Bamboo-steel composite structures

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ABSTRACT: Environment-friendly construction materials and intelligent designs are necessary to maintain sustainable development of human society. Bamboo has high strength to weight ratio, and it is renewable and biodegradable. It has great potential to be used as a structural material once its limitations of application (e.g. dimensional instability, difficult connections, and inadequate bonding) are addressed. With advanced knowledge in material science and new technologies, laminated bamboo plywood, also called ply-bamboo, can be fabricated through the process of crushing, hot-pressing, adhesive spreading and gluing, cold-pressing, and curing. The bamboo plywood has stable dimensions and it is hydrophobic, and resistant to fungi and bacteria attack. Bamboo-steel structural members are composed of laminated bamboo plywood made from moso bamboo and cold-formed thin-walled steel sheet, which are bonded by structural adhesive and strengthened by screws. The cross section of a structural member with large radius of gyration and moment of inertia is easily formed using thin-walled steel sheet with less steel, but the structural member inclines to buckle globally and locally with increased width to depth ratio of the section. The laminated bamboo plywood is bonded to the surface of the steel sheet to keep the stability of the cross section. Various light weight bamboo-steel composite structural systems have been developed through several sponsored research projects e.g. slabs, walls, columns, and beams. Lab testing has indicated excellent performances of the structural members. This paper introduces the fabrication of the bamboo-steel composite slabs, walls, columns, and beams, summarizes the findings from the lab testing to evaluate their structural performance, and discusses the design methods to determine the load bearing capacities of the structural members.

KEYWORDS: Bamboo Plywood, Cold-Formed Thin-Walled Steel Sheet, Composite Structures

INTRODUCTION

Sustainable development is an enormous challenge facing the seven billion people who are living on the earth. As a huge source of carbon emission and energy consumption, construction sector should be handled responsively to the natural environment and human society. Environment-friendly construction materials need to be carefully selected and applied with the intelligent design to "*satisfy the present needs without compromising the ability of future generations to meet their needs* (Brundtland, 1987)". Characteristics of sustainable construction materials include high recycled and recyclable contents, rapid renewable and biodegradable products, regionally available resources, etc. Bamboo, a collection of giant grass species, has already attracted considerable attentions of architects, engineers, and researchers from all overall the world as a sustainable construction material.

Among 1,250 species of bamboo in the world, many can reach 15 meters (49 feet) high within 2 to 4 months, and the diameters of the plant can reach 15 centimeters (5.9 inches) within 3 to 8 years (Liese,1987; Lee et al, 1994). Phyllostachys pubescens, known as Moso bamboo, native in China, and Guadia angustifolis, known as Guadia bamboo, native in South America, are two most commonly cultivated species for structural purposes. It is interesting to notice in many Asian countries where bamboo is native, bamboo has already been used for structural purpose in building industry. But in the U.S. and the European countries, bamboo is commonly used in non-structural applications e.g. floor board, furniture, etc for ornamental purposes. Possibly this is because in many western countries, structural bamboo is not as widely available as wood, but it is totally opposite in many developing countries. Actually, structural bamboo possesses many mechanical properties superior to those of wood products. Table 1 compares strength and modulus of elasticity of moso bamboo culm with that of a dimension lumber made from southern pine in the US. In addition, comparing with other conventional materials such as wood, steel and concrete, bamboo has high strength/stiffness to weight ratios, shown in Figure 1.

Table 1: Strength and modulus of elasticity of moso bamboo culm compared with southern pine.

