PROTOCOL OF ERROR

The design and construction of a bending-active gridshell from natural bamboo

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Abstract. This paper advocates alternative methods to overcome the impossibility of realising ‘perfect’ digital designs. It discusses Hong Kong’s 2015 ‘ZCB Bamboo Pavilion’ as a methodological case study for the design and construction of architecture from unprocessed natural bamboo. The paper critically evaluates protocols set up to deal with errors resulting from precise digital design systems merging with inconsistent natural resources and onsite craftsmanship. The paper starts with the geometric and tectonic description of the project, illustrating a complex and restrictive construction context. Bamboo’s unique growth pattern, structural build-up and suitability as a bending-active material are discussed and Cantonese bamboo scaffolding craftsmanship is addressed as a starting point for the project. The paper covers protocols, construction drawings and assembly methods developed to allow for the incorporation and of large building tolerances and dimensional variation of bamboo. The final as-built 3d scanned structure is compared with the original digital model. The paper concludes by discussing the necessity of computational architectural design to proactively operate within a field of real-world indeterminacy, to focus on the development of protocols that deal with imperfections, and to redirect design from the virtual world towards the latent opportunities of the physical.

Keywords. Bamboo; bending-active gridshells; physics simulation; form-finding; indeterminacy.

1. Introduction

Bamboo is one of the most environmentally sustainable construction materials due to its fast rate of growth and material strength. Yet, bamboo is rarely
used in its natural form as a structural material for permanent architecture, and when used it is primarily applied in replacement of steel or wood rather than in ways tailored to its specific qualities. Its potential to be used for the construction of resource efficient form-active gridshell structures has yet to be exploited (Rockwood, 2015).

Figure 1. ‘ZCB Bamboo Pavilion’ during an evening event: a light-weight bending-active bamboo gridshell covered with a glass-fibre-reinforced plastic polymer membrane.

Natural bamboo has unique potential in its unprocessed form as a light-weight structural material with high elastic bendability. This is due to its typical cylindrical cellular build-up and strong longitudinal fibre structure. The ‘ZCB Bamboo Pavilion’ research project explores this latent property through the design and building of a large bending-active bamboo structure. The ‘ZCB Bamboo Pavilion’ is a four-story-high, thirty-seven metres spanning gridshell completed in Kowloon Bay, Hong Kong in October 2015 (Figure 1). It serves as a public event space for three hundred people and aims to promote innovative and ecological architecture. The structure combines traditional Cantonese bamboo scaffolding with digital design techniques for form-finding and construction documentation. It is built from unprocessed bamboo poles, hand tied together with metal wire following traditional scaffolding techniques, and is covered with a translucent glass fibre-reinforced polymer membrane.

The ‘ZCB Bamboo Pavilion’ research project overturns the conventional sequential design workflow of architectural projects by introducing a laboratory-based design & build approach. In this the roles of architects, engineers, consultants and contractors allow for an overall setup where feedback from all parties remained possible throughout the construction process. In order for the final construction to be feasible within the constraints of the site, protocols were put in place allowing material deviations, onsite inaccuracies, unpredictable material behaviour, and errors to be managed and included as
enablers rather than restrictors. This paper covers the final steps of the project and illustrates the simplifications of the construction process that were put in place to build this large architectural structure in a short time with minimal available onsite means or skills.

2. The indeterminacy of bamboo

2.1. EXPANDING CANTONESE BAMBOO SCAFFOLDING CRAFTSMANSHIP

Traditionally, Cantonese construction uses hand-tied natural bamboo as structural material for its scaffolding, temporary theatres, and temporary places for religious festivities). These structures are very adaptable in shape, dimension, and plan and rely on predetermined typologies, forms, and construction methods for their materialisation. Without need for architectural drawings they are designed and built onsite by licensed craftsmen who continue to sustain their century-old traditional methods.

The pavilion discussed here is part of a larger research ambition seeking methods for architectural innovation through the introduction of digital design tools into pre-existing construction methods. This specific project explores the potential of combining computational form-finding and construction documentation methods with Cantonese bamboo scaffolding craftsmanship.

2.2. BAMBOO

Bamboo is rarely used in construction as a structural material, partly due to its widely varying material properties when used in its natural form and to the lack of information on the structural strength of its connection methods.

