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Failure analysis of typical glubam with bidirectional fibers by off-axis tension tests

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HIGHLIGHTS

- First hand data on bi-directional behavior of laminated bamboo material, glubam.
- Theoretical analyses of the bamboo based new material.
- Mechanical background for further study of glubam.
- Modified model that can potentially be used in design of glubam.

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ABSTRACT

Glubam is a new construction material using laminated bamboo with bidirectional fibers. In this paper, we present the failure analysis of glubam with bidirectional fibers using Hankinson formula and Tsai–Wu failure criterion. Off-axis tension tests were performed on glubam specimens with longitudinal to transverse fiber ratio of 4:1. The glubam specimens were designed to study its tensile properties in different directions to the main fiber. A revised Hankinson equation suitable for glubam are developed yielding satisfactory agreement with the test results. It is found that the interaction coefficient F_{12} in Tsai–Wu failure theory can only be established from the 15° off-axis tension test. Also, three approximation methods, Tsai–Hill, "Hoffman", and "Mises–Hencky" methods, are applied to estimate the value of interaction F_{12}. Four failure envelopes of glubam have been presented and compared. By comparing with off-axis test data, the failure envelope from Tsai–Wu theory provides unconservative prediction when in-plane shear is ignored. Even when in-plane shear is considered, the failure envelope obtained from Tsai–Wu theory is still deemed unsuitable to represent the behavior of glubam. Therefore, it seems the empirical approach is currently appropriate to represent the behavior of the 4:1 glubam subjected to biaxial tensile stress state.

1. Introduction

Similar to wood, bamboo can also be considered as a type of natural fiber-reinforced composite with orthotropic properties. Wood is widely used as construction material and structural wood products are well developed in North America and Europe including glued-laminated timber (GluLam), dimension lumber, plywood, oriented strand board (OSB), parallel strand lumber (PSL), laminated veneer lumber (LVL), etc. For the use of bamboo, some industrial structural composites have been developed in recent years, which may be classified into two main types: one is thick-veneer Laminated Bamboo Lumber, also known as LBL (Laminated Bamboo Lumber); another is thin-veneer Laminated Bamboo Lumber which is also trade marked as GluBam by Xiao et al. [1–4]. The thick-veneer lumber was invented from round bamboo as construction material and studied by many researchers [5–10]. LBL is made by pressure gluing a few layers (typically three or five layers) of relatively thick bamboo strips. The top of the line products in the market are flooring plates [2]. Glubam is made by laminating approximately 2-mm thick bamboo strip mats layer by layer, and the thickness of product used in construction ranges from 10 mm to 30 mm. Glubam sheets with 10 mm thickness is commonly used

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as concrete formwork in China, normally called ply-bamboo, while the 30 mm thick sheets are used by Xiao et al.'s research team in making various types of structural components, such as shear wall grids, trusses, frames, columns and girders. Xiao et al.'s team has used glubam in many commercial projects including truck-safe bridges, foot bridges, multistory buildings, etc. [2,11]. Because of the abundant bamboo resources, developing technology for manufacturing glubam with good mechanical property [12], may provide another alternative material for sustainable construction.

The most distinctive property of glubam is its bidirectional fiber orientation. Most materials like LBL, Parallel Strand Bamboo (PSB) are designed with single directionally oriented fibers. However, glubam with its thin strip mat can be designed as a structural composite and lay up to achieve specific fiber ratios in both longitudinal and transverse directions or even in the off axis directions. Glubam sheets with longitudinal to transverse fiber ratio of 4:1 is illustrated in Fig. 1, where each layer of the bamboo strip lamina is about 2 mm thick.

To be used as a construction material, the strength properties of glubam need to be well understood. The characteristic of fiber distribution in glubam being bidirectional (longitudinal and transverse) makes glubam sheets different from other wood or bamboo composites. In this paper, glubam sheets are analyzed as a lamina. For typical unidirectional lamina, failure criteria including Hankinson formula [13], maximum stress theory, Tsai–Hill theory, Tsai–Wu theory, "Hoffman" criterion, and "Mises–Hencky" criterion are usually used [14]. Maximum stress theory, Tsai–Hill theory, especially Hankinson formula was also proved to be good at predicting strength of LVL according to grain variation [15]. However, these theories are seldom used in composites with minor fibers in transverse direction [16–18] like glubam sheets.

In this work, off-axis tension tests were conducted with typical bidirectional glubam sheets with fiber ratio of 4:1 to find interaction strength F_{12} in Tsai–Wu theory. For further research, off axis tension test could be used in evaluating shear property of glubam material. On the other hand, the results of off-axis tension test could make comparison between glubam materials with different fiber ratio, which will help choose or optimize the material. So, glubam sheets with other fiber combinations in different loading directions are also under study; however, the 4:1 is the most typical material for constructing major structural girders and columns and the primary research in this paper is focused on 4:1 glubam material.

