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Thermal relaxation of laminated bamboo for folded shells

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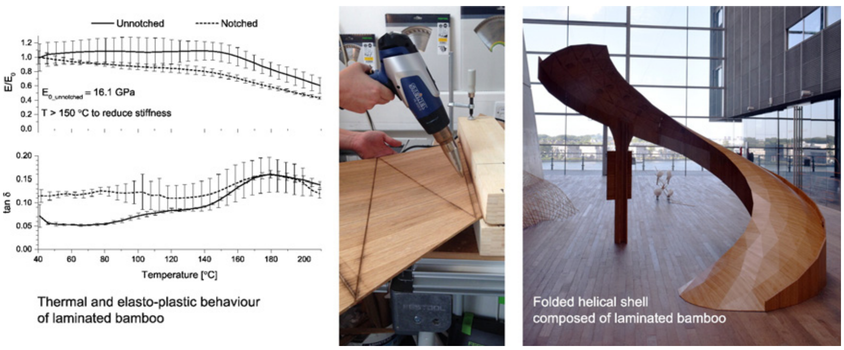
HIGHLIGHTS

- 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

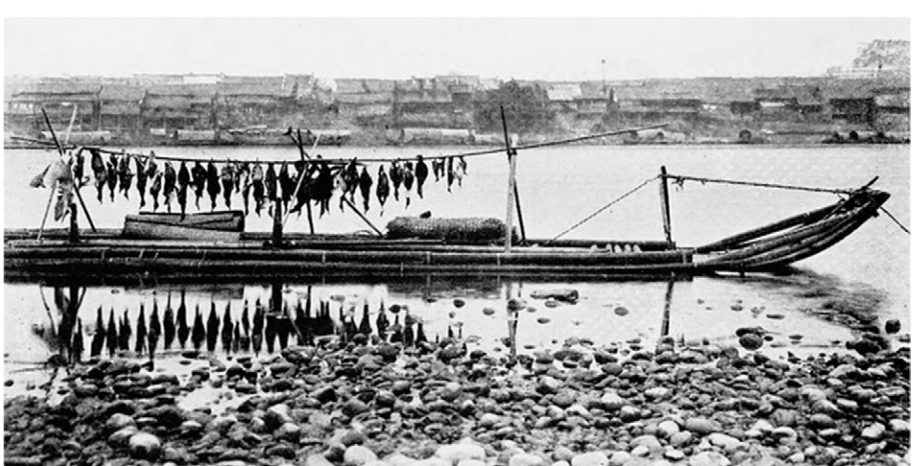

Fig. 2. Heat-bent prow of bamboo boat [4].

softwood, with a greater degree of residual deformation observed in the bamboo than in wood. The high residual set of bamboo, defined as the percentage of residual, permanent deflection (upon unloading) to the initial deflection (upon loading), was associated with the thermal-softening properties of lignin [10]. The study suggests that the chemical composition of bamboo provides a basis for thermal modification of shape.

2. Material characterisation

2.1. Materials

To explore the effects of thermal modification on bamboo, research was conducted using 5 mm thick laminated bamboo sheet (Supplier: Moso International BV), fabricated in China from 'caramelised' Moso (*Phyllostachys pubescens*) bamboo. The typical age of the bamboo at harvest is between 4 and 7 years [5]. Chemical composition of the raw bamboo consists of cellulose, hemicellulose and lignin, with some variation in their relative content observed between species [11]. The general commercial process for caramelisation comprises steam treatment at a pressure of 0.21–0.25 MPa and a temperature of 120–130 °C, for two periods of 150–170 min [5].

2.2. Thermogravimetric analysis

The thermal decomposition behaviour of the material was analysed by conducting thermogravimetric analysis using a TA Instruments TGA Q500. This was done by heating sawdust from the material from ambient temperature to 700 °C at a heating rate of 3 °C/min under a 100 mL/min nitrogen gas flow (i.e. inert conditions).

