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Flexural behavior of bamboo–fiber-reinforced mortar laminates

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Abstract

This paper reports the flexural behavior of bamboo–fiber-reinforced mortar laminates. The laminate considered in this study is a sandwich plate combined with reformed bamboo plate and extruded fiber-reinforced mortar sheet. Due to its high strength to weight ratio, the reformed bamboo can remarkably strengthen the mortar and reduce the total weight of the laminate. Test results show that, for the laminates with reformed bamboo plate on the bottom as tensile layer and fiber-reinforced mortar sheet on the top as compressive layer, the flexural strength values can be improved to greater than 90 MPa.

Keywords: Bamboo; Composite; Flexural strength; Mortar

1. Introduction

Bamboo is a natural perennial grass-like composite and contains ligno-cellulosic-based natural fibers. It occurs in the natural vegetation of many parts of tropical, subtropical and mild temperature regions, with about 1250 species identified throughout the world [1,2]. Due to its superior properties like high strength to weight ratio, high tensile strength and other factors like low cost, easy availability and harmless to the environment during service, bamboo has constantly attracted the attention of scientists and engineers for use as reinforcement in cementitious composites. Recently, many researchers have tried to use bamboo as substitute of steel in reinforced concrete. Chembi and Nimityongskul [3] and Winarto [4] have reported its use in construction of water tanks. Ghavami [5] has used it for reinforcement of lightweight concrete beams. Venkateshwarlu and Raj [6] and Raj [7] have developed bamboo-based ferrocement slab elements for roofing/flooring purpose in low cost housing. Kankam et al. [8,9] have studied its applications in reinforced concrete slabs.

However, wide applications of bamboo in civil engineering were limited by its disadvantages in the past. The principal disadvantages in its natural form are its poor bond with concrete, low modulus of elasticity, high water-absorption tendencies, low durability, and low resistance to fire. Nowadays, some of these shortcomings can be significantly improved by subjecting the bamboo to appropriate treatments [10]. In addition, when bamboo is reformed to a plate form, its performance can be improved further.

This current study investigated the preparation and flexural properties of a newly developed bamboo–fiber-reinforced mortar laminate. The laminate was a sandwich plate combined with reformed bamboo plate and extruded PVA fiber-reinforced mortar sheet. Test results showed that the reformed bamboo plate can greatly strengthen the fiber-reinforced mortar and reduce the total weight of the composite, and the flexural strength values of the laminate can be improved to greater than 90 MPa.

2. Materials and specimen preparation

2.1. Materials used

2.1.1. Reformed bamboo plate

Reformed bamboo plates with dimensions of 600 × 50 × 5 mm were supplied in this study. They were innovated from the raw bamboos, so that the superior properties like high tensile strength, etc. were fully made use of, and limitations

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Table 1
Average properties of reformed bamboo, natural bamboo and PVA fiber reinforced mortar sheet

Properties	Natural bamboo	Reformed bamboo	PVA fiber reinforced mortar
Fiber volume fraction, %	29.2	43.6	2.0
Density, g/cm^3	0.66	0.87	2.26
Tensile strength, MPa	206.2	271.5	12.9
Tensile modulus, GPa	20.1	29.0	–
Flexural strength, MPa	210.3	276.6	17.5
Flexural modulus, GPa	13.1	18.2	28.6
Compressive strength, MPa	78.7	104.7	85.9

such as low modulus of elasticity, lesser durability, etc. were duly taken care of. The fabricating process of reformed bamboo plate consists of three procedures. Firstly, the culms of raw bamboo were split and cut into the required sizes. Secondly, steaming to make them soft enough so that the shape can be changed. Thirdly, applying hot press to change the shape from a natural circular cross-section to a plate form and hold a certain period of time to fix the plate form. Additional mention is that bamboo strips are processed by super heat steam, which not only killing moth inside but also carbonizing the strips. Thus, the reformed bamboo has features of moth, mildew resistant and will be more durable when compared with nature bamboo.

The average properties of reformed bamboo and natural bamboo were listed in Table 1. It was found from the table that all the properties of reformed bamboo are obviously better than that of natural one.