Material	Tension parallel to grain		Compression parallel to grain		Bending		Shear parallel to grain		Modulus of Elasticity: Tensile parallel to grain		Modulus of Elasticity: Compressive parallel to grain		Modulus of Elasticity: Bending	
	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi	MPa	psi
Moso bamboo culm [a]	191	27,688	65	9,442	149	21,596	18	2,654	11,400	1,653,430	6,370	923,890	11,600	1,682,437
Southern Pine [b] (Dense select structural)	11	1,650	16	2,250	21	3,050	1	175	13,100	1,900,000	4,757 [c]	690,000 [c]	13,100	1,900,000

[a] Data from Li et al (2007); [b] Data from National American Wood Council (2005); [c] minimum modulus of elasticity

Bamboo has a great potential to be used in building construction as a structural material. van der Lugt et al (2006) performed a life cycle analysis to evaluate the environmental impact of utilizing moso bamboo shipped from Shanghai, China to Rotterdam, Netherland, in construction, and concluded the bamboo could be used as a sustainable building material for western countries within certain boundary conditions. However, the bamboo swells once it absorbs moisture, it is difficult to connect bamboo members due to the hollow tube shape, and the bamboo culm is prone to fungi and bacteria attack. Therefore, it is of interest to develop laminated bamboo lumber or bamboo plywood, also called ply-bamboo (Janssen, 2010), by gluing bamboo strands or flattened surfaces taken from the bamboo culm to create shapes more suitable for modern structural applications.

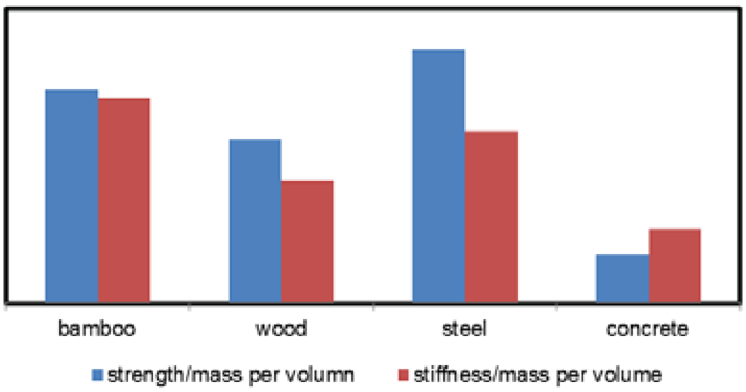


Figure 1: Strength and stiffness of different materials (adapted from Janssen, 2000).

Mahdavi et al (2011) reviewed three processing techniques to manufacture laminated bamboo products, and discussed the challenges and viability of using laminated bamboo lumber as an alternative structural material in North America. Mahdavi et al (2012) developed a low-technology approach using hand tools and economical adhesives to fabricate a laminated bamboo lumber which is suitable for use in building construction. Li et al (2012) investigated the technique of processing moso bamboo culm into laminated bamboo plywood through crushing, hot-pressing, adhesive spreading and gluing, cold-pressing, and curing. The end product has a normal thickness of 10 mm (0.39 inch) to 25 mm (1 inch). With advanced knowledge in material science and new technologies, as well as development of structural adhesives, the fabricated laminated bamboo plywood overcomes the disadvantages of bamboo culm. It is dimensional stable, hydrophobic, and resistant to fungi and bacteria attack. However, this product is usually used for concrete formwork or other applications in low technological end in China. On the other hand, thin-walled steel sheets are easily cold-formed to a cross section with a large radius of gyration and moment of inertia. Comparing to standard steel sections, the structural members formed using thin-walled steel sheet are much lighter, consuming much less steel, and they have been applied as roof rib beams, floor beams, wall supporting structure, etc. But the cold-formed thin-walled steel structural members incline to lose its global and local stability with increased width to depth ratio. To address this problem and take advantage of the economic value created by laminated bamboo plywood, the bamboo-steel composite structures are engineered by bonding the laminated bamboo plywood to the surface of the steel sheet.

Various light weight bamboo-steel composite structural systems have been developed through several sponsored research projects e.g. slabs, walls, columns, and beams. Lab testing has indicated excellent performances of the structural members. This paper introduces the fabrication of the bamboo-steel composite slabs, wall, columns, and beams, summarizes the findings from the lab testing to evaluate their structural performance, discusses the design methods to determine the load bearing capacities of the structural members.