2.3. Dynamic thermal mechanical analysis

Additional tests were conducted through dynamic thermal mechanical analysis on specimens with and without a notch to determine the effects of reduced section size on the bending properties. Unnotched specimens had dimensions of 40 mm × 10 mm × 5 mm, and notched specimens had the same dimensions, with a 3.2 mm deep, 45° v-shaped notch line at the centre. The grain ran along the longest dimension of the specimen. They were loaded onto a Triton TTDMA in three-point bending mode, with a span length of 30 mm. We applied a sinusoidal load (giving a displacement amplitude of 20 μm) with a frequency of 1 Hz, over a thermal scan from 40 °C to 210 °C at a heating rate of 3 °C/min, to study the evolution of viscoelastic properties with temperature. The viscoelastic properties measured included the storage modulus E′, loss modulus E″, and phase difference δ, which are defined according to (Fig. 3), and Eqs. (1)–(3). The storage modulus E′ is a measure of the material's elastic behaviour, and the loss factor or damping ratio tan δ is a measure of the energy dissipation of the material (under cyclic loads).

$$E' = \frac{\sigma_{max}}{\epsilon_{max}} \cos(\delta) \quad (1)$$

$$E'' = \frac{\sigma_{max}}{\epsilon_{max}} \sin(\delta) \quad (2)$$

$$\tan(\delta) = \frac{E''}{E'} \quad (3)$$

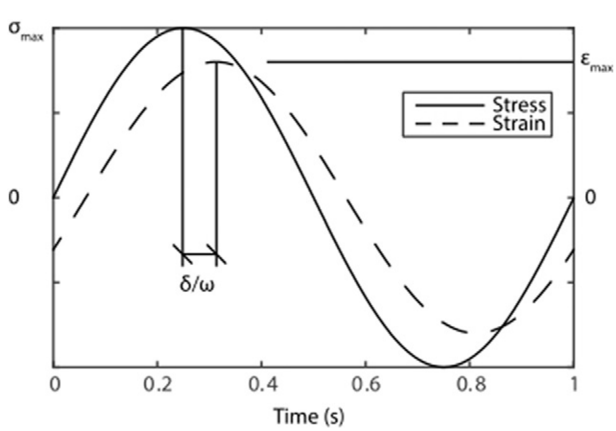

Fig. 3. Principles of Dynamic Mechanical Analysis – σ represents stress, ε strain, ω the circular frequency and δ the phase difference.

2.3.1. Structural analysis

The structural resistance of the material depends on its ability to resist in-plane forces and bending moments. The notches cut into the material affect both strength and stiffness under these forces. The effect of the notches on stiffness can be investigated by considering a beam with notch (Fig. 4), which is a simplified two-dimensional representation of a load path in the three-dimensional panel.

If the beam in Fig. 4 is subject to a constant bending moment, the relative reduction in stiffness due to the notch can be represented by the following ratio (see supplementary information for full derivation):

$$R = \frac{e^2(f+k)^2}{f^2(h+e)^2 + e^2\left(2fk + k^2\right)} \quad (4)$$

The geometry of the notch for the material used in the laminated bamboo pavilion is h = 3.2 mm, f = 1.3 mm and e = 1.2 mm. The notches are a grid of triangles with side length of approximately 200 mm, so a mean space between notches of 100 mm is considered representative. This gives k = 50 mm. The resulting R is 99.6%, and is not sensitive to k: the ratio is over 90% even for k = 10 mm. The reduction in stiffness due to the notches is therefore negligible for a simple analysis of deflection of the structure. The effect on axial stiffness will similarly be negligible, because the notch occupies a small part of the length of the surface.

The effect of the notches on bending strength is far more pronounced: the generation of the stress concentration factor for this geometry was beyond the scope of this study, but the simple bending stress scales with depth squared, which suggests a factor of eight increase in the stresses at the notch. The axial stress scales with the depth, so the stress at the notch would be approximately three times that in the adjacent unnotched part.

