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Fatigue in bamboo

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ABSTRACT

This paper describes the results of an experimental programme to determine the fatigue behaviour of bamboo. Bamboo is subjected to cyclic loading, both in the plant itself and subsequently when the material is used in load-bearing applications in the construction industry. However, there is currently no data in the literature describing fatigue in this material. We found that sections of bamboo culm loaded parallel to the culm axis did not undergo fatigue failure: samples either failed on the first loading cycle, or not at all. By contrast, fatigue was readily apparent in samples loaded in compression across the diameter of the culm. The number of cycles to failure increased as the cyclic load range decreased in a manner similar to that found in many engineering materials: fatigue occurred at applied loads as small as 40% of the ultimate strength. Two different species of bamboo were tested and found to have different ultimate strengths but similar high-cycle fatigue strengths. Finite element analysis was used to help understand the progression of fatigue damage and the effect of stress concentration features. Some tentative design rules are proposed to define stress levels for the safe use of bamboo, taking fatigue into account.

1. Introduction

Bamboo is an important structural material, grown in many parts of the world. Being very fast growing it provides a renewable resource which is extensively employed in construction work and other load-bearing applications. The literature on this material contains a number of excellent studies reporting static mechanical properties such as Young's modulus, ultimate strength under various different types of loading, and fracture toughness. The bamboo plant grows as a series of hollow, tubular stems known as culms. Static mechanical property data have been published for tests carried out on intact lengths of culm [1,2] and also on specimens machined from the culm wall [3–8].

In the growing plant, cyclic forces will be experienced, principally in the form of wind loading. When bamboo is used in construction, for example in scaffolding and space frame structures, cyclic loading can also be expected. So it is surprising that there is no data in the published literature recording the fatigue behaviour of bamboo. The fibres of the bamboo plant, being relatively stiff and strong, have been used to make fibre composites in combination with various matrix materials, and several of these have been characterised as regards their fatigue properties (e.g. [9]), but these data give no insight into the fatigue behaviour of bamboo when used in the form of culms.

Our primary aim for this work was to determine whether fatigue failure occurs in bamboo and, if it does, to determine the number of cycles to failure for a range of applied cyclic loading conditions. The material is highly anisotropic, being much stronger and stiffer when loaded along the culm axis and much weaker when loaded perpendicular to the axis, so we aimed to investigate fatigue behaviour in different orientations. Finally, since fatigue behaviour is strongly affected by the presence of notches and other stress concentration features, we planned to carry out a limited number of tests to investigate the response of bamboo to such features.

2. Methods and materials

Most of the testing was carried out using the species of bamboo known as Moso (*Phyllostachys Pubescens*) which is one of the most commonly used species for structural purposes. The material was obtained from a local supplier (Bamboo Suppliers of Ireland, Dublin). A limited number of tests was carried out on a different species, obtained from the National Botanic Gardens, Dublin, under the name *Dendrocalamus gigantea*. All samples were tested in the air-dried condition in which they would normally be used for structural applications.

Mechanical testing was carried out using an Instron 8874 servo-hydraulic machine. Fig. 1 summarises the experimental programme. Samples were obtained in the form of culms several metres in length. Bamboo culms are hollow tubes in which the

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diameter and wall thickness stay fairly constant along the length: we used culms from plants which were 2–3 years old, with diameters in the range 32–47 mm and wall thicknesses of 2.9–4.4 mm. Culms also have periodic nodes at branch points: we avoided taking samples from close to the nodes, using only the internodal material.

Our choice of test specimen was made based on the experience of ourselves and others in conducting monotonic tests on this material, and also knowledge of how the material is loaded in use. Because bamboo is extremely anisotropic (having much greater strength and stiffness in the longitudinal direction) it invariably fails during monotonic tests by the initiation and propagation of longitudinal cracks, irrespective of the specimen shape and applied load [1,4]. Machining of standard test samples such as waisted tensile specimens or compact tension specimens, which has been done previously [6,10] is complicated by the need to obtain these from the tubular culms. As a result these samples must either be very small, or they must have a curved shape. Furthermore, the composition and properties of the material vary through thickness, the outer layers having more fibres and more hardening by lignification, making them stiffer and stronger [10] but probably less tough [6] than material closer to the centre. For these reasons we decided to test samples in the form of simple tubes obtained by cutting lengths from the culm. These tubes were loaded in two different ways, as follows.

