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Prelude: the future of structural bamboo

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Abstract

Prelude demonstrates the possibilities for engineered bamboo in structural applications. Our pavilion is composed of a spiral pathway that cantilevers from the base and embodies the function of the Muziekgebouw through a lightweight design that mirrors a musical prelude in structure, concept and form. Inspired by Guastavino´s masonry vaults, the structure evokes the image of a spiral staircase originally constructed from thin tiles, transformed in a novel material with properties distinct from structural masonry. With a growing need for the development of sustainable materials, engineered bamboo combines the benefits of a natural fibre composite with the advantages of a laminated material. Highly renewable, large diameter bamboo used for structural applications is harvested every 4-5 years. Once harvested, the raw material can be processed into strips, which are then laminated into a board product. The processing reduces inherent geometric and mechanical variability of the natural material that currently limit the application of bamboo products. Currently promoted as a decorative material, *Prelude* is an example of the potential use of engineered bamboo beyond surface applications in architecture.

Keywords: engineered bamboo, shell structures, laminated composite

1. Introduction

Prelude is a pavilion comprised of a cantilevered helix that acts as a stiffened shell supported by an edge board and a base from which the freestanding section appears to spring upwards. The structure serves as an introduction to structural bamboo and to the potential the material offers. Structural bamboo is composed of the raw bamboo material in a laminated composite form. The advantage of bamboo as a material is the rapid renewability of the plant, which is ready for harvest in 4-5 years. Commercially produced, the laminated board product is mostly used in architectural and surface applications. While the material provides a unique appearance, there are additional structural properties which have yet to be fully explored. *Prelude* exemplifies the possibilities of bamboo in shell structures.

2. Background

Shells are thin plate structures that transmit forces in plane of the surface. Most well-known examples are constructed from reinforced concrete (Garlock and Billington [1]), however they have also been built in masonry for hundreds of years. Raphael Guastavino was a Spanish architect and engineer who constructed thin tile vaults, also known as timbrel vaulting, in Spain and the USA (Collins [2] Oschendorf [3]). Thin tile vaults consist of a unique construction method, which allowed for various forms to be achieved rapidly with little or no formwork. The spiral staircase in the First National Bank in Paterson, New Jersey is an example of Guastavino's work (Figure 1). The masonry tiles are connected through thick mortar joints that allow double curvature with planar units and transfer the stresses across the tiles into the supports. The structure served as inspiration for the pavilion.

Figure 1: First National Bank, Paterson, New Jersey, ca. 1890, Raphael Guastavino.

As a raw material, a bamboo culm is a hollow cylinder with fibres functionally graded within a matrix (Figure 2). The gradation within the culm wall is a natural optimisation in response to the wind forces along the height of the culm, with the densest fibres located on the exterior of the culm wall to increase the bending resistance. The inherent strength of bamboo is in the longitudinal direction of the fibres (along the height of the culm) with lower strength perpendicular to the fibre direction.

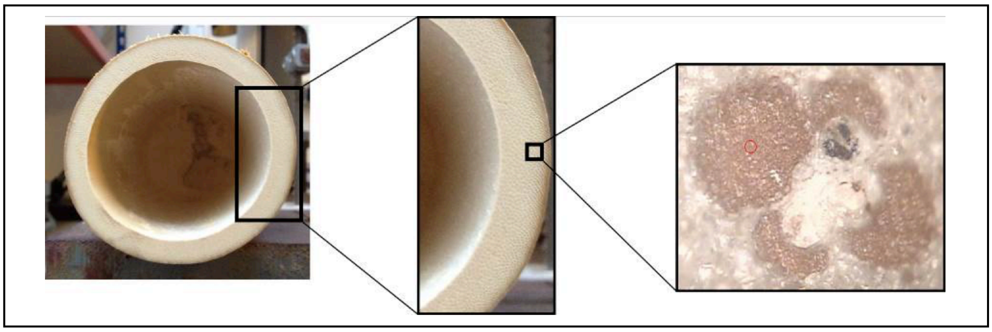

Figure 2: Bamboo as a raw material.

Structural bamboo is made by processing the raw material into strips that are then laminated into a board product of varying dimensions (Figure 3). The process maintains the longitudinal direction and continuity of the fibres thus translating the strength properties inherent in the raw material (Sharma et al. [4]).

Figure 3: Manufacturing process for bamboo strips.

The properties of structural bamboo are unique and have immense potential. Table 1 presents a summary of the mechanical values of structural bamboo in comparison to timber products. While bamboo is often thought of as analogous to timber, it has greater strength and flexibility, suggesting an expanded role in structures made from natural materials. As an example of this potential, *Prelude* demonstrates the possibilities for bamboo in structural applications.

Table 1. Properties for structural bamboo and comparable bleached bamboo and timber products (adapted from Sharma et al. [5]).

