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Glued-laminated bamboo: Node and joint failure in bamboo laminations loaded in tension

A. J. M. Jorissen[1,*], J. Voermans[1] and M. H. Jansen[2]
[1]*Department of Architecture, Building and Planning Structural Design, Eindhoven University of Technology, Postbus 513, 5600 MB Eindhoven, The Netherlands*
[2]*Katholicke Universiteit, Leuven, Belgium*

Abstract: In glued-laminated bamboo beams loaded in bending, failure is initiated at the outermost lamination on the tension side. Failure can be initiated by a weak zone in the material or joint depending on the efficiency of the latter. Since the outermost laminations at the tension side of the beam are subjected to nearly a uniform tension force, failure in both unjointed and jointed laminations loaded in tension was studied. Based on an analytical study in combination with numerical simulations, it was found that failure of unjointed laminations for *Phyllostachys pubescens* is always initiated at a joint in such a way that stresses are not able to redistribute. This was confirmed by experimental tests. To lengthen the laminations, scarf-joints with a slope of 1 in 10 turned out to be very effective. By experimental tests it was found that a joint efficiency of 93 per cent could be achieved. Due to the stochastic behaviour of the strength of nodes and joints, failure in beams can be initiated by both.

Key words: Phyllostachys pubescens, tensile strength, node failure, joint failure, scarf-joint, laminated bamboo.

INTRODUCTION

In construction, the use of bamboo is shifting from its original cylindrical form as load-bearing member to engineered material. Bamboo can be modified in such a way that user-defined forms and shapes are possible which can be standardized. Additionally, the mechanical properties are more uniform which lead to higher strength and stiffness values.

Several studies (Lee *et al.*, 1997; Ahmad, 2000; Nugroho, 2000; Nugroho and Ando, 2000; 2001; Amino, 2002; 2003; 2004; 2005; Wan Tarmeze, 2005) have described various types of bamboo-based load-bearing members for structural applications. Wan

*To whom correspondence should be addressed; E-mail: a.j.m.jorissen@bwk.tue.nl

Tarmeze (2005) has carried out a numerical analysis on the prediction of strength and stiffness of LBSL (Laminated Bamboo Strip Lumber) beams. However, there is no experimental study so far on the load-bearing capacity of glued-laminated bamboo beams based on full-scale tests taking into account the influence of joints.

The present paper aimed at an empirical model for the load-bearing capacity of glued-laminated bamboo beams loaded in bending and the behaviour of the individual laminations. It was assumed that the bending strength of laminated beams is determined by the outermost lamination on the tension side, where failure can be initiated by a weak zone in the material or joint depending on the efficiency of the latter. Since the outermost laminations on the tension side of the beam are subject to nearly a uniform tension force, failure in both unjointed and jointed laminations loaded in tension was studied. Additionally, since bending is a combination of tension and compression, the behaviour of laminated pieces loaded in compression was also examined.

Influence of nodes on the tensile strength

In general, it can be said that nodes have a negative influence on stiffness and strength. Wan Tarmeze (2005) has explained the anatomical structure of a node in which a part of the vascular bundles deviate from their axial orientation. Consequently, when loading in tension parallel to the grain, tensile stresses in nodes are not parallel to the grain and hence, the tensile strength is reduced compared to that of the internode. In culms loaded in tension, the tensile strength is assumed to be directed by that of the node. However, in laminations loaded in tension, redistribution of stresses may occur due to the fact that the negative influence of nodes might be counteracted by internodes. The extent to which this occurs depends on the mechanical properties and the scatter of nodes throughout the volume of the lamination.

Prediction of nodes coinciding

In laminations loaded in tension under clamped conditions, stresses are not able to redistribute when a certain percentage of nodes, termed critical percentage, is exceeded. Additionally, nodes are assumed to interact within a certain distance from each other. When this critical percentage is exceeded, failure is initiated by a node in such a way that stresses are not able to redistribute.