2.1.2. PVA fiber-reinforced mortar sheet

PVA fiber-reinforced mortar sheet was mixed with white cement, microslag, discontinuous PVA fibers, silica sand, superplasticizer and water, extruded from a special vacuum extruder which had a screw rotation speed of 12–70 ppm. The mixture proportions were 0.5:0.5:0.325:0.01 of cement:microslag:silica sand:superplasticizer and water to binder ratio of 0.28, all measured by weight. The short PVA fibers with volume fraction of 2% used in this experiment have a length of 6 mm with an average diameter of 14 μm, a density of 1.3 g/cm^3 and an average tensile strength and elastic modulus of 1500 MPa and 36 GPa, respectively. A vacuum chamber was arranged between the two screw sections, namely mixing section and extruding section. The function of the first section is to further mix all the fed materials and push them into the vacuum chamber in which the surplus air in the materials is removed. The second one extrudes the deaired materials forward and out through a designed die. After the extrudates were pushed out of the thin sheet die with a thickness of 6 mm, they were covered by a plastic plate to prevent the elastic swell. Then the extrudates were placed in a KATA Isothermal Testing System Chamber (SSE-28CI-A) for 28-day equivalent low-pressure steam curing. The properties of this PVA fiber-reinforced mortar sheet were also shown in Table 1.

2.1.3. Adhesive

Thermoplastic ethylene–acrylic acid copolymer (EAA) polybond granules with an average diameter of 4 mm, an average softening temperature and melting temperature of 125 and 140 °C, were used in making bamboo–fiber-

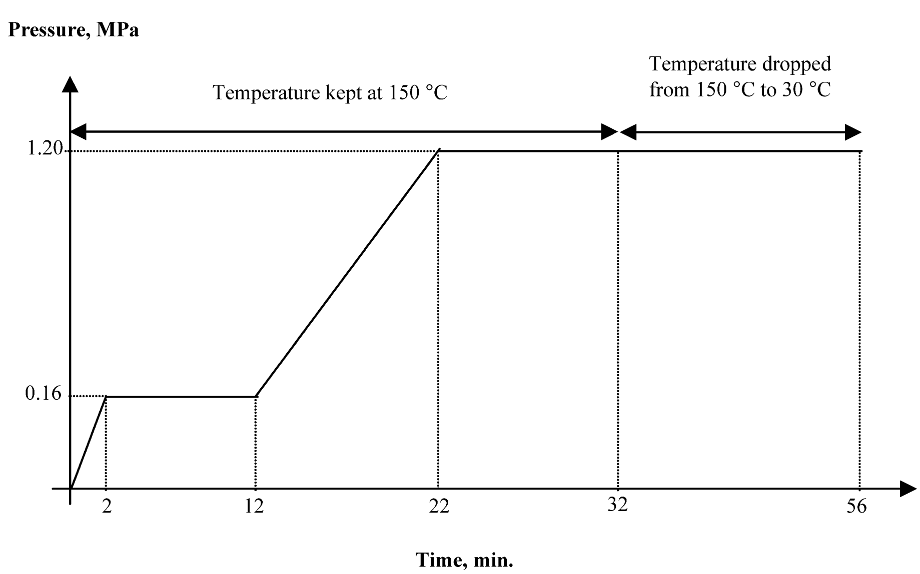

Fig. 1. Temperature–time profile for adhesive bonding under hot pressure.

reinforced mortar laminates. When EAA granules were used, the composite should be prepared with a hot-press.

2.2. Specimen preparation

The general procedures for the specimen preparation were described as follows.

(a) Due to the size limitation of the hot press machine, we cut the reformed bamboo plates and fiber-reinforced mortar sheets to a planer size of 350 × 50 mm.

(b) Removed dust from the surface of reformed bamboo plates and fiber-reinforced mortar sheets with compressed air.

(c) Adhesive bonding between reformed bamboo plate and fiber-reinforced mortar sheet with a hot press. The temperature versus time profile used for cure of adhesive was shown in Fig. 1.

