# BUILDING INDETERMINACY MODELLING – COMPUTATIONAL DESIGN AND LOW-TECH CONSTRUCTION OF A HONG KONG BAMBOO GRIDSHELL

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**Abstract:**

This paper discusses the 'ZCB Bamboo Pavilion' as a case study for the computational design and building information modelling of structures where both applied materials and available craftsmanship are highly unpredictable in terms of accuracy and precision. The 'ZCB Bamboo Pavilion' is a thirty metres spanning, light-weight, and bending-active gridshell, completed in Hong Kong in September 2015 as a public event space. It is built from unprocessed bamboo poles, hand tied together according to traditional Cantonese bamboo scaffolding craftsmanship, and covered with tensile fabric.

The paper begins by describing the geometrically complex and structurally high-performing project, and illustrates the low-tech context in which it was realised. Built from flexible components, the pavilion's tectonic system is a diagrid shell structure that folds down into three large hollow columns. It was developed using physics simulation engines and physical model prototyping. The bamboo used has widely varying geometric, dimensional, and performative properties, and the scaffolding industry, on whose principles it was based, does not use conventional architectural drawings for its intuitive construction, creating a highly indeterminate and complex field of operation.

Next, the paper discusses the building information modelling protocols put in place to respond to indeterminacies. It discusses the digital design models, the abstractions, and the assumptions that were strategically applied when developing the singular digital design proposal. The paper examines ways in which the digital modelling environment played an ongoing role in design as new refined data was added to the system. It then covers the construction documentation and annotation information that were used for onsite approximation.

The paper then discusses Hong Kong's building code and architectural practice with respect to indeterminacy. The 'ZCB Bamboo Pavilion' highlights how conservative local building cultures can move towards more effective incorporation of natural materials.

The paper concludes by discussing the necessity for digital design practice to proactively operate within a field of real-world indeterminacy. Risk, probability, and ambiguity are to be strategically balanced out against idealized digital set-ups and design priorities.

**Keywords:** high-tech versus low-tech, protocol for error, bamboo architecture, bending-active gridshell, form-finding.

## 1. INTRODUCTION

As global social and political attentions toward sustainability and the environment are rapidly on the rise, greater demand for responsible eco-friendly industry continues to grow. The construction industry is one of the largest consumers of global energy, water, and raw materials. It is also a major contributor to air pollution, gas emissions, and landfill waste. The search for sustainable, regionally accessible, and renewable materials plays a vital role in reducing the overall carbon footprint of global building production.

In most of Asia, bamboo is a locally available natural material that grows remarkably fast with a high strength to weight ratio. It has not been adopted by the construction industry as a viable structural material. When used in architecture, it is most commonly employed similar to traditional wood or steel as a structural compression or tension member replacement instead of being used for its unique inherent bending strength. The bending of large hollow bamboo poles can be assembled into gridshell-like structures, whereby a minimal amount of materials can create large spanning spaces.

The 'ZCB Bamboo Pavilion' research project investigates active bending properties of bamboo through the design and construction of a large bending-active structure. The pavilion was completed in Kowloon Bay, Hong

Kong in October 2015 (see Figure 1). It spans thirty-seven meters, is four stories high, and is wrapped in a lightweight translucent glass-fiber reinforced polymer membrane. The pavilion is situated on public land and is part of a larger government initiative promoting sustainable living and construction practices throughout the region. The structure is created from the combination of advanced digital design and traditional Cantonese methods of hand-tying bamboo.

Figure 1. 'ZCB Bamboo Pavilion' during a night-time event

The research project uses an alternative approach toward design and coordination with consultants, client, engineers, and contractors in order to proceed into uncharted territory with no building code or practice available as guide or reference. Here, the architects began with an initial approximating digital model that throughout the course of investigations became refined based on previously unavailable, newfound knowledge of materials and assembly techniques. Material deviations, construction inaccuracies, and human errors are calculated into the design process in order to stimulate innovation, simplify instructions, and expedite assembly on site. The indeterminacy encountered during the design and construction process and the techniques used to build this large and complex geometric structure with limited time and minimal onsite skillset will now be further explored.

## 2. BENDING-ACTIVE BAMBOO GRIDSHELL

'ZCB Bamboo Pavilion' employs a unique structural system that takes advantage of the inherent bending properties of its components. In traditional building construction, a combined system of tensile and compressive elements are assembled to develop a structure with minimal bending. Bending-active shell structures, however, take advantage of elastic material properties that are activated in often geometrically complex surfaces. These shell structures are comprised of individual elements, connected at nodes, which are then placed under stress in order to maximise stability and strength with minimal material under load bearing conditions. Bending-active gridshell geometry develops from bending planar elements and fixing them into their tensile state. The internal bending moments are transferred continuously until a global force equilibrium is reached.