2.4. Results and discussion

2.4.1. Thermal degradation behaviour of bamboo

The thermal degradation profile of the bamboo sheet material is presented in (Fig. 5). An initial mass loss of ~5.5% was observed during the temperature increase to 100 °C; this was attributed primarily to moisture removal. This may result in an initial stiffening of the bamboo sheet with increasing temperature.

Plant materials, such as bamboo, are typically composed of three generic natural polymers: cellulose, hemicellulose and lignin. The degradation behaviour of these building-block polymers is different due to

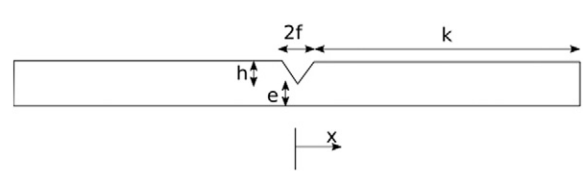

Fig. 4. Schematic of a notched specimen.

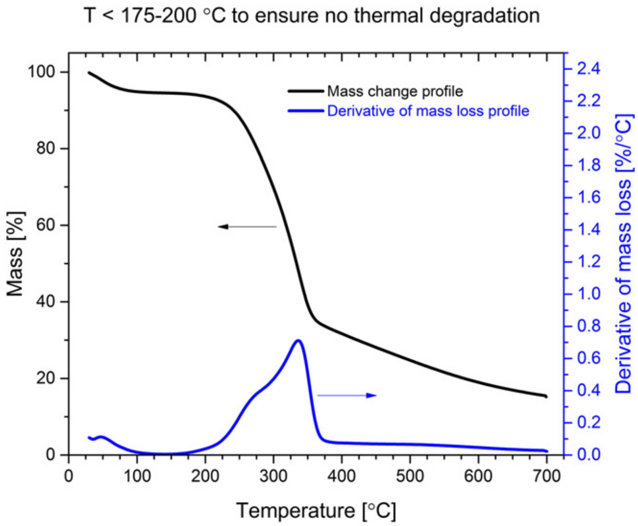

Fig. 5. Thermogravimetric profile of bamboo panel saw dust.

their distinct chemical structures [12–15]. Cellulose is a linear macromolecule comprising of glucose monomer units. Molecular chains in cellulose can exist as amorphous or crystalline [16]. The onset of thermal degradation of cellulose is above 250–300 °C [12–15]. In contrast, hemicellulose and lignin, both of which are amorphous and smaller, branched molecules, have a lower onset of thermal degradation, around 150–200 °C [12–15].

We found that the bamboo material was thermally stable up to 175 °C, showing a reduction in mass thereafter, most probably related to the decomposition of lignin and hemicellulose. The onset of thermal degradation was calculated to be 225 °C and the maximum rate of degradation was at 335 °C. It is likely that the maximum degradation rate of the bamboo sheet coincides with the maximum decomposition rate of the cellulose chains, as cellulose is the primary polymer in bamboo (typical 45–55 wt% [17,18]). Notably, a secondary peak was observed at 275 °C on the derivative weight loss curve (Fig. 5), which may be related to the temperature of maximum decomposition rates of lignin and hemicellulose [12–15].

A more gradual weight loss above 400 °C was likely due to the charring and further denaturation of the natural polymers, probably hemicellulose and lignin [12–15], under the inert conditions. This is because the decomposition of cellulose is rapid (once the maximum thermal degradation temperature is reached) and yields low amounts of char. In contrast, the degradation of hemicellulose and lignin is gradual, extending even up to 700 °C, and in the case of lignin, producing substantial amounts of char.

2.4.2. Thermomechanical behaviour of bamboo panels

The results from the dynamic thermal mechanical analysis on notched and prismatic (unnotched) specimens are shown in (Fig. 6). To compare the variation of stiffness with increasing temperature between the unnotched and notched specimens, the storage moduli were normalised by their respective initial storage moduli at 40 °C (E′ 0). We observed that while the unnotched samples demonstrated an initial increase in stiffness (by up to 9%) as they were heated to 150 °C, the stiffness of notched specimens reduced at a gradual rate of ~2% of initial storage modulus for every 10 °C increase in temperature. Consequently, at 150 °C while the stiffness of unnotched samples was equivalent to their initial stiffness (at 40 °C), the stiffness of notched specimen had dropped by over 20% in comparison to their initial stiffness.

