b). In the longitudinal direction, the narrowing of the bamboo also results in a reduction of the parenchyma towards the culm head [1]. The primary chemical contents of bamboo fibers are cellulose, hemicellulos and lignin [9]. One feature of bamboo fibers is the thick polylamellate secondary walls, consisting of alternating broad and narrow layers with varying fibrillar orientation (Figs. 2b and 2c). The microfibril orientation angles are in the range of 3-10˚ in the broad layers, and are in the range of 30-90˚ in the narrow ones [9]. The structure of parenchyma cells is shown in Fig. 2d, in which two types of cells are observed, i.e., longitudinally elongated cells and short tub-like ones immersed in between [1]. They are separated by thicker walls that become lignified in the early stages of intermodal development.

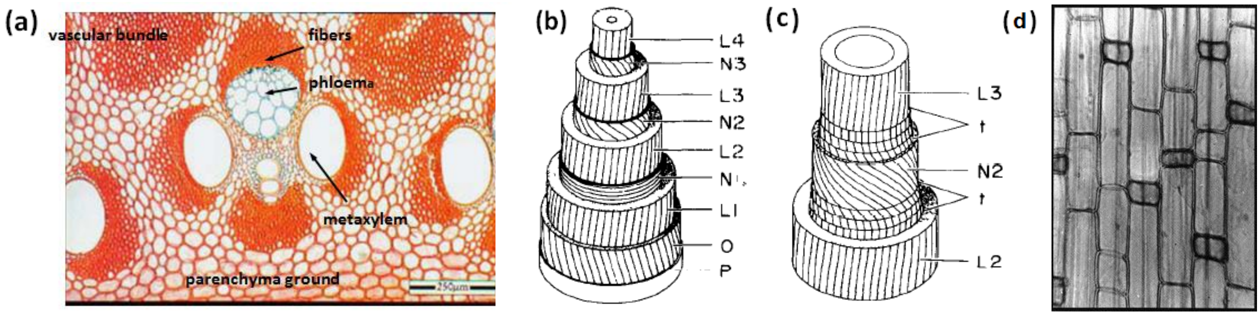
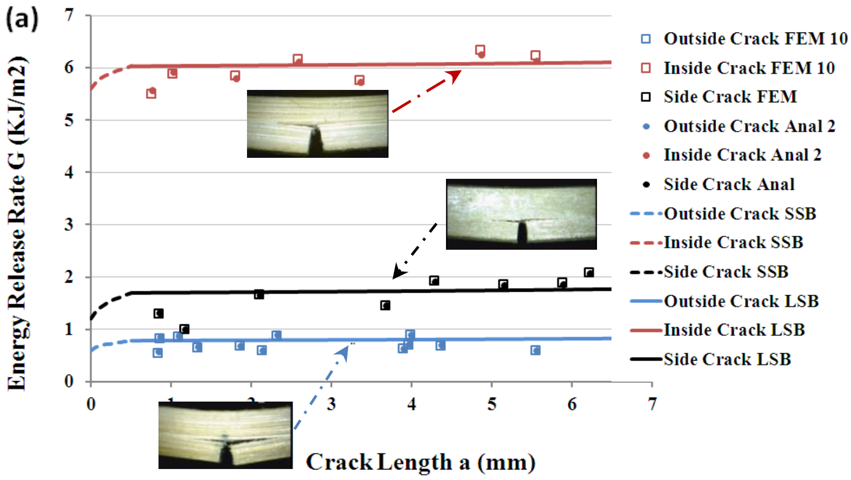


Fig. 2 (a) Vascular bundles in Moso bamboo; The ultrastructure of bamboo fibers (b) Primary wall (P), outermost layer of the second wall (O), broad layers (L1-L4), and narrow layers (N1-N3); (c) the detailed structure showing the transition zone; (d) Parenchyma consisting of longer and shorter cells (450X); (a) and (d) adapted from [1]; (b) and (c) adapted from [9].

This functionally graded pattern enables bamboo remarkable in mechanical properties, including strength, stiffness and fracture resistance [6]. The properties of bamboo fibers and parenchyma (bulk) are different. Prior studies showed that, the elastic moduli of bamboo fibers and parenchyma are ~46 and ~2 GPa, and the tensile strength are ~800 and ~50 MPa, respectively [7]. From the outside to the inside surface, the elastic moduli of bamboo strips degrade from 16 to 4 GPa; and the tensile strength degrade from 750 to 100 MPa. Even though the elastic moduli and tensile strength decrease from the outside to the inside surface, the fracture resistance increases in the same direction [6]. This is because less energy is invested to propagate cracks by splitting the fiber fences closer to the outside surface than breaking the lignin webs closer to the inside surface, in which different bridging types and intensities have been observed (Fig. 3).