(d) Coating 6 of 12 laminates on both sides by using *Epikote 815 Epoxy* with one layer of glass fiber fabric, so that a smooth and shiny surface was standing for engineering applications. The glass fiber fabric has 10 threads per centimeter in both the longitudinal direction and transverse direction. The average thickness of the fabric is 0.1 mm and the tensile strength is 38 MPa. The coatings can act as protective layers for improving the durability of the laminates.

The construction and dimensions of the laminate with coatings are shown in Fig. 2. The laminate incorporated with reformed bamboo- and fiber-reinforced mortar is of attractive advantages, such as higher strength and lower bulk weight (the density of the laminate is about 1.63 g/cm^3) attributed to reformed bamboo, and improved stiffness attributed to fiber-reinforced mortar.

3. Experimental program and results

3.1. Experimental program

The three-point flexural test was conducted according to the requirements of ASTM D3043-87, *standards methods of testing structural panels in flexure*.

The flexural tests were carried out at a loading rate of 0.5 mm/min on a computer controlled MTS810 universal-testing machine with a maximum load of 100 kN. The span for specimens was set as 300 mm. The load was read from the load cell and the midspan deflection was measured by the LVDT. Plot of load versus deflection was shown on the computer screen during the test.

3.2. Test results

The flexural strengths of the laminates were analyzed according to the elementary theory of flexure of beams, which were calculated from the following equation:

$$\sigma_f = \frac{3PL}{2wt^2} \quad (1)$$

where σ_f is flexural strength, P is the maximum applied load, L is the span, w is the specimen width and the t is the specimen thickness.

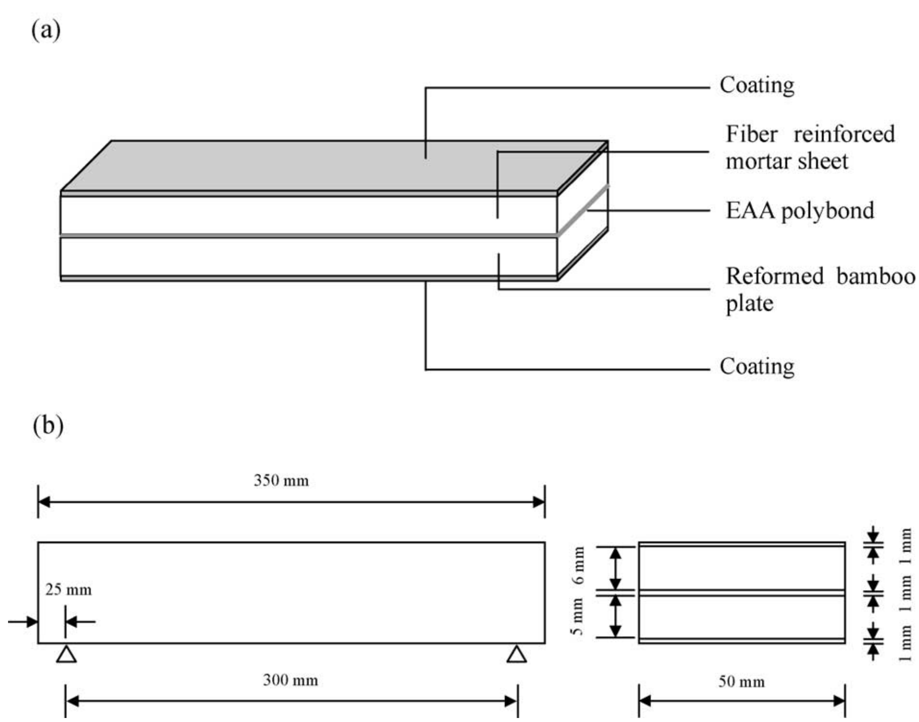

Fig. 2. Construction (a) and dimensions (b) of reformed bamboo-fiber reinforced mortar laminate.