The stiffening behaviour of the unnotched bamboo sheets with increasing temperature can be explained by the loss of moisture in the material, which is confirmed in the thermogravimetric tests discussed

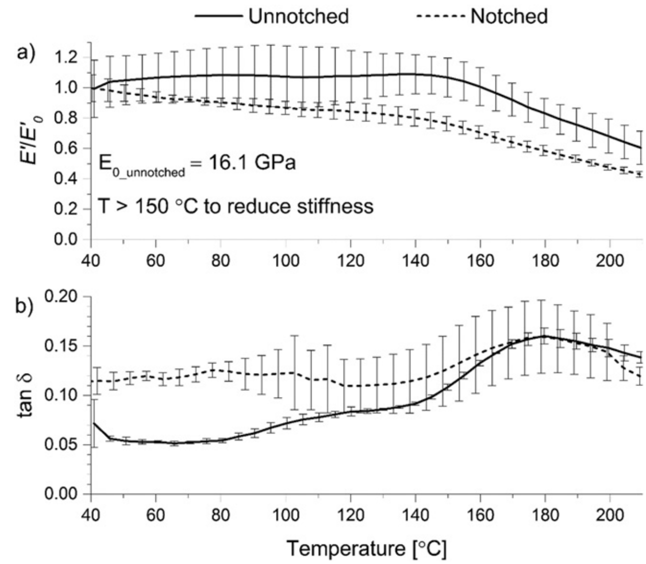

Fig. 6. Evolution of a) normalised storage modulus E'/E'_0 and b) damping ratio tan δ, with temperature for notched and unnotched bamboo. The profiles show averaged data for three repeat specimens, with error bars indicating standard deviation.

previously. Water is known to be a good plasticiser [19]; water molecules increase the mobility of molecular chains, particularly of amorphous phases [19] (such as lignin, in which bamboo is rich, but also hemicellulose and amorphous cellulose), by weakening hydrogen bonding between polymer chains. The removal of water tends to reduce free volume and molecular mobility, thereby stiffening the material. This phenomenon is observed in both natural polymeric materials (such as wood and bamboo) as well as synthetic polymeric materials (such as nylon) [19,20].

The reduction in storage modulus of the notched bamboo material suggests a competing phenomenon undermining the stiffening from water removal. The notched samples maintain a much higher damping factor (i.e. higher ratio of loss to storage modulus) than unnotched samples over the same temperature range (Fig. 6). We think it is unlikely that the presence of a notch (i.e. a stress concentrator) results in fatigue degradation, firstly due to the low stresses involved. Secondly, subsequent tests, in which notched specimens were taken through a second run of the thermal scan, showed that the initial storage modulus of the specimen in both test runs was fairly similar (Fig. 7).

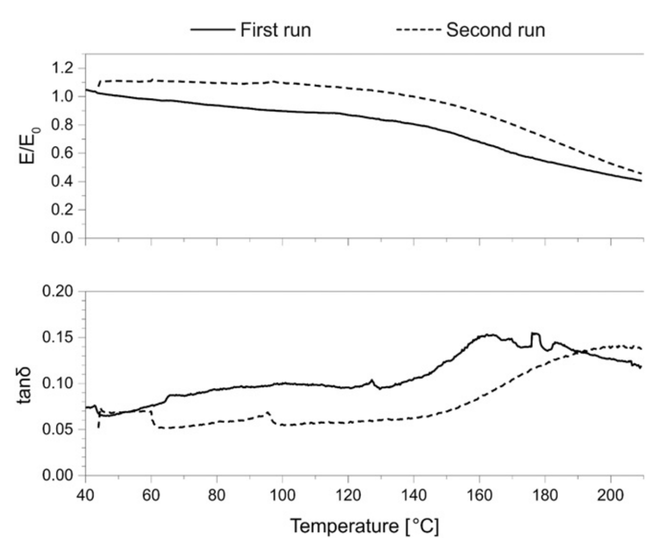

Fig. 7. Repeated temperature scans for a notched specimen.

