Engineering Structures 143 (2017) 540–548

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Design and experimental verification of easily constructible bamboo footbridges for rural areas

T.S. Paraskeva *, G. Grigoropoulos, E.G. Dimitrakopoulos

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay Rd., Kowloon, Hong Kong, China

ARTICLE INFO

Article history:
Received 21 December 2016
Revised 20 April 2017
Accepted 24 April 2017

Keywords:
Bamboo
Low-cost bridges
Bamboo footbridges
Bridge engineering
Experimental characterization

ABSTRACT

The present study examines a new approach for low-cost footbridges as a remedy to the overwhelming lack of bridges in underprivileged rural areas. The proposed truss footbridges can be rapidly assembled, by non-experienced personnel from pre-fabricated full culm bamboo members and steel gusset plate type connections. This paper addresses the challenges of the design and the construction, and highlights important knowledge gaps in the process. Firstly, it evaluates experimentally the physical and mechanical properties of bamboo culms from two species (namely, Kao Jue and Mao Jue). Then, it develops an analytical model and performs the structural design of the bridge. Importantly, the present study introduces a new three-dimensional gusset plate type truss connection for full culm bamboo members. The proposed connection overcomes the assembly problems due to the non-standardized bamboo geometry. The study also reports the construction of full scale bridge prototypes and their experimental testing. The measured deck deflections under vertical loads are reasonably well captured by the analytical model. However, the bridge collapse is due to a local mode failure peculiar to bamboo; longitudinal splitting. The results reveal that the connections and the associated local failure modes of bamboo, are the most sensitive part of the examined structures, and highlight several directions for further experimental and theoretical research.

1. Introduction

In many underprivileged rural areas worldwide, the scarcity of funding and resources results in a devastating lack of even primitive footbridges that hinders socio-economic development. Although several charitable and non-governmental organizations are striving to address the issue [1,2], the demand for bridges in such areas globally is overwhelming.

The present study investigates an alternative inexpensive approach for footbridges assembled out of prefabricated bamboo members. Bamboo is a natural material with remarkable mechanical properties and in abundance in many parts of the world, particularly in many areas of interest [3,4]. Additionally, bamboo structures are eco-friendly and align with the goal for green and sustainable development [3,5–7]. During the last two decades, there is a growing interest in bamboo as a construction material. Research focuses mainly on characterizing the material and its mechanical properties [8–15]. Traditional bamboo structures (e.g. village houses and footbridges) can be found in Asia, Latin America and East Africa [16]. Contemporary bamboo footbridges (mostly arch bridges) using full bamboo culms have been constructed in Colombia [17] and Indonesia [18]. However, in the construction industry, the usage of bamboo culms is still limited. Partly, this is because of the shortage of design codes and standards [15,19]. An interesting exception is the extensive use of bamboo for scaffolding in the HK region, which is supported by pertinent guidelines and documentation [6,20].

The proposed bottom-up approach aims to empower local communities (similarly with [21,22]) offering a design solution that it is easily constructible and scalable. In a nutshell, the present study proposes "Do-It-Yourself" (DIY) bamboo footbridges mimicking the "IKEA" paradigm. Thus, the proposed footbridges can be assembled by non-experienced personnel from (pre-fabricated) full culm structural members and steel connections following simple instructions. The present study reports the first phase of this research which concerns the design, prototyping and experimental validation of (full-scale) bamboo footbridge models. A particular objective of this paper is to highlight the challenges of the design and the construction process, and to identify points that merit further research.

* Corresponding author.
E-mail address: thparask@gmail.com (T.S. Paraskeva).

http://dx.doi.org/10.1016/j.engstruct.2017.04.044
0141-0296/

2. Design of the proposed footbridge model

2.1. Physical and mechanical properties

This study uses culms of two bamboo species, namely Bambusa Pervariabilis (or Kao Jue) and Phyllostachys Pubescens (or Mao Jue). The Kao Jue culms have a nominal diameter (ND) equal to 50 mm, while the Mao Jue culms 100 mm. Since bamboo is a natural material, some of its physical and mechanical properties may vary significantly among different culms, or even along the length of bamboo culms. Therefore, a set of mean values of the physical and the mechanical properties of the bamboo used is specified through a series of tests in the Structural Engineering Laboratory of HKUST.

The selection of the specimens is in accordance with ISO22157 [23]. The samples are collected from the bottom, middle and top regions along the culms, and from various culms. The bamboo culms used herein are of 3–6 years of age, and they were air dry for at least 2 months before testing and using. Table 1 lists the mean values and standard deviation (SD) of the main physical properties of bamboo culms: the external diameter (D), the wall thickness (t), the density (γ), and the moisture content (MC). The MC is an important physical property since it is directly connected with the mechanical properties of the bamboo [24]. The culm diameter (D) and wall thickness (t) taper from bottom to top. For the Kao Jue culms used herein, the D/t (mean) values at the bottom, middle and top region of the 6 m long culms are roughly 50.71 mm/8.64 mm, 48.13 mm/5.15 mm and 36.10 mm/4.13 mm, respectively. For the Mao Jue culms, the corresponding values are 93.56 mm/10.88 mm, 70.35 mm/6.51 mm, 48.67 mm/4.98 mm, respectively.

