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Dowelled structural connections in laminated bamboo and timber

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A B S T R A C T

Structural sections of laminated bamboo can be connected using methods common in timber engineering, however the different material properties of timber and laminated bamboo suggest that the behaviour of connections in the two materials would not be the same. This study investigates the dowelled connection, in which a connector is passed through a hole in the material, and load is resisted by shear in the connector and embedment into the surrounding material. Steel dowels were used in a connection between a laminated bamboo member and a steel plate in a central slot in the bamboo, and the behaviour of this connection was compared with a similar connection in timber. The laminated bamboo was made from Moso bamboo (*Phyllostachys pubescens*) which had been treated by one of two preservative processes, either bleaching or caramelisation. Following testing, substantial qualitative differences between the bamboo and timber specimens were observed: the bamboo failed most often by the formation of a shear plug whereas the timber failed by a single split. The two preservative treatments resulted in different behaviour: the bleached bamboo had a degree of ductility roughly twice that of the caramelised bamboo. Digital image correlation provided full-field strain measurements, which gave further insight into the differences between the materials, particularly between bamboo and timber. Shear strain is dominant in the bamboo, compared with tensile strain perpendicular to grain in the timber. Numerical modelling showed that this difference in the strain field could be explained by the different orthotropic elastic and frictional properties of the two materials.

1. Introduction

The embedment behaviour of laminated bamboo loaded by a steel bar through a drilled hole was studied. This form of connection is widely used in timber construction, and is known as a dowelled connection. For timber, plastic theory by Johansen [1] allows prediction of the load-carrying capacity of these types of connections, and forms the basis of design standards such as Eurocode 5 [2]. Since laminated bamboo has not been widely used for structural framing, the behaviour of this type of connection in bamboo has yet to be fully characterised.

In Johansen's method, the behaviour of both materials is modelled as being rigid before yield, and perfectly plastic thereafter. Therefore, the diameter and yield strength of the steel dowel are required, in order to calculate the work done in the plastic hinges formed in the dowel at failure. The other parameter required is the embedment strength of the timber around the dowel. This is not a fundamental mechanical property, but a function of fundamental properties used as a measure of how a dowelled system behaves under load. No reliable method exists to calculate this directly from the mechanical properties of the timber. Empirical rules provide a correlation between embedment strength and density. The rules in Eurocode 5 Ref. [2] relate embedment strength to density based on a series of tests carried out by Whale et al. [3].

Other research has sought to investigate the stress distribution and fracture properties that lead to failure of the timber in embedment. Full-field strain measurement by digital image correlation [4,5] and grey-field photoelasticity [6] has provided insight into the deformation of the timber around the connector. This work has shown that orthotropic elastic models of the timber can replicate the measured strains, as long as the frictional contact between connector and timber can be adjusted to match the measurements. This frictional behaviour is very difficult to predict *a priori*, and studies have shown its importance to the embedment strength and stress distribution, in experiments using dowels with high- or low-friction surfaces [5,7].

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This form of connection is not limited to natural orthotropic materials, and has been widely studied in manufactured fibre-reinforced composites. As manufactured materials, their behaviour may be more accurately predicted based on the known mechanical properties of the materials forming the composite. As a result, finite element models generally show good correlation to experimental results, for prediction of stress distribution [8] and failure modes [9]. Failure criteria have been developed for fibre-reinforced composites, which allow for failure by matrix cracking, fibre-matrix shearing and fibre breakage [10]. A similar approach to describing failure mechanisms should be possible in bamboo.

In timber, the ultimate failure of the connection is generally by a crack originating near the centre of the loaded edge of the hole, in mixed-mode shear and tension [11]. Before the ultimate failure, a yield point is apparent [12]. In timber, this yield point, associated with local bearing failure, is not well defined and requires standard rules to determine its value from force–displacement curves [13].

Fracture in timber connections generally occurs as a single crack initiated from the edge of the hole, progressing in the grain direction, a process referred to as splitting. The fracture toughness K_{IC} measured for such a crack ranges between approximately 200 and 500 kPa $m^{1/2}$ for softwoods [14,15]. The fracture toughness of full-culm bamboo for a crack progressing parallel to the longitudinal axis of the culm is slightly lower, ranging from 150 to 200 kPa $m^{1/2}$ [16]. In both timber and bamboo, the fracture toughness is an order of magnitude or more higher perpendicular to the grain [14,17]. Both timber and bamboo are formed from many long cells, and crack propagation through the material follows a path around the cells through the lignin matrix [18]. These similarities in microscale properties suggest that if the distribution of stress in the material is the same, the cracks formed in bamboo and timber may be similar. Yet our observations suggest otherwise.