The pavilion's tectonic system is a diagrid shell structure that folds down into three large hollow columns (see Figure 2). The tripod column configuration expresses the three layer system of bamboo poles that are attached to one another with galvanized steel wire at intersection points. The bending and triangulation of bamboo elements creates a strong and stable lightweight system capable of spanning large distances without the need for additional support. The individual bamboo poles used were categorized and selected by size and bendability, and appropriately deployed in areas where specific amounts of curvature were required. This selection process allowed for extreme variation in radius of bending based on the requirements of the design and helped to avoid going beyond the material breaking limits.

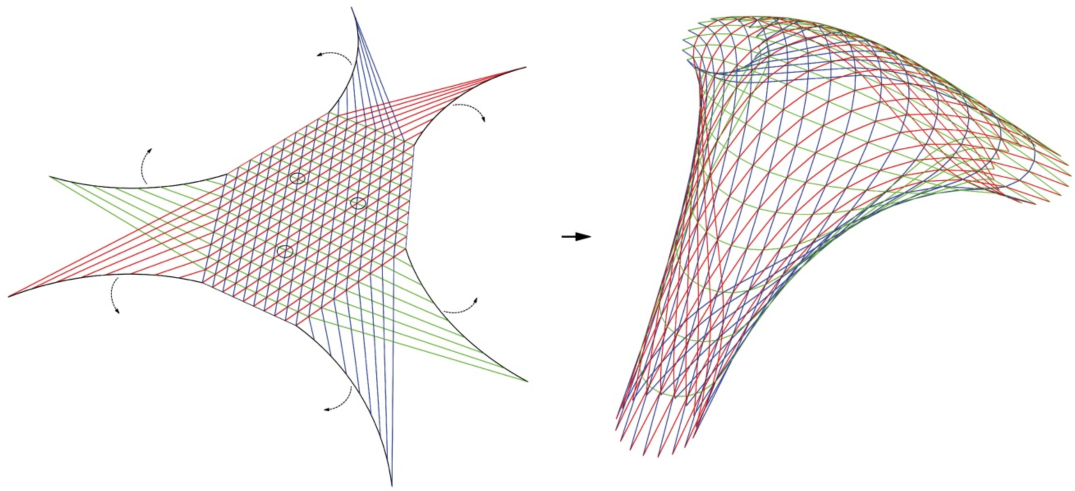

Figure 2. Digital spring-particle physics simulation engine as form-finding tool

The 'ZCB Bamboo Pavilion' was developed using digital physics simulation engines and physical model prototyping at a variety of scales. Digital simulations were extensively used in order to develop a workflow from initial design geometry and to create an output of information deployable in the field (i.e. data containing lengths and intersection points for assembly by traditionally trained bamboo scaffolders). Analog prototyping created an opportunity to insert new information into the digital model for re-computation and analysis. This dialog between digital simulation and analog deployment continued throughout the entire construction and assembly process, as unpredictable elements continuously arose that required design system changes (see Figure 3).

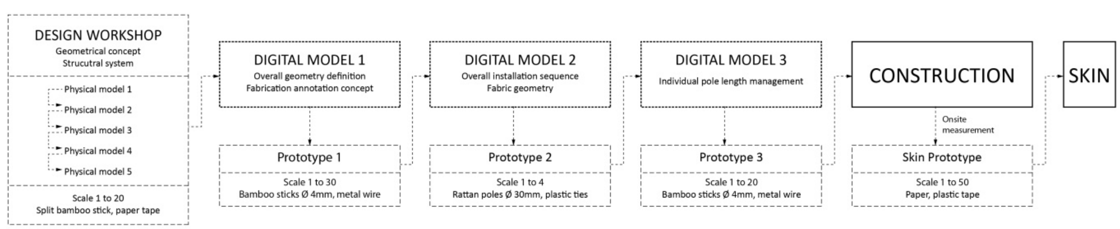


Figure 3. Design sequence using digital and physical models

The bamboo used has widely varying geometric, dimensional, and performative properties, and the scaffolding industry does not use conventional architectural drawings for its intuitive construction, creating a highly indeterminate and complex field of operation. The nature of unpredictable material and unconventional assembly, required instructions deployed into the field to be clear enough to minimize any misinterpretation of data, assembly technique, or order of operations, while simultaneously remaining an open system that could adapt to urgent changes in detail or geometry. The use of digital technology was imperative to this pliable and volatile method of operation in order to quickly make adjustments and update the 3d model with more sensitive data.

## 3. PROTOCOLS SET UP FOR INDETERMINACY

The approach to developing a digital model included the ability to update assumed variables relating to physical material properties, construction techniques, detail design, and structural concerns as data became more specific throughout the design and construction process. The final output of construction documents clarified the complex geometry into the simplest of possible instruction sets, capable of crossing language and cultural barriers. The documents were also able to maintain a high level of accuracy toward the overall setting out, location, and intersection points for connection.