MATERIALS AND METHODS

Configuration of nodes along the culm height

The distribution of nodes along the culm height is not uniform. The internode length increases from the base towards the middle part of the culm and then decreases further upwards. Parametric functional data analysis on several samples of 15 botanical species has led to the following expressions for the internode length as a function of the internode number (Janssen, 1991). The following expression holds for the lower part of a culm:

$L_{i;lower} = 25.13 + 4.8080 \cdot x - 0.0774 \cdot x^2$ Eq. 1

and for the upper part:

$L_{i;upper} = 178.84 - 2.3927 \cdot x + 0.0068 \cdot x^2$ Eq. 2

where:

$L_{i;lower}$ = internode length, lower part of the culm
$L_{i;upper}$ = internode length, upper part of the culm
x = total number of internodes

It is assumed that only the lower part of the culm is processed into strips. Using the parametric functional data analysis of Janssen (1991), it was found that a 20 m long culm contains 73 nodes and, hence, the maximum length of an internode is 457 mm.

Configuration of nodes along the strip length

To determine the configuration of nodes along the strip length it is assumed that the first 9 m of the culm is cut into required lengths of 1 m which are split into strips (Fig. 1). Furthermore, the position of the first saw cut is assumed to be uniformly distributed on the interval [0, 1000]. Hence, the coordinates of nodes in relation to the saw cuts vary and the number of different strips is infinite.

Simulations

The probability of the occurrence of at least a certain percentage of nodes coinciding within at least one cross-section within a certain area (termed interaction area) was simulated by the Monte Carlo method. This problem is complex to be solved analytically since multidimensional integrals with complex boundary conditions are involved.

The simulations were carried out by a program written in MATLAB 6.1. With this, a lamination was virtually assembled out of strips after which the probability was computed. The following assumptions are made:

- The probability of strips originating from the same culm assembled into the same lamination is negligible; in other words, strips are independent from each other.
- Strips are randomly assembled into laminations.

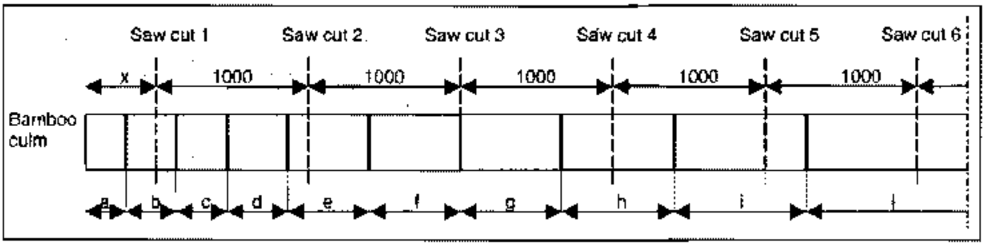


Figure 1. Configuration of nodes along the strip length

Failure of the laminations is always initiated by nodes if more than a critical percentage of the cross section consists out of nodes. A critical percentage of 3.3 was found for *P. pubescens,* and, because of this low value, it can be stated that failure of laminations is always initiated by nodes in such a way that stresses are not able to redistribute. Furthermore, this critical percentage is hardly affected by the interaction area within a range of 10 to 60 mm.

The method employed is very simplistic and does not completely resemble the real behaviour of nodes in laminations. However, this method along with the simulations is suitable for a quantitative understanding of the phenomenon.

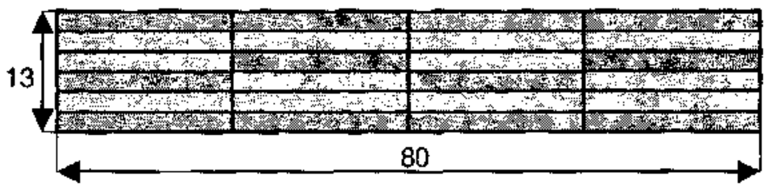
Influence of joints on the tensile strength of bamboo laminations

Finger jointing of laminations by using a standard profile used in timber turned out to be very difficult. Due to the low strength perpendicular to the fibre, splitting of the material at the finger roots occurred when end-pressure was applied to glue the pieces of laminations together. It was found that the efficiency of the joints was very poor since only about 41 per cent of the tensile strength parallel to the grain could be transmitted by the finger joints. However, the scarf joints were very promising.