As for mechanical properties, the compressive strength parallel to the grain, the edge bearing strength, the shear strength parallel to the grain, the dowel-bearing strength, the ultimate tensile strength, as well as, the corresponding modulus of elasticity (E) are estimated by laboratory testing (Fig. 1). The tensile tests concern specimens with and without nodes. As expected, the presence of nodes reduces significantly the ultimate tensile strength of the material. Hence, the design checks are based on the tensile strength of the specimens with nodes, since it is the most critical. The edge bearing test is conducted according to [13,25,26] since ISO 22157 standards [23,27] do not provide pertinent specifications. In addition, the dowel-bearing strength is estimated from experimental tests following the guidelines of ASTM D5764 [28,9]. For the bending strength of the bamboo culms, we adopted the values proposed by Chung and Yu [20]. Table 2 presents the average values of the ultimate strength for Kao Jue (ND = 50 mm) culms, determined either by direct laboratory testing or from the literature. As for the mechanical properties of Mao Jue culms (ND = 100 mm), we conducted a limited number of experimental tests, since, they compose solely the outermost vertical members of the structure (and are not critical in this study). Our sample results are in agreement with those in [20], but due to the limited number of specimens we adopted the values proposed in [20].

An open challenge is the value of the safety factor in bamboo structures. Chung and Yu [20], propose a safety factor for the design of bamboo scaffolds ranging from 1.83 up to 2.4, depending on the species and the considered mechanical property (i.e. compression or bending). The [29] proposes a safety factor equal to 2.25 for the design of bamboo structures, without specifying the species, or the type of the structure. For the design of the proposed herein bridge a higher safety factor equal to 3 is judiciously chosen, and the allowable (design) values of Table 2 are applied. Recall that this value is similar to that used when designing for other natural materials, such as soil. Thus, the allowable (design) values are equal to 1/3 of the tested mean ultimate values, and approximately the 1/2 of the characteristic values as estimated according to [30]. Note that if one uses the characteristic values instead of the mean values for the calculation of the design values, then a lower factor of safety (e.g. 1.5 or 2.0) should be considered [31]. More generally though, the appropriate safety factor for bamboo structures is an issue which beckons for further research.

2.2. Structural system and geometry

The proposed structural system of the bamboo footbridge is a well-documented Pratt truss braced at both upper and lower levels. From the standpoint of this research this structural form offers the following advantages: (i) simple and easy assembly, (ii) lightweight structural members, and (iii) modular structure. The diagonal members form a V-shape towards the bottom center of the deck so that under gravity loads the vertical members are in compression while the diagonal members are in tension (Fig. 2). Horizontal transverse members and crosswise steel wires connect the two planar trusses together at both chord levels to form diaphragms in the XY plane. In the transverse direction (YZ plane) V-braces, along with the vertical and horizontal members, create structural frames. The planar trusses are inclined towards the longitudinal axis of the bridge to reduce the bending moments induced from lateral loads in the vertical members while X-braces are also placed at the outer bays of the trusses (XZ plane) to relieve the neighboring vertical members from excessive axial load. To reduce variance, all truss members are made of multiple culms combined together.

Fig. 2 presents the geometrical characteristics of the bridge. The total span of the bridge is equal to 8 m, the length of each bay is 2 m, the bridge deck width is 1.2 m, the distance between the two planar trusses at the top is set to 0.8 m, and the overall height of the bridge is 2.3 m. For the deck, four plywood plates of $2 \times 1 \times 0.017$ m in size, are placed on top of 6 m long overlapping bamboo beams (one culm each) which are positioned along the bridge at intervals of 0.15 m. The parts of the bamboo culms (along the longitudinal direction) of the deck that are in contact with the bottom transverse members are filled with mortar at the crossing points, as reinforcement against local crushing. For the same reason, the top culm of the 2-culm section of the bottom transverse members (i.e. BT1, BT2, BT3, BT4 and BT5) is also filled with mortar along its whole length.

2.3. Design loads and structural analysis

A numerical model is developed using the structural analysis software SAP2000 v18.1.1 [32]. Frame elements and pin connections simulate the (bamboo) truss members and the joints of the

Table 1
Physical properties of the bamboo culms used in this project.

species	ND (mm)	D (mm)	t (mm)	γ (kg/m^3) (*)	MC (%) (*)
Kao Jue	50	47.7 (SD = 4.04) (88 specimens)	5.9 (SD = 1.16)	673.50 (SD = 98.31) (74 specimens)	11.75 (SD = 1.20)
Mao Jue	100	84.0 (SD = 7.25) (36 specimens)	8.4 (SD = 1.07)	651.0 (SD = 54.03) (26 specimens)	13.82 (SD = 0.64)

(*) The experiments are conducted according to ISO 22157 standards [23,27].