Bamboo first grows up to 80% of its total height in the first month, after which its cell walls thicken by growing inwards (lignification phase) over a span of seven years or more without substantially changing its appearance. Bamboo gains its strength from a unique build-up of cylindrical interconnected cells separated by reinforcing diaphragms (Figure 2, left) and its longitudinal fibre structure. Each species has different material properties and the strength of each individual pole is further defined by the soil composition at its place of growth, climatic exposure, water availability, etc. Typically fresh cut bamboo has more flexibility due to a high water content.

The bamboo species Phyllostachys Edulis, also known as Moso Bamboo, or Mao Zhu (毛竹) was selected. This is a temperate species of giant timber bamboo native to China’s Guangdong province (Figure 2, right). Freshly cut, flexible bamboo aged between three and five years was used for this project.
Regulations on how to use this species of bamboo in a bending-activated structure was unavailable at the start of the project. The architectural and structural design therefore resorted to the rigorous use of physical and digital simulation models and prototypes to assess structural behaviour in the design phase and to define practical construction methods, detailing, and installation sequence (Figure 3).

**Figure 3.** Project design sequence through digital and physical prototyping.

### 3. Geometry definition

Pioneering engineers like Frei Otto employed physical models, such as hanging chain models or soap films, as 'physical computers' to generate a structure’s optimal form for resisting specific design loads. The ‘ZCB Bamboo Pavilion’ follows this tradition, but incorporates digital real-time physics simulation engines in the workflow to define a suitable form for a bending-active gridshell.

The pavilion’s structure uses a hyperstatic hybrid system. This was the outcome of a series of 1 to 20 scale physical study models made from split bamboo that were seeking structural solutions appropriate to program and site. The structure consists of an extended triangulated diagrid that folds down onto itself to form three large hollow columns.

The digital design sequence was set up using Kangaroo as a computational form-finding tool. Kangaroo is a plug-in for Rhinoceros® and
Grasshopper® that uses particle systems in which interconnected networks of geometry control points respond to applied forces following laws of physics. The sequence started off from an intersecting planar curve network that was folded onto itself into the final geometry. This was primarily done by using two force types: Spring-From-Line forces, and Bending forces. The first applies an elastic spring force is between the end points of each curve segment aiming to maintain a specific rest-length. The second applies a bending force in between each curve’s adjacent line segments aiming to straighten the curve. The resulting intersecting curve model was developed further to a non-intersecting axis model incorporating bamboo diameters and individual lengths of overlapping poles.

4. Protocols for indeterminacy

The construction was done by a local general contractor and a subcontracted bamboo scaffolding master. Neither had previous experience working with complex geometric configurations or bent bamboo. A construction system needed to be developed that was simple enough to bypass language and cultural barriers, and clever enough to incorporate the material variations of the bamboo poles and the construction tolerances of hand-tied connection knots. The system had to enable construction from temporary bamboo scaffolding without the use of architectural drawings.

4.1. HAND-TIES AND ONSITE COLD BENDING

Traditional hand-tied knots easily allow connecting poles of various dimensions. Cantonese scaffolding knots are made such that they allow tightening by winding the wires. These are locked in by sliding through the knot itself. As the poles do not have a constant diameter, but slightly narrow down in the middle of the internodes (Figure 2), the connecting of poles away from the nodes prevents them from sliding. As traditional knots are not fireproof
they were replaced with bundles of 0.7mm diameter metal wire (Figure 7, left).

The individual poles, with lengths of up to 7.2m and diameters of 80mm to 120mm, are very difficult to bend. Interconnected, however, the curves can be more easily shaped. To prepare for this shaping, base anchor points needed to be prepared and curve intersection points needed to be marked up.

4.2. BAMBOO PREPARATION

A practical labelling system was set up to mark the curve intersection points onto each pole. By matching corresponding labels onsite an installation system became possible where the structure could independently and gradually ‘find’ its form as all poles gently pushed back to the imposed curvature, aiming to straighten out.

To prepare the bamboo, all poles were cleaned, sorted according to material properties, and cut to length following a spreadsheet with information extracted from the digital model. Individual poles were tied together and labelled (Figure 7, middle). A sticker with all node intersection and pole information was placed at the correct distance (Figure 6).