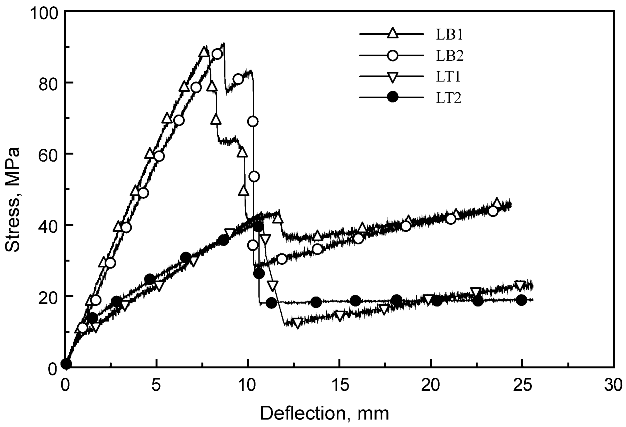

Fig. 3. Stress–deflection curves of bamboo-fiber reinforced mortar laminates.

The flexural curves of stress–deflection at the middle of span are shown in Fig. 3. The coated laminates with bamboo on the bottom and the top were denoted as LB1 and LT1, respectively. While the corresponding control laminates without coatings were denoted as LB2 and LT2. The curves shown in Fig. 3 indicate that there is little effect between the laminates with and without coatings. (The average flexural strengths are 90.4 and 91.1 MPa for LB1 and LB2, while 42.8 and 40.7 MPa for LT1 and LT2, respectively.) However, it can be seen that the flexural behavior of the laminates with bamboo on the top and those with bamboo on the bottom are obviously different. From the testing results, it is found that up to nearly the stress of 10 MPa, both of the laminates show the same rigidity. Then, with the increase of stress, the gradient of the curves for both of LB1 and LB2 does not change, but there is a very noticeable change of the gradient for the curves of LT1 and LT2. The large increase in the deflection of the laminates with bamboo on the top, as compared with that of the laminates with bamboo on the bottom, was attributed to the relatively low value of the tensile strength of fiber-reinforced mortar. Thus, after the point of stress of 10 MPa, the fiber-reinforced mortar located on the bottom of the laminate was fractured, and the applied load was supported mainly by the bamboo located on the top of the laminate. In this case, the ultimate flexural stress σ_f' was expressed as

$$\sigma_f' = \sigma_{fb}\left(\frac{t_b}{t}\right)^2 \quad (2)$$

where σ_{fb} is the flexural strength of reformed bamboo and t_b is the thickness of the reformed bamboo plate. Since the value of flexural strength of reformed bamboo is 276.6 MPa, the thickness of the reformed bamboo plate is 5 mm, thus, the ultimate flexural stress of the laminate with bamboo on the top is about 40.9 MPa in theory, which was in good agreement with the experimental results.

For the laminate with bamboo on the bottom, up to the stress of 90 MPa, it showed a linear behavior. The ultimate flexural stress for this kind of laminate is twice higher than that of laminate with bamboo on the top. This is mainly related to the high compressive strength of the fiber-reinforced mortar and the high tensile strength of the reformed bamboo. Test results indicated that when the reformed bamboo plate was put on the bottom of the laminate as tension layer and the fiber-reinforced mortar sheet was put on the top as compressive layer, the laminate showed a high flexural resistance. Then, after the peak stress, due to the compressive failure of fiber-reinforced mortar on the top of the laminate, the flexural stress dropped gradually with the increase in deflection.

However, the predominant ductility characteristics were displayed for the laminates. It can be seen from Fig. 3 that, even when the midspan deflections reached 24 mm, the residual flexural stresses of about 40 and 20 MPa are obtained for the laminates with bamboo on the bottom and the laminates with bamboo on the top, respectively.

4. Conclusions

Due to its high strength to weight ratio, when reformed bamboo combined with fiber-reinforced mortar, it can remarkably strengthen the mortar and reduce the total weight of the composite. While the bamboo in the composite can also be stiffened by the mortar. The results of this investigation show that for the laminates with reformed bamboo plate on the bottom as tension layer and the fiber-reinforced mortar sheet on the top as compressive layer, the flexural strength values can be improved to greater than 90 MPa.

It is should noted that bamboo is a cheap and replenishable agricultural resource and abundantly available in some countries such as China, India and within the Southeast Asia region. Thus, it would be expected that the low-cost bamboo-reinforced constructional and housing products have a widely market in present and future time in Asia.

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