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Empirically derived connection design properties for *Guadua* bamboo

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HIGHLIGHTS

- Test methods for embedment, slip and screw withdrawal in bamboo are proposed.
- Over 390 tests were performed.
- Predictive empirical equations were derived through regression analysis.
- Strength related equations were adapted to output characteristic values.

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ABSTRACT

Three connection design properties (dowel embedment strength, slip modulus and screw withdrawal capacity) were determined for one species of bamboo (*Guadua angustifolia* Kunth) using experimental methods adopted from timber engineering. 151 embedment strength and slip modulus tests were undertaken using smooth dowels with diameters ranging from 3 to 16 mm, whilst 240 screw withdrawal tests were undertaken using 3.5–5 mm diameter self-tapping screws. Using regression analysis, predictive equations for the three connection design properties were derived, based on fastener diameter, density and bamboo wall thickness. Coefficients of determination (R^2) ranged from 0.45 to 0.82. The predictive equations for embedment strength and screw withdrawal were adapted to output characteristic values and then compared to similar equations derived for timber contained in Eurocode 5, the latter would seem inappropriate for bamboo.

1. Introduction

Adoption of bamboo as a structural material has numerous environmental benefits, this is attributable to its fast growth and reproduction through rhizomes, resulting in a very effective carbon sink in well managed forests, with the potential to reduce pressure on other forest resources and substitute energy intensive products such as steel and concrete, and help recover degraded lands [1]. However, as stated by Janssen [2], making joints in bamboo is difficult due to its tapered, hollow, and not perfectly circular section, with nodes occurring at irregular intervals. Janssen adds that bamboo will only be truly accepted as a structural material once joint design has been resolved.

Since the beginning of the 21st century a number of test, design and construction codes or standards have emerged throughout the world, including an international design standard [3]. To the authors' knowledge only the Colombian design code (NSR-10) [4] contains any numerical values for joint design, and these are limited to *Guadua angustifolia* Kunth (*Guadua a.k.*) connected by through-bolts combined with mortar infilled internodes (Fig. 1). NSR-10 does not provide a process for derivation of these design values, and does not provide slip moduli, K_{ser}, either, without which accurate calculation of frame deformations is not possible. Research into bamboo joints, such as [5] has tended to focus on undertaking a small number of tests to determine the joint capacity for a configuration. This approach limits the reliable prediction and inference of joint capacities. More recent work has recorded other joint properties such as joint-slip and ductility, which are also required in design [6,7], yet the size of the tested sample tends to be small ($n \leq 20$). Overall, an attempt to describe and quantify the mechanics of bamboo joints in a statistically rigorous manner is uncommon, and potential similarities to timber connection design theory are often overlooked. This paper seeks to address this shortcoming by attempting to edify a bamboo-specific approach for connection design using metal fasteners – specifically self-tapping screws, smooth dowels and bolts. Metal fasteners have been selected because of their ubiquity, ductility and poten-

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Nomenclature

D	diameter of the culm
d	diameter of the dowel or outer thread diameter of screw
d_1	inner thread diameter of screw
F_{ax}	Maximum withdrawal load or withdrawal capacity of screw
f_{ax}	withdrawal parameter
f_h	Embedment strength
F_{yield}	Yield load
K_{ser}	Slip modulus
MC	moisture content
n	sample size
t	thickness of bamboo culm wall
ρ_k	characteristic density
ρ_m	mean density
ρ_{test}	density at the time of test
ρ_{12}	density adjusted to 12% moisture content

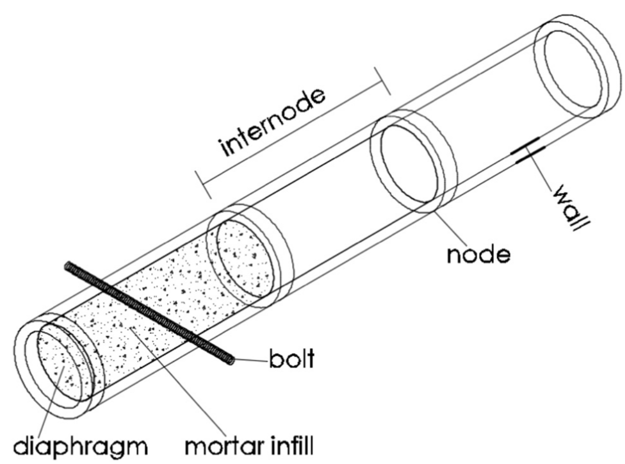

Fig. 1. Schematic representation of bamboo culm with through-bolt and mortar infill.