2.0 FABRICATION OF BAMBOO-STEEL COMPOSITE STRUCTURES

2.1. Materials

Moso bamboo plywood was used in the fabrication of all composite structures in this paper. The zephyr strand mats were produced by crushing moso bamboo culms using a roller crusher. After hot-pressing between 150°C and 180 °C to achieve a stable dimension, and removing inner and outer layers of the mats, the mats were glued together using a resorcinol-formaldehyde resin. The fabricated panels were cold-pressed for several hours until all layers were fully bonded and then cured at least two weeks at 25°C and 65% relative humidity (Li et al, 2012). The bond created by the structural glue is resistant to water, as well as chemical and biological attacks. The modulus of elasticity (MOE) and modulus of rupture (MOR) of eight bamboo plywood samples were measured according to ASTM D 4761 and listed in Table 2. Table 3 shows the MOE and MOR of common construction materials. The bamboo plywood is more flexible and stronger than the Douglas-Fir dimension lumber. It is expected the lifetime of the laminated bamboo plywood is equivalent to or even longer than the lumber and glued laminated wood products. The MOE and MOR of a typical structural steel are 200,000 MPa and 400 MPa respectively. The MOR to MOE ratio of steel is 0.002. For bamboo plywood, the ratio is 0.0064 (Table 2). This means bamboo plywood has larger deformation capacity than structural steel when rupture occurs. When the two materials are bonded together, the strength of the steel can be fully developed if the bonding does not fail. At the end of life, landfill of the bamboo plywood does not cause environmental concerns because of its biodegradability.

Table 2: Mechanical properties of bamboo plywood

Bamboo Plywood	MOE		MOR	
	MPa	psi	MPa	psi
Mean	5896	855,142	96.5	13,996
Standard deviation	412	59,756	6.65	965
Coefficient of variation	0.070		0.069	

Table 3: Mechanical properties of common construction materials (Mahdavi et al, 2011)

	MOE		MOR	
	MPa	psi	MPa	psi
Douglas-Fir	13600	1,970,000	88	12,760
Aluminum Alloy	69,000	10,005,000	200	29,000
Structural Steel	200,000	29,000,000	400	58,000

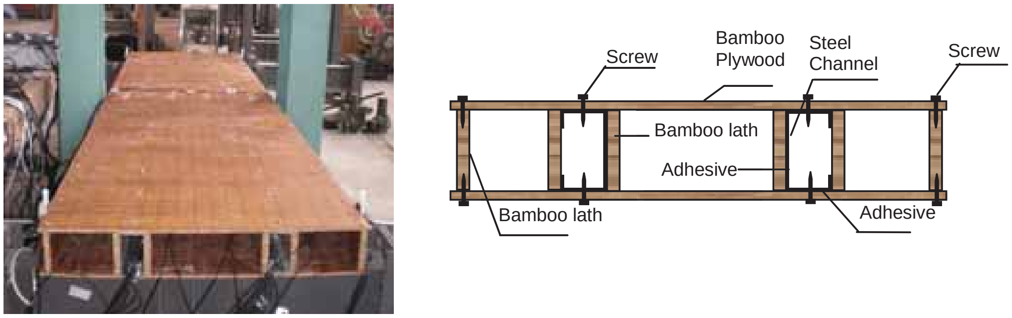
The cold-formed thin-walled steel sheet used for the manufacture of composite structures has a nominal MOE of 206 GPa (29,878 ksi), a nominal yield strength of 235 MPa (34 ksi), and a nominal ultimate tensile strength of 375 MPa (54 ksi). The thickness of the steel sheet ranges between 1 mm (0.0039 in) to 2 mm (0.079 in). The steel sheet can be recycled into another product at the end of its life.

The bamboo-steel composite structures are composed of bamboo plywood and cold-formed thin-walled steel sheet bonded by structural adhesive, and strengthened by self-tapping screws (enhanced connection). The enhanced connection minimizes the slippage at the interface of the two materials due to external forces or temperature change. The structural adhesive is a common rapid curing and high strength epoxy resin used for bonding metal, wood, and other construction materials. The amounts of structural adhesive used in various composite structural members are discussed in Section 3.0. Zhang et al (2015) developed a theoretical model to evaluate the performance of pure adhesive bonding of the bamboo-steel composite structure. The authors of this manuscript are investigating the bonding strength and slippage of the enhanced connection under the short term and long term static loads. Fabrications of the composite structural members will be discussed in the following sections. Composite slabs, walls and columns have hollow cross section, which can be filled with different materials for insulation or sound-proofing. In addition, the electric wires, cables, or pipes easily pass through these hollow structural members.

