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Mechanical behavior of connections for glubam-concrete composite beams

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HIGHLIGHTS

- Proposed a new composite beam with glued laminated bamboo or glubam and concrete.
- Tested behaviors of various connections for glubam and concrete composite beams.
- Several connectors are identified as suitable for glubam concrete composite beams.

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ABSTRACT

This paper reports testing results of various connections for composite beams made of concrete slab and glue-laminated bamboo (glubam) beam. Six types of composite connectors, commonly used in timber-concrete composite (TCC) beams, were tested under direct shear condition. The shear force-slip relationships were measured and all the relevant mechanical properties such as slip moduli and shear capacities were obtained. Compared with typical TCC beam connections, the Glubam-concrete composite (BCC) systems present several different characteristics. The shear failure along the notch, typical in TCC notched connectors was not observed for BCC system, however, the delamination cracking along the lamination layers occurred in some types of BCC connections. Based on the test results and analysis, six types of connectors can be classified into two categories, one with higher strength and stiffness but low ductility, and the other with lower strength and stiffness but higher ductility. A set of regression equation with a bilinear descent segment is also provided for simulating the shear-slip behaviors of each type connector. It is found that some of the connection systems including the notched connector, steel mesh connector, screw connector and pre-tightening notched connector, are more suitable and recommended for constructing BCC structures.

1. Introduction

Concrete and steel are two most widely used conventional structural materials in modern construction. But the problems such as the high-energy consumption and the high pollution in production process are becoming unbearable burden in today's trend towards the sustainable development. Utilizing renewable natural resource as the main structural material to replace steel and concrete in a certain extent is a possible way leading to sustainable construction. At present, wood is the most widely used natural and organic material in many industrialized counties in North America and Europe. With limited wood resource and the strict policies of preserving forest, wood structure and wood buildings find few development in the past thirty years in China. On the other hand, China is one of the world's richest countries with bamboo resource. Therefore, using bamboo as a structural material and developing bamboo structures may become an alternative way for the sustainable development in China.

Glubam, a new type of glue-laminated bamboo, was developed by Xiao et al. [1]. Glubam is different from traditional bamboo veneer which is mainly used as concrete framework, and is designed with special laminate structure of bamboo fibers. The main nominal mechanical properties of glubam shown in Table 1 are equivalent or higher than glulam, which is a type of engineered lumber product using structurally graded timber laminations [2–5]. Glubam shows excellent durability under indoor conditions

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Table 1
Basic material properties of glubam sheet.

Type	In-plane longitudinal compressive strength (MPa)	In-plane longitudinal tensile strength (MPa)	Bending strength (MPa)	Density (kg/m^3)	Elastic modulus (MPa)
Nominal	54	80	75	880	9400
Actual	57	86	79	886	9460

Note: 1. Moisture content of specimens was 12%; 2. Nominal values are the mean values obtained for this type of glubam and actual values are the values obtained for the batch used in this program.

and it can have acceptable durability exposure to outdoor conditions with simple protection measures [6,7].

Till now, several modern bamboo structural buildings have been constructed with glubam as the basic structural material [3]. For glubam-only flexural members, the main drawback of mechanical properties is of relatively low stiffness which may lead to increased deflection compared with reinforced concrete structure or steel structure. The development of the timber-concrete composite (TCC) beams has been demonstrated as a good solution to timber structures. The TCC beam is composed of a lower timber beam and an upper concrete slab, which are connected by shear connectors. The excellent performance of two materials can be utilized, in which timber carries tensile force and concrete resists compression. The TCC systems have been investigated by many researchers and are widely used in floor structures and bridges [8]. Related to the key issues of connection of TCC beams, Ceccotti [9] designed several types of fasteners for connecting concrete slab and timber and sorted the connectors as flexible and rigid according to the load-slip relation. Gutkowsi et al. [10] and Yeoh et al. [8] tested notched connecters for wood-concrete beams. The results showed that the length of the notch, the presence of a lag screw and the prestressing of the screw have important effects on strength and stiffness of connections. Clouston et al. [11] selected adhesive to bond metal shear connectors and performed shear-slip tests of TCC specimens. The glued connection system exhibited near full composite action besides the advantage of being easy to install. Eisenhut et al. [12] investigated adhesive-bonded TCC system in which the interface was connected by epoxy resin only. A so-called "rigid bond" can be achieved but its composite effect was sensitive to internal stress, temperature and moisture. With the aim of developing a fully prefabricated TCC system, Lukaszewska et al. [13] chose seven types of connectors in their tests. Some connection types have acceptable simplicity and relatively low cost for the composite system. Crocetti et al. [14] also designed and tested two types shear connectors, steel tubes and wooden anchor keys, used in TCC structures with prefabricated fiber-reinforced concrete (FRC) slabs. Both of the proposed connection systems showed a high degree of composite action and all specimens were very easy to assemble. Auclair et al. [15] presented a new composite connector for TCC system which consists of a composite cylinder made of ultra-high performance fiber concrete shell with a steel cylindrical core. Analysis showed that TCC beam with such connector can obviously enhance its ductility without significant loss of flexural stiffness and load bearing capacity.