The distribution of stress and strain in the material resulting from the force applied by the connector is dependent on the orthotropic properties of the material. The bamboo species used in this study is Moso (*Phyllostachys pubesecens*). The comparison of the properties of Moso bamboo with Sitka spruce in Table 1 shows higher axial strength in the bamboo, but similar axial stiffness in the grain direction, for example. These differences may be expected to lead to different distributions of stress and strain in the material around the connector, affecting the response of the connection to load.

2. Objectives

The present work aims to characterise the performance of dowelled connections in engineered Moso bamboo. The experimental results are compared to timber to ascertain the differences in material embedment and fracture behaviour. Numerical modelling of the strain around the connector is presented for further comparison and compared with full-field strain measurements made during tests.

3. Experimental program materials and methods

To compare both embedment and fracture behaviours in the materials tested, specimens were loaded using a steel dowel in the arrangement most prone to splitting: a loaded edge in the grain direction, as shown Test A in Fig. 1.

The test procedure followed EN 383 [19], the European norm for embedment testing of timber, with an adjustment to allow full-field strain measurement. The surface of the specimens needed to be exposed to allow digital image correlation (DIC) to be used for strain measurement, so a central steel plate was used to apply the load. The materials were loaded using a 12 mm diameter steel dowel passing through a 6.35 mm thick steel plate located in an 8 mm wide central slot machined into each specimen. A tensile load was applied to the specimen, and resisted by embedment of the dowel into the timber or bamboo. The specimens were clamped top and bottom in hydraulic wedge grips. The displacement of the steel plate was measured relative to the edge of the specimen using a single clip gauge to measure the relative displacement of two brackets, one fixed to the specimen, and one to the steel plate, as shown in Fig. 2. The clip gauge effectively measures the average relative displacement at the outer edges of each specimen. The total loaded thickness of the material was 30 mm, or 2.5 times the diameter of the dowel, complying with the requirement of EN 383 [19].

This study used a commercially available laminated bamboo board made from Moso bamboo and a soy-based resin (Smith & Fong Plyboo). The specimens were built up from 19 mm thick laminated bamboo sheet (2440 × 1220 × 19 mm), cut and further laminated into sections of the required dimensions using polyurethane adhesive (Purbond HB S309). The adhesive was applied manually with a glue proportion of 180 g/m^2 (final product). The laminas were pressed using manual clamps to apply a pressure of 0.6 MPa for 4 h. The laminas were orientated so that the radial direction in the culm from which they were cut was in the plane of the specimen, with the tangential direction aligned with the axis of the dowel.

Two types of laminated bamboo board were used: bleached and caramelised. These differ in the commercial processing they have undergone, both of which treat sugars that would otherwise result in biodeterioration. The bleached bamboo strips are soaked in a bath of hydrogen peroxide solution at 70–80°C; the caramelised bamboo are treated with steam at 120–130°C [20].

For the timber specimens, Sitka spruce grown in Wales was used and graded as C16 according to EN 338 [21]. All timber specimens were cut from a solid section and no gluing was used. The ring structure of the timber was orientated so that the tangential

Table 1
Mean values of material tensile and shear properties (coefficient of variation is given in brackets when available).

Material	Tensile strength parallel to grain	Parallel to grain modulus	Tensile strength perp. to grain	Perp. to grain modulus	Shear modulus
	MPa	MPa	MPa	MPa	MPa
Bleached bamboo	124[a] (0.15)	–	3.14[a] (0.14)	–	–
Caramelised bamboo	90[a] (0.26)	8114[f] (0.10)	1.98[a] (0.13)	1208[f] (0.24)	945[c]
Sitka spruce C16 timber	67[b] (0.19)	8000[d]	2[e]	270[d]	500[d]

[a] [23].
[b] [24] (based on bending of small clear specimens, modulus of rupture).
[c] [25].
[d] [21].
[e] [26].
[f] [27].