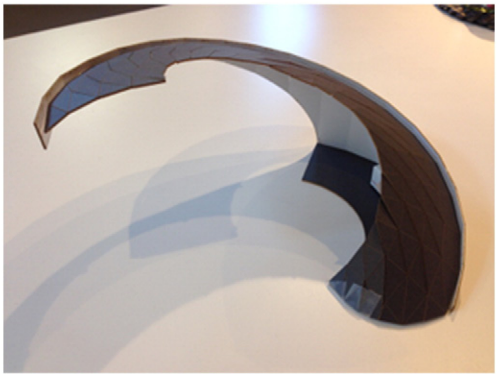

Fig. 8. Laser-cut paper prototype of helical structure.

It has been established [21] that for wood, the strain limit of the linear viscoelastic region, below which strain level does not affect viscoelastic properties significantly, is of the order of 0.1%. This limit has not been established for bamboo, and to do so would be beyond the scope of this study, but the strain in these tests, 0.07% for the unnotched and 0.02% for the notched specimens is of that order. It is therefore possible that the difference in strain levels between the two specimens leads to the difference in their measured variation of modulus.

When further heated to temperatures above 150 °C, both unnotched and notched samples exhibited a dramatic reduction in stiffness at a rate of 5.7–8.0% of initial storage modulus for every 10 °C increase in temperature. Notably, at these higher temperatures the damping factor in the two sample types was also similar (in both values and trends), showing a peak at approximately 180 °C of around 0.16.

Polymers commonly show a clear transition temperature at which storage modulus degradation begins and is typically followed by, or coincides with, a peak in damping factor. This is referred to as the glass-rubber transition temperature. Both notched and prismatic specimen materials exhibited similar transition temperatures, first, suggesting that the rate of temperature increase used in the testing procedure was appropriate, so that the whole volume of the specimen was heated evenly. Second, and more importantly, the transition temperature range of 150–180 °C coincides with the glass transition temperature of lignin [22,23]. As lignin is an important constituent polymer in bamboo, accounting for ~25–30 wt% of the dry material [17,18], the observation of a distinct transition in the thermo-mechanical profile is not surprising. For the purposes of process optimisation, it is most appropriate to use the temperature at the onset of stiffness degradation (i.e. 150 °C) as a guide to the lower-bound temperature to bend the bamboo sheets to shape.

We observed that at 210 °C, the unnotched and notched specimens had a storage modulus about 60% and 40% that of their initial storage modulus at 40 °C. In the one test which was taken as high as 250 °C, the storage modulus reduced to below 1% of its initial modulus. However, at such a high temperature the material would have at least partially thermally degraded – as was shown by the thermogravimetric analysis in the previous section.

Finally, a test with two thermal heating cycles on a notched specimen showed that for a peak temperature of 210 °C the initial storage modulus was recovered upon cooling. Although the subsequent thermomechanical properties were altered: the storage modulus was higher and constant up to 100 °C (like the unnotched specimen in the single thermal scan), and the glass-transition temperature, read from the peak in damping factor, was raised from 180 °C to around 200 °C. This suggests that some irreversible chemical change appeared to have occurred. A shift in glass transition temperature to the right may be due to increased cross-linking. This in-turn would explain the higher initial stiffness of the bamboo sheet in the second thermal scan. The engineered bamboo product studied here, having seen high temperatures during processing, would be expected to have gone through some such irreversible change, and it would therefore be likely that untreated bamboo would exhibit a lower glass transition temperature than observed in these tests.

