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A new joint to assemble light structures of bamboo slats

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HIGHLIGHTS

- A new mechanical joint to connect *Guadua angustifolia* slats is presented.
- The joint is based on applying compression along the thickness of the slats.
- Light structures assembled with the new joint presented a good mechanical behavior.
- Light trusses of bamboo slats are a feasible option to support house floors and roofs.

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ABSTRACT

Guadua angustifolia (GA) is an American species of bamboo. It is a sustainable anisotropic material that exhibits high strength along the longitudinal direction of the culm and low strength on the planes of the fibers, which usually leads to premature fissures and failure in the joints of GA structures. Based on the ductile behavior of the material under compression along the thickness of the culm or radial direction, a new joint to connect GA slats was developed. The joint connects two GA slats by using two small curved steel plates, a bolt, and a nut, which are used to apply high compressive deformation in the radial direction. Experiments of the proposed joint showed about a twofold significant increase of strength with respect to a joint without radial compression. To further determine the performance of the joint, two beam prototypes were developed and tested. First, a small beam of 0.93 m length and 70 N weight that was loaded under three point bending supported a maximum load of 15,500 N and failed by buckling and subsequent rupture of a compression element. Next, a prototype of about 3 m length and 310 N weight that was tested under a 12,000 N distributed load showed maximum deflections of about 18 mm and complete integrity of the joints and the compression elements. Deflections under constant loading were about 30% of the total for the nine days of testing. Experiments of the beams showed full integrity of the proposed joint, which is a feasible alternative to produce light prefabricated trusses to support house floors and roofs. This joint is a first step for the improvement of structural connections of GA elements, with the intention to extend this idea to join whole culms.

1. Introduction

Guadua angustifolia is a species of bamboo native of South and Central America. It is a fast growing plant and thus its controlled use does not represent a threat for the natural plantations [1]. Due to its excellent mechanical properties along the axial direction of the culm it has been frequently used in the construction of rural houses and temporary structures. Hence, this plant is a potential candidate to help solving the housing deficit in the world [2]. However, there is a need to accomplish further studies in order to increase the acceptance of the material and to develop industrialized methods for construction.

GA culms have a cylindrical hollow shape with transverse diaphragms localized at variable distances along the length of the culm. It is composed of a matrix reinforced with fibers aligned in the longitudinal direction. In addition, like others species of bamboo, it is a functionally graded material as the density of the fibers increases radially toward the crust while the inner surface is relatively soft [3–5].

Therefore, GA is an anisotropic and heterogeneous material which provides higher stiffness and strength along the axial direction compared to those along the transverse axes. In particular, it has been shown that the elastic properties and tensile strength of the material along the radial and circumferential directions of the culm are low [6–9]. Hence, GA culms usually develop

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longitudinal fissures, particularly in the structural joints, which are locations of stress concentrations. These fissures frequently lead to premature failure that avoids taking full advantage of the high longitudinal strength of the material.

Many types of structural joints have been proposed to connect bamboo culms as described in various documents [10–12]. Ancestral joints are made by cutting curved surfaces in the culms intended to increase the contact area between the elements that are next tied with vegetable fibers [13]. Bamboo joints evolved to incorporate pins, bolts, hooks, and mortar that is used to fill the culms to avoid buckling of the walls [14]. Other modern bamboo culm connections, that are relatively expensive, use sophisticated metallic parts and epoxy materials [15].

In an inventory presented by Janssen [16] that classified the joints with regards to the form and direction in which the forces are transmitted from the culm, it is recognized that efforts have to be made to design new alternatives that may be amenable to produce modular systems. Due to the irregularities of this natural material and the hollow shape of the culm, efficient joints used for solid wood elements cannot be easily implemented for GA structures. Hence, the joints are usually expensive and need to be practiced in a personalized manner, which increases costs and avoids the use of the material in applications such as low-cost house construction projects.

Slats can be easily produced by splitting GA culms along longitudinal planes. Slat thickness varies along the length but the width can be controlled to standard dimension during cutting. Only nails and bolts have been used to connect GA slats for assembling open web joists that showed relatively high deflections [17]. Janssen [16] documents a joint for bamboo slats made with thin galvanized steel strips that was used for doorframes. The objective of this paper is to present a new joint for GA slats, which can be used to produce light structures to support house floors and roofs.