	Density	**Compressive Stress**		**Tensile Stress**		**Shear Stress**	**Flexural**	
	ρ	Parallel to grain	Perpendicular to grain	Parallel to grain	Perpendicular to grain	Parallel to grain	Modulus of Rupture	Modulus of Elasicity
	kg/m^3	MPa	MPa	MPa	MPa	MPa	MPa	GPa
Caramelised Bamboo	686	77	22	90	2	16	83	10.8
Raw Bamboo *Phyllostachys pubescens*	666	53	--	153	--	16	135	9
Sitka Spruce	383	36	--	59	--	9	67	8
Douglas-fir LVL	520	57	--	49	--	11	68	13

3. Design

3.1. Concept

Our pavilion is composed of a helical pathway that cantilevers from the base and embodies the function of the Muziekgebouw through a lightweight design that mirrors a musical prelude in structure, concept and form (Figure 4). Building upon masonry shell construction, the pavilion includes a cantilevered spiral constructed from a rapidly-renewable structural material with immense potential.

Guastavino's shells are constructed to act in compression. In contrast, the bamboo shell acts in bending and tension, utilising the inherent properties of the material to form the structure. To utilise the helix as the support for a stairway, the shell would need to act in compression through the addition of wall supports and a thrust connection at the upper end, improving its overall performance.

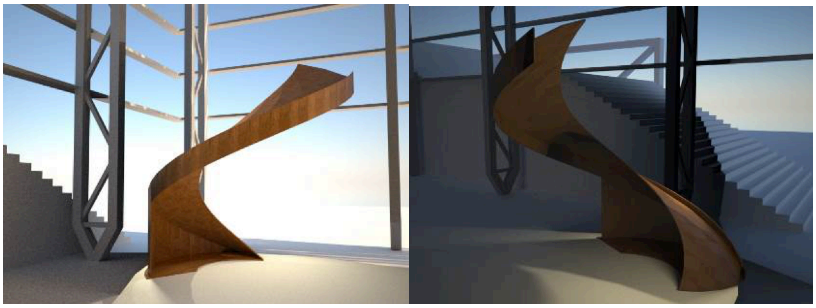

Figure 4: Prelude design concept.

3.2. Design

To explore the design of the spiral, a 3d NURBS (Rhinoceros [6]) and parametric model (Grasshopper [7]) 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 manufactured on CNC equipment.

The geometry and edge supports were optimised based on comparison with a structural analysis (Autodesk Robot [8]), with the geometry modeled as planar elements assigned a relevant thickness and structural properties as shown in Table 1. The base was given fixed supports and the structure was analyzed under gravity load (Figure 5).

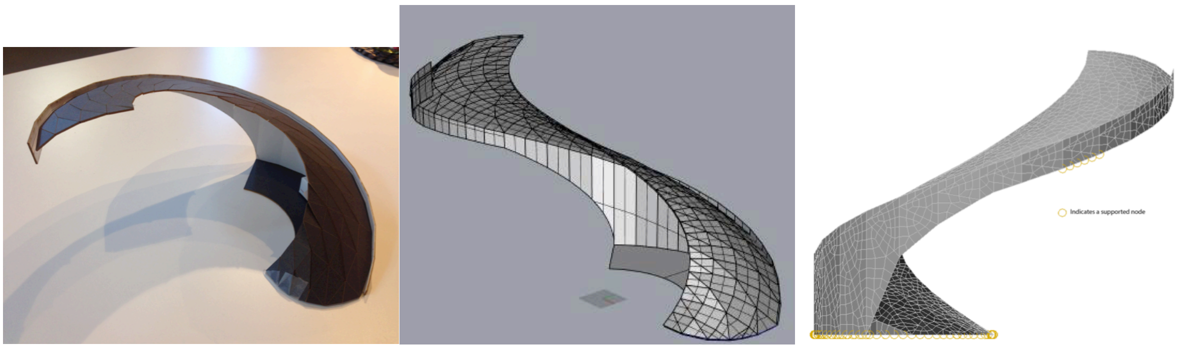

Figure 5: Scale model (left), Rhino model (middle), and Robot model (right).

3.3. Prototype

The final design was tested in a prototype section of the spiral (Figure 6). The shell was constructed with a 5mm laminated bamboo panel boded to a 19 mm edge board. The panel was cut and shaped to match the curvature of the shell.