In addition, the removal of water, a plasticiser of amorphous natural polymers, could perhaps influence the glass transition temperature as, once water is removed, more energy would be required to move molecular chains [19]. This would depend on water still being present in the specimen approaching the glass transition temperature during the first thermal cycle. In wood, Startsev et al. [24] saw little influence of initial moisture content on the transition temperature, and hypothesised that any water present in the specimen would have been lost at a lower temperature.

The combined results from the thermogravimetric analysis of bamboo and dynamic thermal mechanical analysis helped to identify the ideal temperature range in which the heat-bending of bamboo sheets could be effectively performed, avoiding thermal degradation (mass loss) of the material.

3. Structural realisation

The pavilion is composed of a helical shell that cantilevers from the base and edge (Fig. 7). To explore the design of the helix, a 3d NURBS [25] and parametric model [26] were created. The inside and top outside edges follow the same helical equation controlled by the inner radius, outer radius, total rotation and overall height. The cross-section of the shell is defined by the drop from top height to the edge board. The lower curve on the outside is controlled by a two-step function to climb rapidly then meet the upper curvature smoothly. Overall the structure is designed to be flattened in CAD and manufactured on 2D CNC equipment (Figs. 8 and 9).

To achieve the curvature in the model, a system of triangulation was required. The laminated bamboo used in the characterisation tests (Section 2.1) was also used in the construction. Initial experiments with 19 mm thick sheets and biscuit jointing were neither successful in achieving the necessary curvature nor the lightweight form inherent to a shell structure (Fig. 10). To realise the form, scoring and targeted heat were investigated. A series of small-scale tests were conducted using various orientations of 5 mm sheets and varying depths and cut-angle of scoring in both birch plywood (Fig. 11a) and laminated bamboo (Fig. 11b). The birch plywood specimens did not demonstrate the residual set of deformation that was achievable in the laminated bamboo.

In full-scale fabrication, a v-shaped notch line was cut into the surface of the 5 mm thick bamboo sheet, leaving 1.8 mm thickness at its base. This was done so that the sheet could be bent along a particular notch line and to improve the penetration of heat into the material along that line.

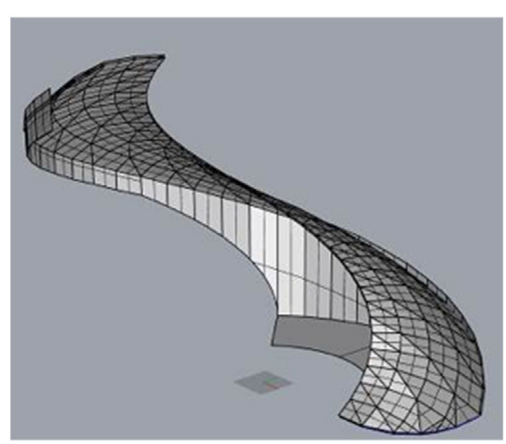

Fig. 9. Grasshopper & Rhinoceros CAD model.

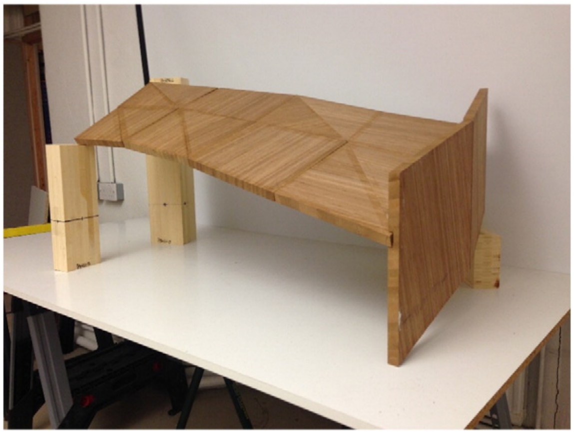

Fig. 10. Bamboo ply prototype with 19 mm thick boards.