2. Materials and methods

2.1. Material

The slats of bamboo species *G. angustifolia* were cut from culms between three and five years of age grown in rural areas of the Eje Cafetero (Colombia, South America) at an altitude of about 1500 m. The culms were selected, marked, cut, treated, and dried following well established practices described elsewhere [7]. The average humidity content of the slats used in this study was 12.99% (SD 0.24%).

2.2. Description of the joint

GA culms can be easily split along longitudinal planes to produce slats with standard widths (Fig. 1). Previous studies with other species of bamboo and GA [3–4,18] have shown that the material is functionally graded as the fiber density is higher toward the external surface of the culm while the inner part is relatively soft. In addition, a recent study [19] shows that GA is ductile under compression along the thickness of the culm, or radial direction, since it can sustain nominal strains of around 40% before failure.

Hence, to assemble the proposed joint, holes of 10 mm diameter were first drilled near the ends of two GA slats that were next superimposed on their internal soft surfaces. Subsequently, compression was applied by a 9.5 mm (3/8") diameter bolt and a nut that transmitted and distributed the load to the external hard surfaces of the slats through two curved steel plates of 3 mm thickness (Fig. 2). The distance between the center of the holes and the ends of the slats was 35 mm and the width of the splits was 40 mm. About four turns were applied to the nut to induce radial compression, which caused a high degree of deformation and interlocking between the elements, as shown in Fig. 2. Because of the ductility of the material along the radial direction and its soft nature toward the inner part of the culm, this radial compression did not cause failure. In addition to distributing the precompression load, the two curved steel plates also provided confinement to the material around the holes.

2.3. Mechanical tests of the joint

To determine the mechanical behavior of the joint, the configuration of Fig. 3 was tested, which was devised considering the standard ASTM D5652 [20], that applies to wood bolted connections. Two sets of five samples each were initially tested, one with radial compression (mean thickness $t = 11.5$ mm, SD 2.8) and the other without radial compression ($t = 10.3$ mm SD 2.1), using a universal testing machine ZD (formerly Veb Werkstoffprüfmaschinen, Leipzig, Germany) with a force resolution of about 39 N. As this machine did not provide a precise control of velocity and force for the small loading levels of these tests, other two sets, each of five samples ($t = 7.3$ mm, SD 0.9; $t = 7.3$ mm SD 0.7, for the samples with radial, and without radial compression, respectively), were tested using a Instron 1011machine (Instron®, Norwood, United States) having a maximum load capacity of 5052 N. The stiffness of the joint was also determined in this machine by measuring displacement with a LDVT Omega LD 621-15 (OMEGA Engineering Inc, Stamford, United States) as shown in Fig. 3. These tests were accomplished using displacement control at a velocity of 1 mm/min.

Statistical analyses were performed to determine significant differences using an analysis of variance (ANOVA). Significant difference was assumed if p was lower than 0.05 and a value of p between 0.05 and 0.10 indicated a trend. Since the specimens with radial compression tested in the Instron machine did not fail, the variance homogeneity assumption was not verified in the ANOVA. Therefore, a nonparametric analysis Mann–Whitney test was also performed.

2.4. Description of the prototypes and the experimental set up

The prototypes were manually assembled by two undergrad students with no carpentry experience. No special devices were built for facilitating the assembly. Only a meter, a pencil, a caliper, a driller, and a hack saw were used. Small defects like natural longitudinal curvatures or fissures were present in the elements. This procedure was followed in order to reproduce conditions that may be found when assembling this type of structures in rural areas.

The first prototype of 0.93-m length was formed by two parallel planar trusses (called trusses even though some elements may be under some degree of bending), each composed of six slats: two forming the upper and lower chords, two diagonal and two vertical elements at the ends (Fig. 4). Transversally, these two plane trusses were connected by six slats of about 0.13 m length. Small angles of 25.4 mm × 25.4 mm were used to accomplish the connection between the planar trusses and the transverse elements. Slats were cut at a nominal width of 40 mm and the average thickness was 10.3 mm (SD 3.2 mm). The test was performed using a universal testing machine ZD previously described in Section 2.3.

Fig. 1. GA slats that can be easily obtained from culms.