Laminations

Laminations, commonly used in flooring, were directly obtained from Fustar Bamboo and Lumber Co., Ltd. The species was *P. pubescens*, one of the most potential species of China with respect to availability, dimensions and mechanical properties. The laminations were assembled out of three strips on top of each other and four strips side by side, as shown in Figure 2. By this configuration warping due to shrinkage and swelling was prevented and the variation in hardness at the top side was small which is important in flooring.

Melamine-urea formaldehyde (AKZO NOBEL, Cascomin 1240 with hardener 2540) was selected owing to the positive test results of block shear and delamination tests described in Voermans (2006). The mixing ratio of adhesive and hardener was 100:30 by weight. A glue spread of about 500 g/m^2 was applied manually (by a brush) single-



Note: dark color: outer part culm wall; light color: inner part culm wall

Figure 2. Composition of three-layer laminations

sided. The configuration of the test specimens was based on EN 408 (European Committee for Standardization, 1995) and is shown in Figure 3.

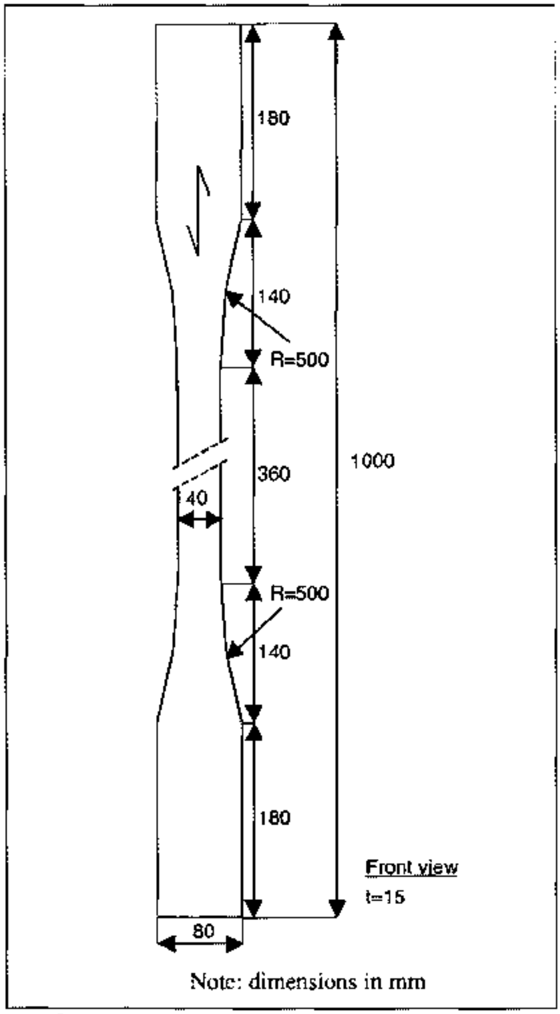


Figure 3. Geometry of tension test specimen

The laminations were scarf jointed by machining them across their thickness by a table saw (CNC controlled). The slope applied was 1 in 10. To bond the two laminations together, pressure was applied by hand-screws. Hence, the pressure applied was not quantified. The geometry of the joint, shown in Figure 4, was located in the middle of the test specimen.