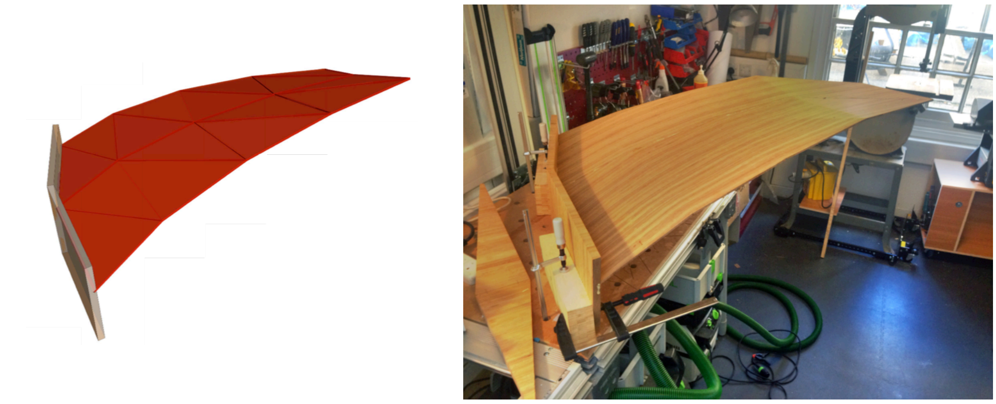

Figure 6: Prototype construction.

3.4. Preliminary construction

To construct the final design, the parts were cut from 1200x2440mm boards. The base and edge supports were connected using biscuit joints (Figure 7). 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. To aid with final construction the spiral was preassembled into six sections, although the structure was designed to fit the original size constraints of the Expo. These sections were dry joints, only connected through bolted connections.

Figure 7: Base and edge construction and assembly.

Figure 8: Edge board connection (left) and shell joints (right).

3.5. Analysis

The deformed shape of the structural model is shown in Figure 9. The structure is formed of two connected parts: the 5mm-thick triangulated shell, and the 19mm-thick vertical edge panel. 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.

In the lower section, where the edge panel is in contact with the ground, the in-plane forces are predominantly compression – the inner edge of the shell is steeply sloped and relatively stiff under vertical load in comparison to the rest of the shell, which arches between this stiff edge and the support of the edge panels. In the upper portion of the structure, the whole cross-section cantilevers away from the supported end, supported at the edge mid-way along the cantilever. The shell restrains the edge board against lateral torsional buckling, so that the edge panel can act as a cantilever from the lower section. The shell, in turn, cantilevers away from the edge panel, resulting in a band of radial tensile stresses in its top surface, shown in Figure 9. The grain of the bamboo does not generally run in the direction of the main forces applied, but has been chosen to achieve the greatest bond strength in the glued joint between the individual bamboo panels.

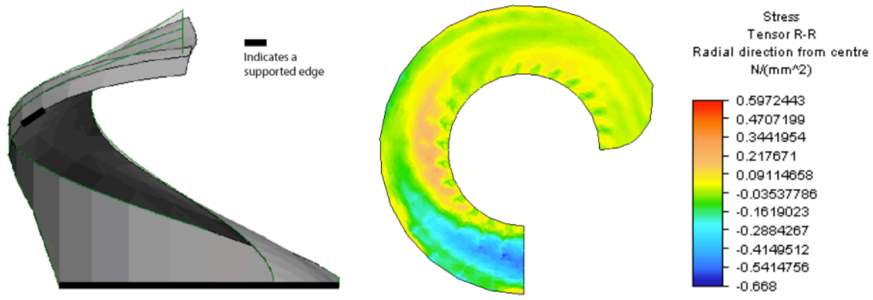

Figure 9: Robot model with deflected shape and stress analysis.

3.6. Final Construction

Prelude was constructed onsite in six sections using a bolted connection on the underside of the shell. The connection was used to allow for disassembly of the structure. The construction process is shown in Figure 10 and took 8 hours with a four-person team.

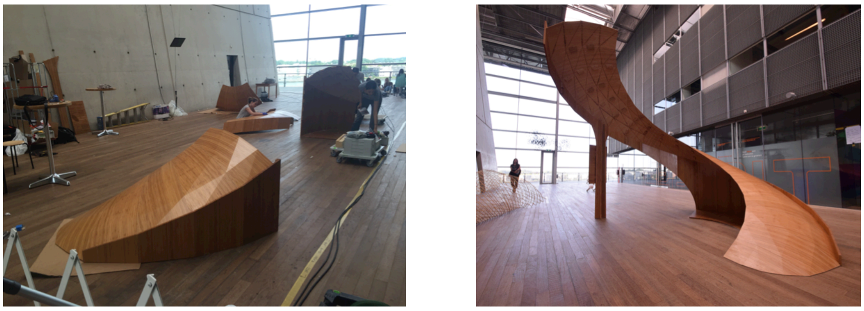

Figure 10: Final construction.

4. Summary

Prelude demonstrates the possibilities for structural bamboo. With exceptional structural properties, there are applications that have yet to be explored. Through parametric design and structural analysis the cantilevered helix was prepared for the Expo at the Muziekgebouw. The process of construction and assembly enabled further understanding of the engineering and construction benefits, possibilities and limitations of building with structural bamboo. The structure serves as an illustration of structural bamboo in engineering applications.

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