2. Glubam material and its off-axis experiment

Off-axis tension test can be used to study multidirectional symmetric laminates under uniaxial loading at an angle with one of the principal laminate axes [19]. Glubam sheets with 15 cross laminae are tested, in which 12 layers are longitudinal and the remaining 3 layers are transverse, as shown in Fig. 1. The nominal thickness of the tested glubam sheets is 30 mm.

2.1. Manufacturing and processing of glubam

Moso bamboo aged 3–5 years with the average perimeter of bamboo culms of 35 cm or larger is usually used as raw material for glubam. Firstly, round bamboo which meet requirement for maturity are selected and prepared manually for bamboo strips with 2–3 mm thickness and 20–30 mm width, during which process wax on inner and outer skins of bamboo culms are removed. After the process of splitting bamboo strips, further steps are needed: one is to boil them in hot water aiming at eliminating part of organics within these strips; the other is to air dry the boiled bamboo strips until their moisture content (MC) is around 20%. During these two processes, bamboo strips from different parts of bamboo culms are mixed randomly.

Air-dried bamboo strips are aligned in parallel and string netted to form a curtain layer, which are basic parts of glubam sheets. The process can be completed manually or using semiautomatic machine. Due to the manually manufacturing condition, gap smaller than 8 mm in between bamboo strips is tolerated. The thin layer bamboo curtains are flexible than thick ones for LBL and need less accuracy in arranging them. Once pressed, fewer voids are formed within the bamboo plies.

The bamboo strip curtains are cleaned then are saturated in phenol formaldehyde resin. The resin saturated curtains are dried again and stored with keeping the moisture content to be approximately below 15%. About 15 layers of resin saturated bamboo strip curtains are stacked in parallel or orthogonally, depending on its design. Finally, the stacked bamboo layers are pressed with a temperature of about 150 °C, and pressure of 20 MPa for about 15 min, using a procedure similar to manufacturing plywood [20].

The typical glubam sheets are 30 mm (±2 mm), 1220 mm wide and 2440 mm long with longitudinal to transverse fiber ratio of 4:1. These laminated bamboo sheets after cutting, gluing, stacking and compressing, finger-jointing can finally form different structural elements.

2.2. Specimens

Seven groups of specimens were prepared by water jet cutter as shown in Fig. 2. Each group has ten replicates. As shown in Fig. 3, there is an angle α between the main fiber direction 1 and the loading direction 2. The loading directional angles α were chosen to vary from 0° to 90° with interval of 15°. The dimension of specimen was determined in reference with ASTM D143 [21], but was not weakened in the direction of the thickness. Specimens were kept in room condition (about 20° temperature and 45% humidity). Specimen moisture content (MC) was tested by handheld wood moisture meter. The average MC prior to test was 14.0% and its density based on oven dried weight and volume was about 0.85 g/cm^3.

It is quite well known that when the specimen is clamped at the ends during loading, the shear deformation between fibers in plane is constrained and specimen cannot deform freely, which may induce shear and bending moment at the ends, causing premature failure. However when the specimen aspect ratio L/w (length to width, the same below) is sufficiently large, for example, $L/w = 24$ for E-glass/epoxy, the shear coupling effect becomes independent of clamping conditions [22]. As shown in Fig. 3, within the loaded portion of the specimen, the aspect ratio L/w is around 21–52. So in this test the shear coupling resulting from clamping condition is assumed to be minimal.

2.3. Tensile tests

Off-axis tensile test was conducted on a universal testing machine with maximum load capacity of 50 kN at a loading rate of 2 mm/min. The built-in load cell of the testing machine and the displacement sensor with a gauge length of 50 mm recorded the applied load and deformation, respectively. As shown in Fig. 4 the specimen was connected to the test machine fixtures with the horizontal twisting constrained. The universal hinges of the machine assured the applied tension load to be parallel to the axis of the specimen.

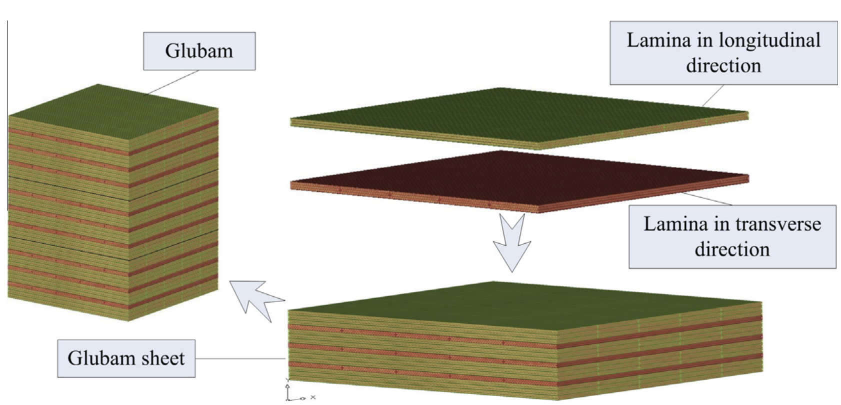

Fig. 1. Configuration of 4:1 glubam sheets.