4.3. FOUNDATION DRAWINGS

In parallel to the bamboo preparation, concrete foundations were cast. Bamboo poles are locked in place by anchoring them into a stone foundation plinth and casting protruding starter bars into the bamboo pole cavity.

Three 5.4m diameter, 500mm high concrete foundations were cast. The fifty-four starter bars were then bent into the correct angle using a hollow steel pipe and reference triangles cut from paper (Figure 6, left). PVC drainage pipes were hand-cut to angles, and used to cast the smaller foundation plinths for each pole (Figure 6, middle). Upon installation each pole was first
placed over its rebar. Once tied into place, non-shrink grout was poured into the poles through a small hole drilled above the rebar until the entire lower section was filled. The irregular interior section of bamboo (Figure 2) inhibits sliding off. For safety additional metal clamps were added to prevent separation in case of bamboo cracking.

4.4. BAMBOO INSTALLATION

The installation of interconnected bamboo poles started by lifting them onto scaffolding in two to three parts. End segments were placed over the starter bars (Figure 6, right) and corresponding intersection points were brought together (Figure 7, right). Key preliminary points were projected on the ground to give a 2D reference location. Subsequent nodes found their own position automatically as each pole tried to straighten itself out. A precise installation sequence had been set up that guaranteed the distribution of the poles into three layers. This prevented the localised tight bending radii weaving would require, and gave the pavilion its distinct striated look where certain directions can be seen pushing through the taut membrane.
4.5. Membrane

The ‘ZCB Bamboo Pavilion’ was covered with a tailor-made, waterproof, non-elastic, translucent, glass-fibre reinforced composite tension membrane. Its fabrication required onsite measurement of the as-built pavilion. This could not be done through 3D scanning as the complexity of the scaffolding underneath would make it impossible to isolate the structure. A manual method was developed where workers used a cloud-based spreadsheet in which each triangle edge length was fed after measuring them by hand. From these edge lengths triangles were cut from fabric using a computer controlled cutting table. The triangles were welded into long strips (Figure 8) that were then welded together into one giant ‘sock’. This ‘sock’ was then manually fixed to the bamboo structure.

5. As-built

The bamboo structure was erected in less than two months, and its membrane matched the structure closely. The capabilities of the bamboo poles to bend were slightly overestimated and the five poles with the tightest curvature had to be locally notched to allow for adequate bending. All other interconnected poles worked together to find the final form. Combined, the bamboo structure and membrane weigh roughly 7.25 tonnes, a fraction of the 101 tonnes of the concrete foundations and less than twice the weight of the 3,400m³ of air the pavilion contains.

The cumulative impact of changing material properties, geometry deviations, surface deflections and construction inaccuracies, resulted in a structure that matched the digital ambition. A 3D scan shows how closely the as-built structure approximates the digital models (Figure 9). The largest deviations occur in areas where curvature is minimal for two of the three members. Here the third direction seems incapable of preventing the other two from straightening out more, resulting in a slight flattening of the area. This
unforeseen behaviour does not seem to affect the overall structural integrity as the overall synclastic nature of the geometry was maintained.

Figure 9. As-built bamboo structure (left); 3D scanned vs. originally designed: red ≤ 50mm deviation, blue ≥ 1000mm deviation; Top view (middle); bottom view (right).

6. Conclusion

In a country notorious for building speed and construction quality it is vital to question how to overcome the methodological mismatch of aiming to materialise idealised digital designs. Design priorities must be redirected from the ideal virtual realm to the latent opportunities of the physical world.

The ‘ZCB Bamboo Pavilion’ illustrates the complex dynamics of Hong Kong’s bamboo construction industry as it surpassed traditional, technical, cultural, and architectural boundaries. The role of the architect was expanded to that of a facilitator. Computation was strategically used to program building information, simulate behaviour, and orchestrate resources. Indeterminacies were incorporated to allow for straightforward construction.

The ‘ZCB Bamboo Pavilion’ showcases how a constructive dialogue with traditional construction systems allows for experimental prototypes to be possible. By merging both worlds’ methods and processes, alternative and ecologically sustainable futures become possible.

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