2.2. Bamboo-steel composite slab

The bamboo-steel composite floor slab is composed of two pieces of bamboo plywood attached to the flanges of cold-formed thin-walled steel channels, which is shown in Figure 2(a). The flexural behaviors of six slabs with three different types of connections were evaluated by Li et al (2012). The slabs were 0.9 m X 0.33 m X 3 m (2.95 ft X 1.08 ft X 9.84 ft) and the two steel channels were spaced 0.45 m in the middle. Three specimens had simple adhesive connection between the bamboo plywood and the flange of steel channel. One specimen had adhesive connection strengthened by screws. The other two used the bamboo laths to improve the stability of the steel channel by attaching them to both sides of the channel (Figure 2b).

The lab testing indicated the bending capacity, stiffness and stability of specimens were improved by enhanced connection and bamboo laths. The slabs with this type of connection exceeded the structural requirements of floor slabs. Enhanced connection with bamboo laths are recommended for the construction. Strain gages were attached to the steel channel and the bamboo plywood to measure the deformations of the materials. The testing results showed both materials were in the elastic range before rupture occurred. The interface of the recommended connection performed well. Large deformation of the slab was the warning sign of rupture. Therefore, a transformed-section method was proposed by Li et al (2012) to analyze the deformation and bearing capacity of the whole member. The cross-section area of bamboo plywood was transformed to the equivalent area of steel to determine the stiffness of the whole section. The theoretical values predicted by the simplified calculation matched the testing results well. This method can be used in the design of the composite structure.

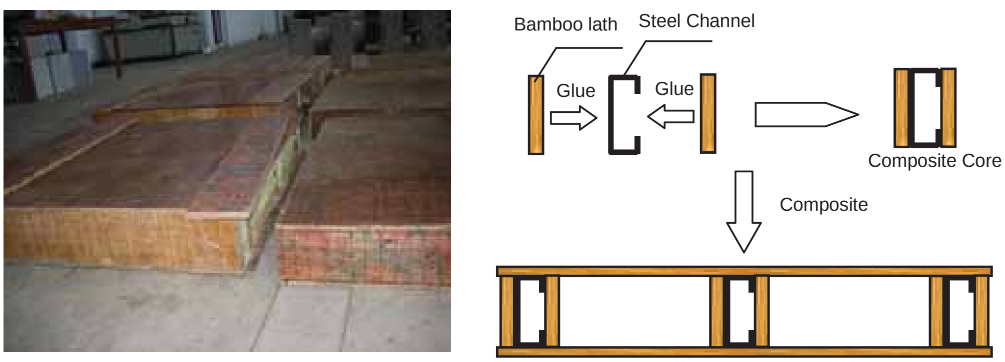


(a) Slab (b) Cross Section

Figure 2: Bamboo-steel composite slab.

2.3. Bamboo-steel composite wall

Two types of composite walls have been developed. The first type is used as building envelope and partition wall, shown in Figure 3. The other is designed to resist lateral forces i.e. wind and seismic loads. The fabrication of exterior or interior walls is illustrated in Figure 3 (b). Two 20 mm (0.79 in) thick bamboo plywood laths are glued to both sides of the cold-formed thin-walled steel channel to form the core of the wall. Then two pieces of bamboo plywood are attached to the top and bottom surfaces of the core. Thirteen specimens with two different insulation materials (glass fibers and polyurethane foam), various wall thicknesses, with/without extruded polystyrene board exterior insulation were evaluated for their thermal behaviors. The thermal conductivity of the composite walls with the two different insulation materials was between 0.145 and 0.387 W/(m^2·°C). The specimens filled with polyurethane foam had better thermal performance than the specimens with glass fibers. The phenomenon of thermal bridge was observed at the location of cores. The effect could be weakened by applying the extruded polystyrene board exterior insulation system, which improved the insulation of the composite walls (Xu, 2012).