To study the composite action, Grantham et al. [16] conducted a full-scale TCC floor test which was converted from an existing timber floor. They found that the actual collapse load could significantly exceed the design load. Gutkowski et al. [17] tested several timber-concrete layered beams connected with notch shear connector and found that the concrete segregation in the notched zone resulted in low performance of the system. Premrov et al. [18] reported an experimental study performed on TCC beams strengthened with carbon fiber reinforced polymer (CFRP). The method was suitable for the reconstruction and strengthening of old timber floors. Ceccotti et al. [19] performed a five-year long-term test on a TCC beam with glued-in rebar connector. The long-term test showed an increase in deflection mainly during the first two years, while the slip rose during the whole testing period. Fragiacomo et al. [20] investigated eight floor/deck system beams with notched connector for a period of 133 days. It was found that the rheological phenomena of the component materials lead to quite large deflections over the entire service life. In parallel with experimental tests, finite element (FE) models were developed to analyze the force-deformation relationship of the TCC systems. Fragiacomo et al. [21,22] presented a one-dimensional (1D) FE model for non-linear analysis to TCC beams, while Chassagne et al. [23] and Dias et al. [24] implemented three dimensional (3D) FE models for non-linear analysis. A comparative analysis between 1D model and 3D model was performed on a TCC beam and results revealed that similar accuracy can be achieved [25]. Recently, on the vibrations and fire performance of TCC systems, Santos et al. [26] studied the mode shapes and frequencies of the TCC floor and Meena et al. [27] conducted experimental and numerical research of fire resistance of the TCC decks, respectively.

For improving the bending performance of bamboo flexural members, the authors develop a new type of composite structure, named as the Glubam-concrete composite or bamboo-concrete composite (BCC) system, based upon the existing technologies of the TCC system. In order to optimize the behavior of the composite beam, stiff and strong connectors should be used so as to achieve high composite action. Many different connectors were proposed and researched for the TCC systems, such as dowel connection, glued connection and notched connection. Considering obvious difference in the fiber structure, manufacturing process and mechanical performance between glubam and timber or engineered wood, research results of the TCC cannot be directly utilized in the BCC. This paper reports the outcomes of an experimental program on testing six types of connectors, in order to obtain the basic mechanical properties such as stiffness and shear strength of different connectors and to evaluate feasibility for selecting connectors in the BCC system.

2. Experimental program

2.1. Materials

Glubam sheets were chosen to manufacture the bamboo section in the BCC beams. Glubam sheet has its own structural characteristics and its fiber laminating direction within board forms three different planes [1–3]. As shown in Fig. 1, two planes perpendicular to axis Z are surfaces; four planes parallel to axis Z are cutting planes. Glubam is a typical orthotropic material with its fiber in longitudinal direction typically designed four times of that for transverse direction. Glubam sheets with 28 mm thick were used in this program and the mean mechanical properties are shown in Table 1.

All connectors used in this research were glued in glubam beams by a two-component epoxy adhesive provided by a local manufacturer. Bisphenol A and low molecular weight Polyamide were selected as epoxy resin and hardener in the adhesive, respectively. Table 2 reports the mechanical properties of the adhesive