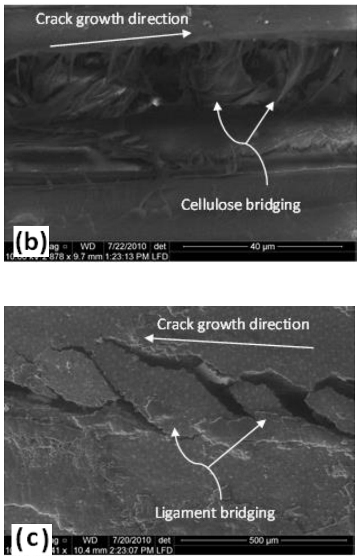


Fig.3. (a) Resistance-curve results of Moso culm bamboo; Scanning Electron Microscopy (SEM) images of (b) cellulose bridging in the outside crack sample; (c) ligament bridging in the side crack sample (Adapted from [4]).

3. Bamboo Reinforced Polymeric Composites

As the ever-growing need for sustainable materials, bamboo fiber reinforced polymeric (BFRP) composites have been widely used for different applications. Bamboo fibers are obtained using either chemical or mechanical methods from natural bamboo culm [9]. Initially, natural bamboo culms are spilt into small strips. The primary matrices for BFRP composites include Polypropylene, Polyester, Epoxy, Phenolic resin, Poly Vinyl Chloride, Polystyrene and Phenol Formaldehyde [7]. After drying, bamboo fibers were alkali treated before mixing with polymeric matrices [10]. Sometimes, extra chemical modifications were performed on bamboo fibers aiming at increasing the adhesion between fibers and matrices. Then, bamboo fibers and matrices were blended above the ambient temperature [10]. The composites will cure at ambient temperature for fabrication, which can be tailored into different geometries based on the functional needs. For example, no less than 200,000 m^2 plybamboo were used to build the roof at the Madrid-Barajas airport (Fig. 4) [11]. This award winning design project synergized the application of sustainable materials and the use of daylight aesthetically. BFRP composites have also been used in various industrial products [12]. To ensure high quality engineering practice, substantial effort is needed to develop technical standards that will control the reliability of the BFRP products, especially on the long term behavior for these composites. Meanwhile, a balance needs to be achieved between the increasing needs for bamboo materials and the plant harvesting, in which the impact on the environment could be minimized.

Fig. 4. Bamboo reinforced composites and their applications (1) plybamboo; (2) strand woven bamboo; (3) A woven bamboo mats glued together with epoxy; (4) Bamboo fiber reinforced thermoplastic composites; (5) Bamboo laptop case; (6) The plybamboo roof at Madrid-Barajas airport; (7) Bamboo helmet; (8) Bamboo spring chair; (9) Pheonix bamboo concept car (Adapted from [7]).

4. Bamboo Inspired Functionally Graded Materials

Functionally graded materials (FGMs) are effective in reducing stress concentrations between different layers, which are critical to the performance of many devices. Innovative FGMs have been synthesized to meet different thermal and mechanical needs, including the ceramic-metal joints [13], piezoelectric actuators [14] and biomimetic cylindrical structures [15]. Aiming at reducing the process induced stresses, Bruck et al. (2002) developed a functionally graded nickel-alumina joint with the gradual transition in microstructure and/or composition. A multi-layered FGM were synthesized by gradually modifying the material properties from pure nickel to pure alumina (Fig. 5a). de Vries (2010) used the 3D print technique to generate functionally graded cylindrical bamboo structure. A series of fiber-matrix composite models were created to simulate the bamboo cross section (Fig. 5b). Preliminary studies were performed to elucidate the relationship between the fiber layers and the enhanced mechanical performance [15], and the manufacturing techniques exhibited potential opportunities for design and development of hierarchical materials.

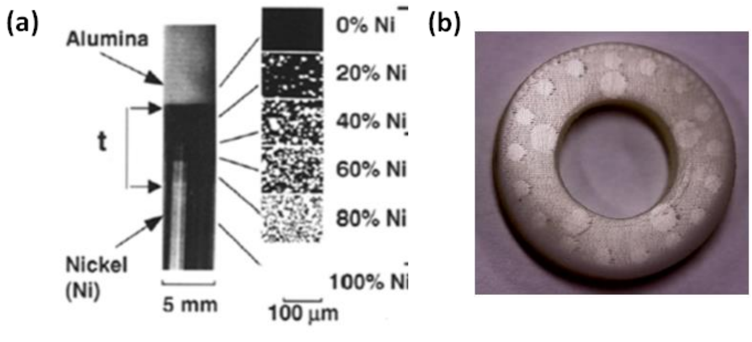


Fig. 5. (a) A synthesized functionally graded ceramic-metal joints from Alumina to Nickel (Adapted from [13]); (b) A 3D printed biomimetic structures of bamboo cross section using functionally graded polymeric structure (Adapted from [15]).