(a) Wall (b) Fabrication and Cross Section of Walls

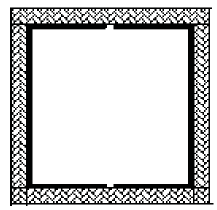
Figure 3: Bamboo-steel composite wall.

The composite walls designed to resist lateral forces have similar cross section shown in Figure 3(b). But the interface between the bamboo plywood and the steel flange was strengthened by screws. A quasi-static testing was performed for six walls with various thicknesses of bamboo plywood and different sizes of steel channel to evaluate their failure mechanisms, seismic behaviors, and lateral force bearing capacities (Li et al, 2013). The thickness of steel sheet and the dimension of steel channel, rather than the thickness of bamboo plywood, determine the seismic behavior and the lateral load bearing capacity of composite walls. The composite walls exhibited good ductility and could dissipate seismic energy. The lateral load bearing capacity of the wall was contributed by the composite core and the bamboo plywood. Both members were bent to failure under the lateral force. The lab testing indicated the specimens had excellent composite performance, therefore it was assumed both the composite cores and the bamboo plywood had same deformation at the connections before rupture. According to the transformed-section method, the lateral load bearing capacity of the composite wall could be established by transforming the cross section area of bamboo plywood to an equivalent area of steel, also assuming the steel yields when rupture occurs. Composite walls with profiled steel sheet in the center of the wall were also evaluated for their seismic behaviors (Li et al, 2010). But their performances were not as good as the walls with composite cores. It's recommended to use the walls illustrated in Figure 3 in the construction.

2.4. Bamboo-steel composite column

The composite column with a hollow square shape is shown in Figure 4. The fabrication is relatively easy. The bamboo plywood is attached to the web and flanges of two pieces of cold-formed thin-walled steel channels by structural adhesive and strengthened by screws. The performance of the columns under axial compression was tested by Xie et al (2012) to explore their failure mechanism and axial load carrying capacities. The testing shows the specimens failed due to the debonding of the connection between bamboo plywood and steel, and the local buckling at the web of steel channel. But before the rupture occurred, specimens exhibited good composite effect.

(a) Column



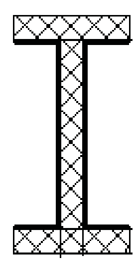
(b) Cross section of composite column

Figure 4: Bamboo-steel composite column.

2.4. Bamboo-steel composite beam

The cross section of the bamboo-steel composite beam is composed of three pieces of bamboo plywood and two cold-formed thin-walled steel channels. The two steel channels are glued to the central bamboo plywood, and then two pieces of bamboo plywood are attached to top and bottom of the section. The failure mechanisms, failure modes, deformations, shear and bending bearing capacities of nine composite beams were investigated by Li et al (2011), in order to understand the influence of flange thickness, web width, thickness of steel sheet, overall sectional dimensions, and ratio of shear span to depth on flexure and shear behaviors of composite beams. As the loading increases, the beam went through elastic, elastic-plastic, and failure, three stages. The nominal bending and shear capacities were determined by the maximum load in the elastic range carried by the composite beam, which is approximately 30-50% of the ultimate load. Debonding of the two materials, local buckling and yielding of the steel occur in the elastic-plastic and failure stages. Higher bearing capacity and stiffness could be provided by thicker bamboo plywood and steel channels. The cross section area and the ratio of shear span to depth are main contributors to shear capacities of the composite beams. The beams exhibited excellent composite effect in the elastic range. Therefore, simplified models were proposed based on transformed-section method and superposition principle. The nominal bending and shear capacities of the beams determined from the models matched well with the experimental values.

(a) Beams



(b) Cross section of beams

Figure 5: Bamboo-steel composite beam.