Determination of tensile strength parallel to the grain

The tensile strength parallel to the grain and modulus of elasticity in tension of non-jointed laminations was determined by tension tests in accordance with EN 408 (European Committee for Standardization, 1995). The tension test was performed

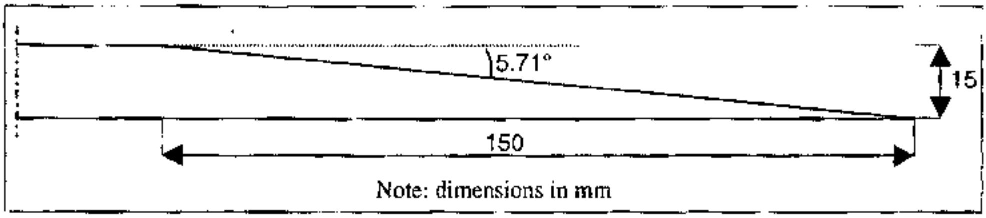


Figure 4. Scarf joint geometry

under clamped conditions by a universal testing machine Schenck (250 KN). A constant cross-head movement was chosen and the maximum load was reached within 300 ± 120 s. This interval is specified for determining the short-term strength of wood. The maximum load was reached within the prescribed time by using a constant cross-head movement of 1.5 mm/min.

Deformation was measured by two LVDT-transducers applied on the wide faces of the test specimens over a length of 200 mm. Measuring the deformation over a relatively large part of the test specimen enabled computation of mean modulus of elasticity taking into account the influence of nodes which were irregularly distributed throughout the lamination. All test specimens were conditioned in a conditioning chamber at 20°C and 65 per cent RH before they were tested. The determination of the tensile strength parallel to the grain of scarf jointed laminations was also carried out similarly as that on non-jointed laminations.

Moisture content and density were determined in accordance with ISO 22157-1:2004 (ISO 2004) by using at least one piece taken from each tension test specimen.

RESULTS AND DISCUSSION

Joint efficiency

The experimental results of the tension tests on non-jointed and scarf jointed laminations are shown in Table 1.

The influence of the joint on the strength was quantified by computing the joint efficiency. This is expressed as a percentage of the strength of a non-jointed lamination at mean levels:

$$\frac{f_{t,j,0}}{f_{t,0}} \cdot 100 = \frac{76}{82} \cdot 100 = 93\%$$

It can be stated that a significant proportion of the tensile strength parallel to the grain of non-jointed laminations can be transmitted by the scarf joint; scarf joints with a slope 1 in 10 are very efficient.

Table 1. Properties of unjointed and jointed laminations loaded in tension parallel to the grain

	Test series	Non-jointed laminations	Jointed laminations
Tensile strength (N/mm^2)			
	Useful samples	8	12
	Mean	82	76
	Standard deviation	15 (18.2%)	15 (19.7%)
Moisture content (%)			
	Sample size	24	15
	Mean	7.7	7.8
	Standard deviation	0.2 (2.3%)	0.3 (3.4%)
Density (kg/m^3)			
	Sample size	24	15
	Mean	606	609
	Standard deviation	31 (5.2%)	54 (8.9%)

Note: The values in parentheses refer to the coefficient of variation

Failure mode

Both unjointed and scarf jointed laminations loaded in tension behaved proportionally and failed in a brittle manner. Failure of the unjointed laminations was always initiated at a node in such a way that stresses were not able to redistribute. Since the used test specimens consisted out of four strips in the gauge length, the percentage of nodes coinciding is at least 25 per cent.

Failure of the scarf jointed laminations was always initiated at the joint. Cracks developed partly along the bond line. The test specimens exhibited predominantly bamboo failure, though the percentage of bamboo failure was not as high as measured by block shear tests described in Voermans (2006).

CONCLUSIONS

- An unjointed bamboo lamination (*P. pubescens*) loaded in tension fails always at the node, in such a way that stresses are not able to redistribute.
- A bamboo lamination (*P. pubescens*) scarf jointed with a slope of 1 in 10 fails always at the joint.
- Scarf joints with a slope of 1 in 10 are very efficient (joint efficiency of 93%) and can be easily applied; although these joints are not as efficient as finger joints, they are useful for adoption by glued-laminated bamboo industry.
- Though all scarf jointed laminations failed at the joint, theoretically failure in beams can be initiated by both joints and nodes due to the stochastic behaviour.

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