3.1. Prototype construction

To determine if the behaviour observed in the experimental tests was scalable to the bamboo sheet material, a prototype panel was constructed. To achieve the curvature of the parametric model, the plates of the shell were cut using a rotary blade and routed partially through the thickness. To determine the cut, different angles and depths were investigated (Fig. 11). Once cut, the plate was heated using heat guns (Steinel HL2020E) and the surface temperature was measured using an infrared thermometer (Fluke 561). The measurements indicated that a single gun set at 450 °C resulted in a surface temperature of 285 °C, whereas two heat guns set at 450 °C resulted in a slight increase in surface temperature to 300 °C. In comparison to the dynamic thermal mechanical analysis tests, the prototype construction utilised a higher heating rate and was conducted in an open air environment. The construction process is assumed to expose the surface of the material to a high temperature, which may cause localised thermal degradation, however the bulk of the material was expected to be within the 150–175 °C range ideal for heat bending without substantial degradation. The prototype structure was formed using two heat guns with nozzle temperature set to 400 °C, with a measured surface temperature of 285 °C. The prototype validated thermal modification for manufacturing the components of the helix.

Fig. 11. Scoring and heating tests on depth and orientation to grain on (a) birch plywood and (b) laminated bamboo.

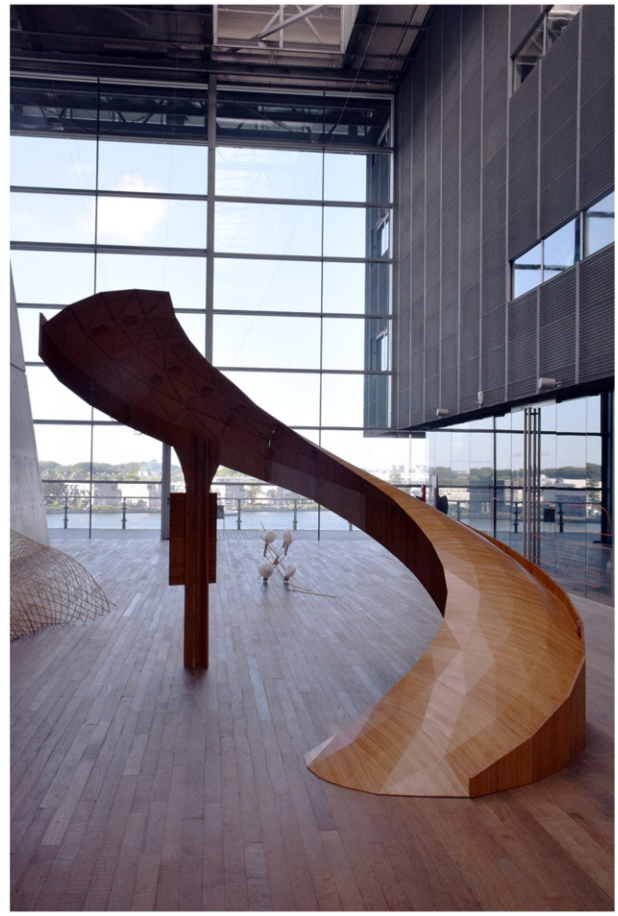

Fig. 12. Completed engineered bamboo helix installed.

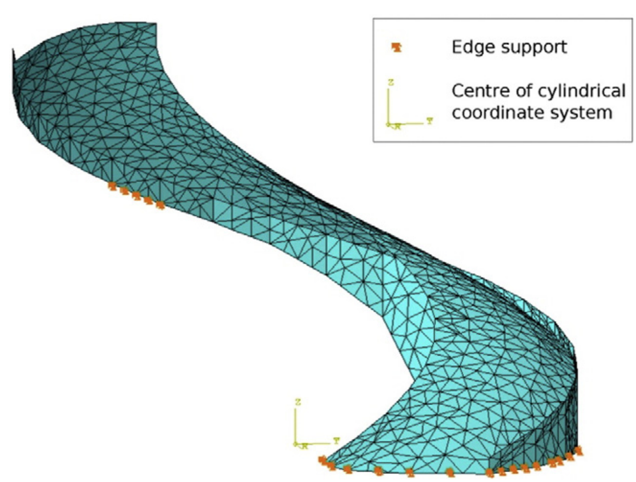

Fig. 13. Finite element mesh used for analysis, showing support conditions and the coordinate system used to define the orthotropic material orientation.