To connect the bamboo-steel composite structure members, regular steel connectors for wood and steel structures can be used. To strengthen the stiffness of the joint, a steel tube was designed by welding four steel plates around the core of the column and beam connection (Figure 6). Two steel "T" connectors were used to bolt the beam with the column. Li et al (2013) performed quasi-static tests on 6 composite beam-column joints with or without stiffener to evaluate the ductility, energy dissipative capacity, and other seismic parameters of the joints with different numbers and grade of bolts. It showed the bolts had little effect on the performance of the joints, but the stiffener and the weld size controlled deformations at the core and ultimate load capacities of the joints. The special connection can be used at the exterior joints of a building to resist large lateral forces e.g. seismic load.

(a) Connection (b) Sketch of the connection

Figure 6: Connection for bamboo-steel composite beam and column.

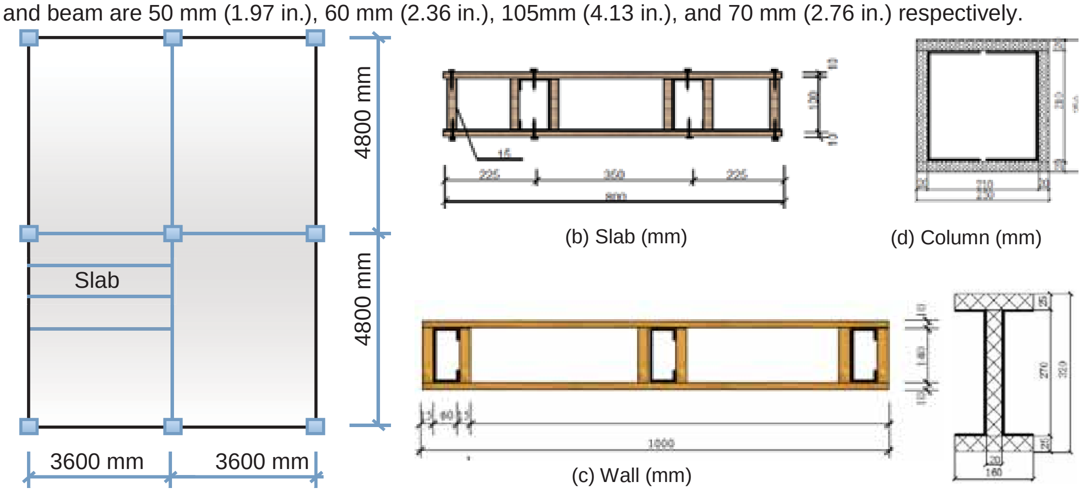
3.0 CASE STUDY

A two story simple building with a floor plan shown in Figure 7(a) was designed to use the bamboo-steel composite structural system. Each story is 2.8 m high (9.2 ft). The following conservative parameters were assumed in the design:

(1) Floor live load: 2 kN/m^2 (42 psf)
(2) Dead load:
- Walls and partition: 1.6 kN/m^2 (34 psf)
- Ceilings, mechanical system, misc.: 1.5 kN/m^2 (33 psf)

(3) Modulus of elasticity:
Bamboo plywood: 5.5 GPa (798 ksi)
Cold-formed thin-walled steel: 206 GPa (29,878 ksi)

According to the design methods for bamboo-steel composite structures proposed by corresponding research studies discussed above, composite slab, wall, column and beam were designed. The dimensions of cross sections are shown in Figure 7 (b). The thickness of steel sheet is 1mm (0.039 in) for slab and wall and 2 mm (0.078 in) for column and beam. The flange widths of the steel channel in the slab wall, column and beam are 50 mm (1.97 in.), 60 mm (2.36 in.), 105mm (4.13 in.), and 70 mm (2.76 in.) respectively.



(a) Floor plan (b) Slab (mm) (c) Wall (mm) (d) Column (mm) (e) Beam (mm)

Figure 7: Floor plan of a simple building.