tial to unleash innovation, though their applicability to bamboo should not be taken for granted – for example common wood-screws and nails should be avoided as they can induce splitting in bamboo. In the context of this paper, connections are deemed to be a subset of joints. Connections are interpreted to be the specific location where two or more members are joined by means of a metal fastener.

1.1. Timber connection design theory

Design of connections using metal dowel-type fasteners in modern timber design codes e.g. Eurocode 5 (EC5) [8] are based on the European Yield Model (EYM). The EYM originates from Johansen [9] and is based on the plasticity of both the fastener and the timber in direct contact under the dowel, known as embedment, or dowel-bearing, strength, f_h. The model has been adopted because it provides a fairly accurate prediction of resistances and can be easily solved in a spreadsheet, however, it does not predict deformations or any other displacement related properties e.g. stiffness, ductility, or energy dissipation [10]. In terms of inference of joint stiffness – known as joint slip - Wilkinson [11] proposed one of the earliest models.

Use of the EYM is underpinned by a reliable knowledge of f_h. Eq. (1) was adopted in EC5 to infer f_h and was first proposed by Whale and Smith [12] following over 3200 tests to determine embedment properties and 420 full joint tests. The authors suggested that Eq. (1) was valid for softwood, hardwood and plywood. Empirical equations to infer the slip (or foundation) modulus, K_{ser}, have also been derived. Eq. (2) from EC5 provides an estimate of K_{ser} for a range of dowel-type fasteners excluding driven nails.

$$f_{h,k} = 0,082(1 - 0,01d)\rho_k N/mm^2 \tag{1}$$

where: d is the diameter of the dowel type fastener, in mm; and ρ_k is the characteristic density for the timber strength class, in kg/m^3.

$$K_{ser} = \frac{\rho_m^{1,5} d}{23} N/mm \tag{2}$$

where: d is the diameter of the dowel type fastener, in mm; and ρ_m is the mean density for the timber strength class, in kg/m^3.

Another property useful to connection design is screw withdrawal capacity, F_{ax}. Blass et al. [13] derived Eq. (3) following 800 tests on spruce and screws with diameters ranging from 6 mm to 12 mm. This equation to infer the characteristic withdrawal capacity was adapted and incorporated into EC5. Blass and Frese [14] expanded the previous work to 1850 withdrawal tests with self-tapping screws with a range of diameters from 4 mm to 14 mm. Hubner [15] derived equations for screw withdrawal in hardwoods following 671 tests.

$$F_{ax,k} = \frac{0,52 \cdot \sqrt{d} \cdot l_{ef}^{0,9} \cdot \rho_k^{0,8}}{1,2 \cdot cos^2\alpha + sin^2\alpha} \tag{3}$$

where: d is the diameter of the dowel type fastener, in mm; l_{ef} is the penetration length of the threaded part of the screw, in mm; ρ_k is the characteristic density for the timber strength class, in kg/m^3; and α is the angle between the screw axis and the grain direction.

Table 1 contains extant data for f_h in bamboo. Only Ramirez et al. [16] undertook regression analysis to determine equations that relate f_h to dowel diameter, however, unlike Eq. (1), the effect of density was not considered.

This paper contains proposed experimental methodologies for the determination of f_h, K_{ser} and F_{ax} for one species of bamboo and the empirical equations derived from the experimental results that could be employed in design, in a similar manner to Eqs. 1 to 3. The species used for all experimentation was *Guadua a.k.*, arguably the most important species from the structural perspective in Latin America.

Table 1
Reported embedment strength values for bamboo.

Bamboo species	Mean embedment strength parallel to fibres (N/mm^2)	Source:
Laminated *Guadua a.k.*	47.5–73.0	[16]
Gigantochloa atroviolacae	41.0	[17]
Bambusa pervariabilis	44.3	[18]
Guadua a.k.	43.5–74.7	[19,20]