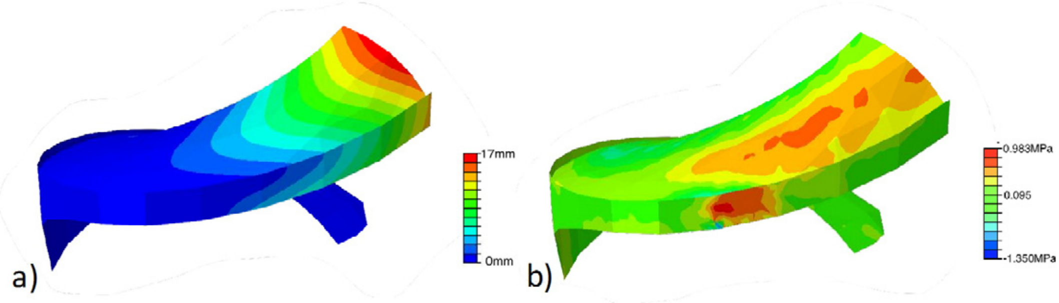

Fig. 14. a) Modelled deflections and b) maximum in-plane principal stresses.

3.2. Full structure construction

The fabrication of the pavilion (Fig. 12) consisted of a laminated bamboo base, prop and edge board, both made from 19 mm thick laminated bamboo. The shell was constructed from 5 mm thick boards. To construct the final design, the parts were cut from 1200 × 2440 mm boards. The boards were routed on the underside along the fold lines and then the cuts were subjected to thermal treatment described above. The process was iterative to ensure curvature matched the curvature of the adjacent plates. The base and edge supports were connected using biscuit joints. For the shell, the individual panels were connected using bamboo dowels and attached to the edge support through a slotted connection. All parts were glued in place using a fast curing polyurethane glue. Additional bolted connections were added to the underside of the shell to facilitate construction, deconstruction, and for additional load transfer in tension between the panels.

The structure works predominantly by transferring forces in the plane of the bamboo panels, although the shell has significant bending stresses in the upper section, where it cantilevers away from the edge panel.

3.3. Finite element model

The spiral was modelled to give an indication of its structural behaviour and to validate the position of the prop as a support to the cantilever. Fig. 13 shows the applied supports at the base, and at the location of the prop. The structure was modelled in Abaqus, using shell elements and orthotropic material properties for the bamboo measured by Yang et al. [27]: an elastic modulus of 8114 MPa in the grain direction and 1208 MPa in the cross-grain direction, an in-plane shear modulus of 945 MPa and a Poisson's ratio of 0.4. Only gravity load was applied to the structure. A cylindrical coordinate system was used to align the material properties of the modelled elements with the built helix.

The results show a peak elastic deformation of approximately 17 mm (Fig. 14a). Peak principal stresses of approximately 1 MPa (the maximum Von-Mises stress is 1.7 MPa) show that the outer edge cantilevers out from the prop, with highest stresses over the support (Fig. 14b). The shell is routed into the edge panels allowing them to work together to resist the cantilever bending as the structure springs from the prop and the support at the base. This results in peak stresses at the top of their curve, furthest from the neutral axis of that composite section (Fig. 14b). The results are not directly validated by experimental evidence, but the model is nonetheless useful for overall design of the physical object.

4. Conclusions

The manufacturing method used in construction of the helical pavilion demonstrated the potential for laminated bamboo in structural applications. The experimental testing illustrated that thermal processing can be used to modify the shape of the material to achieve new forms. The study is a novel application and first to show the potential for thermal modification of laminated bamboo in shape forming and design. Through harnessing the thermal softening and residual set properties, the sheet material is moulded into a folded shell. The method used here will provide the foundation from which to explore development of folded bamboo products which may offset the use of conventional plastics in a variety of applications.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.matdes.2017.07.035.

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