Axial compression tests were carried out on samples cut to a length equal to twice their diameter; diametral compression tests were carried out on samples of length 50 mm. In both cases compressive load was applied through parallel platens. Because fatigue did not occur in axial compression (see below) most of the tests were carried out in diametral compression. To reduce the effects of variability in specimen shape and size we used the following approach: one sample was loaded monotonically until failure occurred at a certain force, F_u. Fatigue tests were then carried out on adjacent samples from the same culm, which had very similar dimensions. Each of these samples was loaded with a maximum force F_{max} which was a fixed percentage of F_u. Cyclic loading was carried out at a frequency of 1 Hz and load ratio R (equal to F_{min}/F_{max}) of 0.1.

Testing was continued until complete failure of the sample: damage developed in a three-stage process described below. To investigate the effect of stress concentrations, some samples of Moso bamboo had 3 mm diameter holes drilled mid-way along their lengths at one of the locations where initial failure occurred in the plain samples. Some samples had longitudinal grooves machined into them at these same locations (see Fig. 1). Monotonic

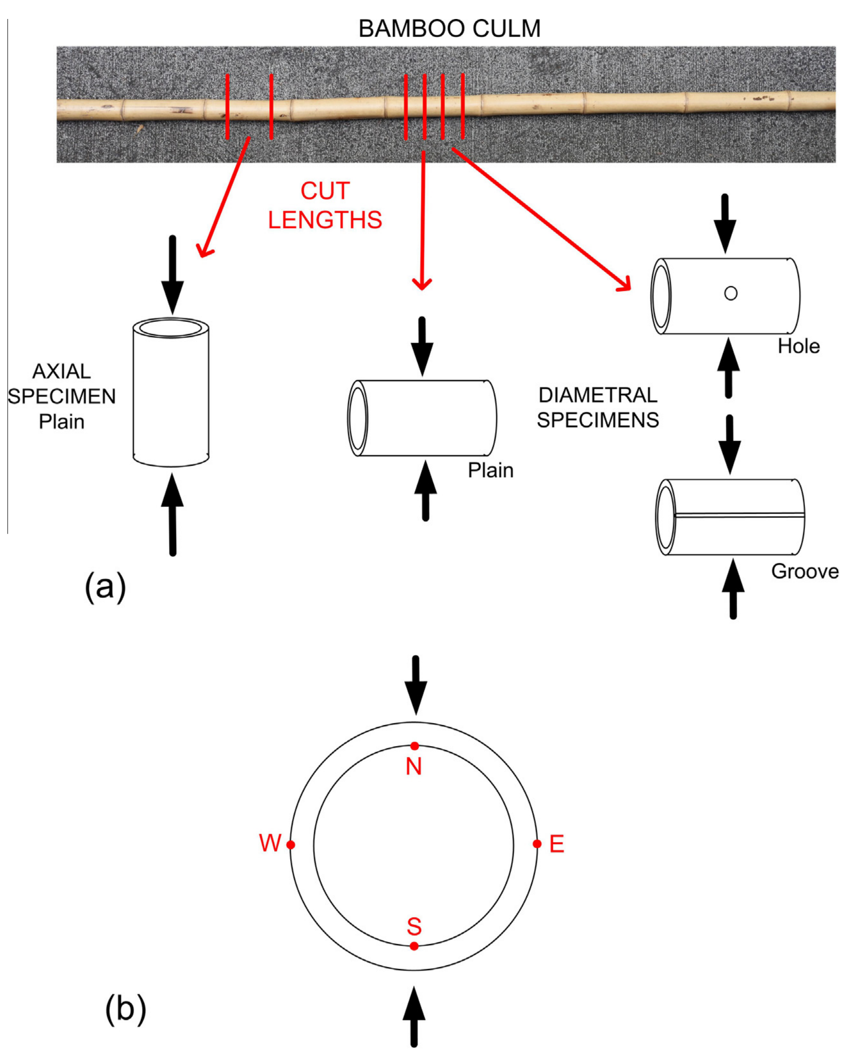

Fig. 1. (a) Samples were cut from internodal regions of the bamboo culm and tested in the form of cylinders. Compression was applied in the axial and diametral directions: some diametral specimens contained stress concentration features (holes or grooves). (b) Diametral compression gives rise to high tensile stresses at four locations around the circumference: the stress on the inside surface at points N and S is approximately twice as high as the stress on the outside at points W and E.