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Thermal relaxation of laminated bamboo for folded shells

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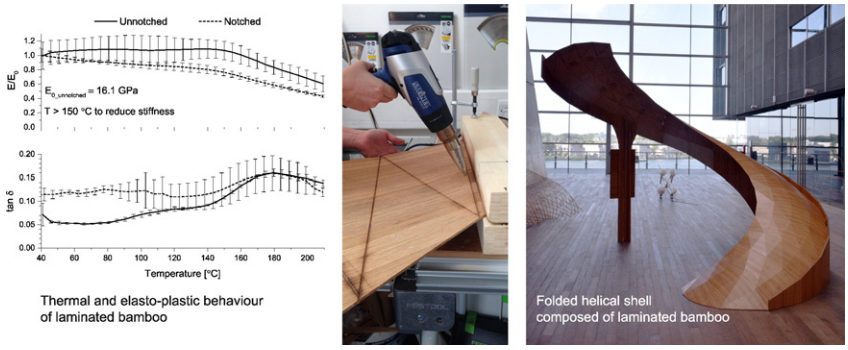
HIGHLIGHTS

- Localised heating promotes elasto-plastic behaviour in laminated bamboo.
- Study of bamboo thermal relaxation behaviour applied to heat bending.
- Method was demonstrated for folded helical shell composed of laminated bamboo.

GRAPHICAL ABSTRACT



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ABSTRACT

Laminated bamboo is emerging as a novel material in design and construction. As a natural fibre composite, it has unique mechanical properties that allow for innovations that are not possible in other materials. Here, we discuss one new application of those properties: the development of a novel bending technique using high temperature, and we explore its implications for design. We have explored the fundamental properties of laminated bamboo and its thermal relaxation as it passes the glass transition temperatures of its constituent polymers. By mechanically thinning engineered bamboo material, score lines allow precise, controlled and localised heating that promotes limited but essential elasto-plastic behaviour. Concentrated heating above the glass transition temperature induces property evolution and structural morphology changes, which results in thermal relaxation with minimal recovery and full set upon cooling. This original technology is then deployed in the design and construction of a folded plate helical shell composed of thin laminated bamboo sheets.

1. Introduction

Engineered bamboo refers to a group of laminated products that use the raw material in composite form [1]. Laminated bamboo is one of these products, comprised of strips of the culm wall laminated into a board. The boards are manufactured in a variety of thicknesses and are commercially produced, mainly in China. Current use and design of laminated bamboo is primarily in surface applications, although there is increasing interest globally in structural applications [2]. An example of the use of laminated bamboo in construction is the roof of the Madrid Airport by Rogers Stirk Harbour + Partners, which consists of strips of laminated bamboo forming an undulating ceiling over the terminal (Fig. 1). In the Madrid Airport the bamboo laths are used as surface material rather than structure.

The material has excellent bending strength [3], but as a plant material, it contains polymers which go through thermomechanical transitions, allowing viscous flow at elevated temperatures. These

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Fig. 1. Bamboo Ceiling, Madrid Airport, RSH + P (photo courtesy MOSO International BV).

properties were used in the development of a laminated bamboo pavilion for the International Association for Shell and Spatial Structures Expo in Amsterdam in 2015 [28]. The paper presents the development of a methodology for controlled and localised heating to cause a change in viscoelastic properties which allows the board product to be used as a folded plate shell. Material characterisation is used as basis to investigate the changes in properties beyond the glass transition. The design and construction of the pavilion and the novel material properties that were discovered are presented.

1.1. Background

Heat bending has a history in practice wherever bamboo is traditionally used. Heat is primarily used as a seasoning, or preservation treatment, but can also be decorative with heat applied to dried culms to modify the colour. Flame treatment is also used to achieve curvature, a technique used in fishing pole manufacturing and in furniture making. In China, rafts are made from *Dendrocalamus giganteus*, or *Nan chu*, to form the boat hull. The culms are lashed together, with the prow bent upwards to provide protection from rocks and shoals [4]. To form the curvature, the culms are heated and weighed with stones to bend the member (Fig. 2).

In laminated bamboo, heat treatment is used to achieve commercial preferences. "Caramelisation" is a process for preservation and colouring that uses pressurised steam to caramelise the sugars and turn them light brown. Further details and effects on the material are described by van der Lugt [5] and Sharma et al. [6]. Other methods of treatment, (e.g. bleaching, alkali treatment, and acetic acid) have been shown to affect the thermomechanical properties of bamboo [7,8]. The effect of steam treatment on the thermomechanical properties of the caramelised bamboo has yet to be established. The implications of the fabrication process for the pavilion revealed a unique property of laminated bamboo, and further experimental investigation explored thermal softening and deformation.

Nakajima et al. [9] explored the use of bamboo through utilisation of plastic working properties. The study used *Phyllostachys bambusoides* from Japan, removing the outer skin through chemical treatment. The thermal softening behaviour was obtained by submersing the specimens in a water bath under load and raising the temperature to 90 °C, then cooling the bath to 20 °C. The results indicated that the thermal softening behaviour of bamboo differs from that of Japanese cypress

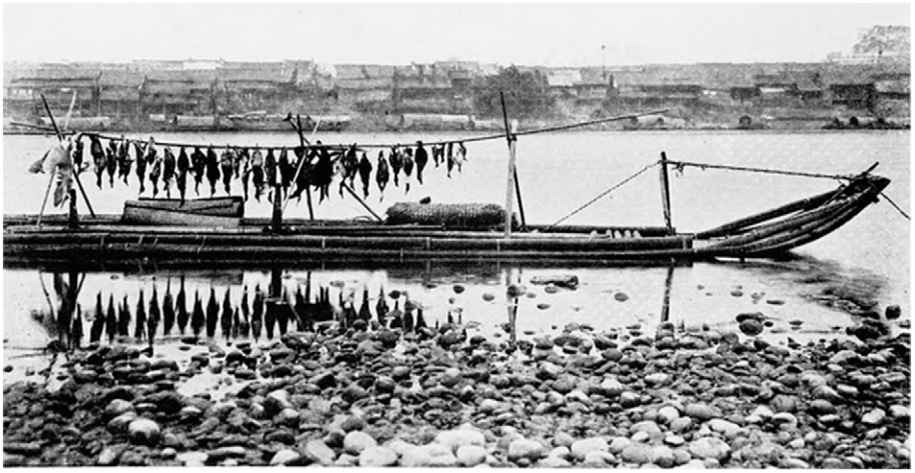

Fig. 2. Heat-bent prow of bamboo boat [4].