The bearing capacity of the composite structural members and the consumption of materials are summarized in Table 4. Shown in the table, structural adhesive accounts for only 1% of overall weight of the composite structures. Its environmental impact is not significant. Because of the regular shape of the cross section, the construction wastes can be minimized. The unit cost of bamboo plywood is \$488/m^3 (\$13.59/ft^3), unit cost of steel sheet is \$780/tonne (\$0.35/lb), cost of structural adhesive is \$6.5/kg (\$2.95/lb), and rate of application is 0.3 kg/m^2 (0.061 lb/ft^2). The material costs of each slab, wall, column and beam are summarized in Table 5. The composite structures will be fabricated in China. The costs of the materials were converted from Renminbi to US Dollars. The composite structures have economic advantage, but the authors don't have specific data at this point to show the economic benefits of the bamboo-steel composite structure in terms of materials by comparing it with other conventional construction material. A comprehensive analysis for life cycle cost and environmental impact needs to be performed to measure and quantify the sustainability of the composite structures.

Table 4: Bearing capacity and materials consumption.

	Bearing Capacity		Volumn of bamboo per specimen		Mass of bamboo per specimen		Volumn of steel per specimen		Mass of steel per specimen		Mass of structural adhesive per specimen	
Slab	12.19 kN·m	8,991 lbf·ft	0.09 m^3	3.18 ft^3	67.5 kg	149 lbm	0.0017 m^3	0.060 ft^3	13.6 kg	30 lbm	0.71 kg	1.56 lbm
Wall	475 kN	107 kipf	0.078 m^3	2.75 ft^3	58.9 kg	130 lbm	0.0024 m^3	0.085 ft^3	18.7 kg	41 lbm	0.84 kg	1.85 lbm
Column	506 kN	114 kipf	0.052 m^3	1.84 ft^3	38.6 kg	85 lbm	0.0047 m^3	0.166 ft^3	36.6 kg	81 lbm	0.77 kg	1.70 lbm
Beam	84.02 kN·m	61,970 lbf·ft	0.064 m^3	2.26 ft^3	48.2 kg	106 lbm	0.0116 m^3	0.410 ft^3	91.3 kg	201 lbm	1.24 kg	2.73 lbm

Table 5: Costs of bamboo-steel structural members.

	Bamboo ($)	Steel ($)	Adhesive ($)	Total ($)
Slab	43.95	10.58	4.64	59.17
Wall	38.21	14.57	5.49	58.27
Column	25.16	28.58	5.03	58.77
Beam	31.41	71.37	8.07	110.85

CONCLUSION

The fabrications and mechanical behaviours of bamboo-steel composite structural members were summarized in this paper. The composite structures are composed of bamboo plywood and cold-formed thin-walled steel channels bonded by structural adhesive and strengthened by screws. Researchers have already shown bamboo has great potential to be used as a sustainable structural material, especially the laminated bamboo lumber and bamboo plywood. The bamboo-steel composite structures discussed in this paper are light weight and easy to fabricate. They take advantage of sections with large moment of inertia and radius of gyration formed by the thin-walled steel sheet, and the stability created by bamboo plywood. The lab testing for composite slab, wall, column, and beam indicated the two materials performed excellent composite effect under proper bonding created by structural adhesive and screws. The transformed-section method was proposed to determine the load bearing capacities of various composite structural members. The theoretical models were used to design the structural members of a two story building. The costs of materials show the composite structural system has economic advantage but the benefit needs to be determined by a life cycle analysis.

However, some issues have not been addressed by the existing studies. Bonding at the interface between bamboo plywood and steel sheet plays an important role in influencing the performance of the composite structures. The authors of this manuscript are investigating the bonding stress and slippage at the interface of the two materials under short term and long term static loads. The behaviour of the interface under the dynamic or reversal loads needs to be evaluated. As the un-braced length of the composite beam increases, lateral torsional buckling of the beam occurs. The simplified model does not consider the influence of un-braced length on the ultimate bending capacity of the beam. The durability of the composite structural members needs to be investigated especially under the extreme environmental conditions. In addition, as discussed in Section 3, a life cycle analysis model for the bamboo-steel composite structure needs to be established to evaluate and compare the sustainability of the composite structures with other conventional structures. These issues will be addressed in the future research studies.

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