5. Bamboo in Renewable Energy Harvesting

Even though bamboo has been used in various applications, its role in renewable energy infrastructure has not been well defined. The authors developed a hybrid energy harvesting system consisting of a bamboo wind turbine and solar panels. The energy harvested from wind and sun will be stored in the battery, and will be used to power the lights on the blades and the pole (Fig. 6). A prototype has been completed using vertical axis bamboo wind turbine and solar panels in the University of Vermont (UVM). The turbine has a diameter of 0.44 m and a height of 0.53 m. NACA0018 air foil is used in a pitch angle of 60 degree and twist angle of 80 degree. The helical blade skeletons are produced using a 3D printer with polymeric materials. Moso bamboo fiber laminates are used for blade surfaces, and epoxy is used in the vacuum infusion method to complete the blade design. LED lights are attached to the blades to generate dynamic light patterns. A microcontroller has been developed to control the wind and solar energy harvested [16]. Bamboo laminates are featured by the hierarchical toughening mechanisms among the multi-layered bamboo fibers and the alternating parenchyma cell walls. Due to its abundance, it will be an ideal material for small-scale distributed wind turbine systems in many areas. Bamboo wind turbines are less intrusive to the surrounding environment based on its intrinsic connection to earth. The idea of "planting" wind turbines will make the renewable energy utilization more appealing and environmentally adaptable. The system is isolated from current electric grids, making it a proper option for remote areas in developing countries. Finally, the light patterns on the rotating blades can be tailored to meet various functional needs in research, education and daily applications.

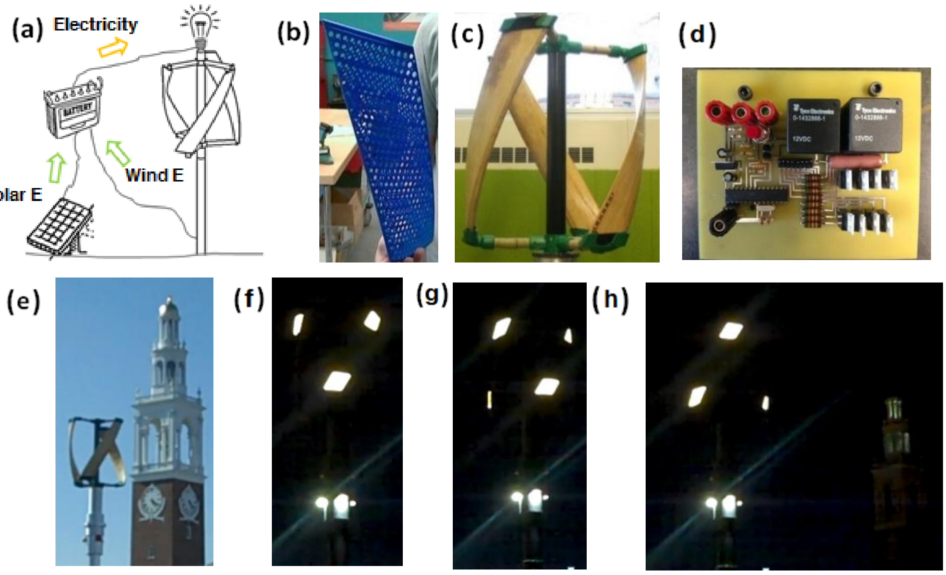


Fig. 6. (a) A schematic of the hybrid wind and solar energy harvesting system; (b) A 3D printed helical blade skeleton; (c) Close view of the bamboo helical wind turbine with the LED lights attached at the edge of the blades; (d) the integrated microprocessor used as the control system; Field view of the turbine on the roof (d) Images in day time; Snapshots of the rotating turbine at night (e), (f) and (g); the background is the Ira Allen Chapel at UVM.

6. Conclusions

This paper performed a review on studies of bamboo inspired materials. As a functionally graded grass composite in nature, bamboo is featured by the hierarchical patterns of the bamboo fibers and parenchyma cell structures, making it remarkable in strength, stiffness and fracture resistance. For a long time, bamboo has been used in many applications including housing and transportation. Due to the growing needs for sustainable materials, Bamboo fiber reinforced polymeric (BFRP) composites have been used to produce industrial products. Meanwhile, various FGMs have been developed to meet the thermal and mechanical needs inspired by the bamboo structure. The authors have developed a hybrid energy harvesting system consisting of a bamboo wind turbine and solar panels for renewable energy utilization. The bamboo abundance and the system independence could make it a sustainable energy solution for many areas in the world.

7. Acknowledgements

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