A range of variables were found to have a major impact on the structural and design aspects of the pavilion and required early study. The overall length of materials cut from the bamboo forest would determine how many poles were necessary to span from one column to the next. This length would also set an amount of work required to combine those individual poles into long strings of material (shorter lengths would require more connections, measurements, etc). The constraint of truck size and practical transportation limits were also a significant factor in limiting pole lengths.

Bamboo pole direction was an area that needed to be stipulated for both structural and visual design priorities. Bamboo as a naturally grown and harvested material is inherently directional, with wider diameters near its base. In the 'ZCB Bamboo Pavilion', all bamboo members needed to end with wide elements facing the ground to ensure the highest strength when connecting to footings on ground level. This also meant that two narrow ended poles would ultimately need to meet for each string of connected poles. This aspect was also embedded into the digital model and included as an important part of the deployed construction documentation.

Bamboo poles grow in a variety of shapes and are rarely perfectly straight. Given that the 'ZCB Bamboo Pavilion's' geometry required a variety of bending materials, a relationship between the design geometry and available stock of materials on site was necessary in order to best deploy poles. After a rigorous visual inspection of the delivered stock, bamboo was categorized based on quality and amount of bending. These poles were then separated into their own piles and appropriately deployed based on the area of surface geometry most needed. This process helped avoid a random selection of bamboo during initial assembly steps. The digital system was updated to categorize poles based on the amount of bending required. This entire process helped in areas that were especially curved (see Figure 4). It should be noted that in area of tightest curvature, a modified system of cutting notches into poles became necessary, as the material properties were overestimated. This occurred on a total of five poles.

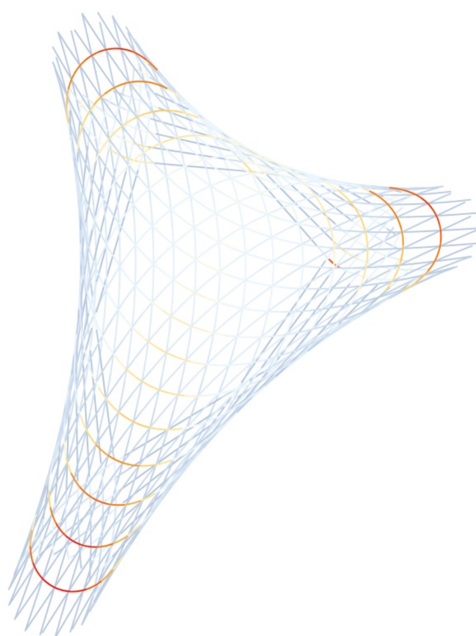

Figure 4. Member curvature analysis

The length of overlap became an additional variable that needed to be studied both physically and digitally in order to best determine the bending ability of material. Through such investigations and based on the available materials that could be harvested, the length of 7.2 meters and an overlap of 1.2 meters was settled upon as a simplified system, ensuring a 4:1 span to support.

These overlaps are moments where two lengths of bamboo are joined together to create longer strands of material. In initial design models this additional detail requirement was known but not investigated. However, it was later inserted into digital models for both visual studies and to maintain accuracy for final output instruction sets. Refining overlaps required offsetting their location to minimize the number of cross connection intersection points with those of another direction. The complexity of design meant the potential for up to six bamboo poles to be in a single intersection point – creating an unwanted density of material that would ultimately take away from the smoothness of overall geometry and increase difficulty to maintain assembly accuracy. An intelligent system was implemented into the computational model that limited the potential for this phenomenon to occur.

Given the unpredictable nature of naturally growing materials, the 'ZCB Bamboo Pavilion's' comprehensive design methods were left as an open system, capable of refinement based on new data, assembly techniques, analysis, and structural concerns. This approach to design and construction allowed for an ongoing dialog between naturally grown materials and traditional assembly techniques. Along with computational analysis, simulation and representation, the comprehensive design process was able to rapidly develop intelligent construction solutions found within the acceptable scope of design intent.

## 4. AS BUILT VS. DIGITAL MODEL

With an overall construction time of under 90 days, the 'ZCB Bamboo Pavilion's' final build was within an acceptable range of deviance from initial digital design models. The construction documentation system invented and deployed into the field worked well to direct contractors with a clear set of measurements and order of operations for assembly. A high-resolution 3D scan was taken of the final geometry and measured against the digital design model (see Figure 5). With very few instances of the design model exceeding the expectations of the bamboo poles' ability to bend, the majority of bending members found their final form with less than 50mm deviation. Only in two areas of minimal curvature did the structure attempt to flatten out. Considering the complexity of project, limited amount of time on site, unique digital design and documentation process, and experimental nature of assembly, the overall construction and completion was a successful investigation into the possibilities of digital design and unpredictable nature of natural unprocessed materials.

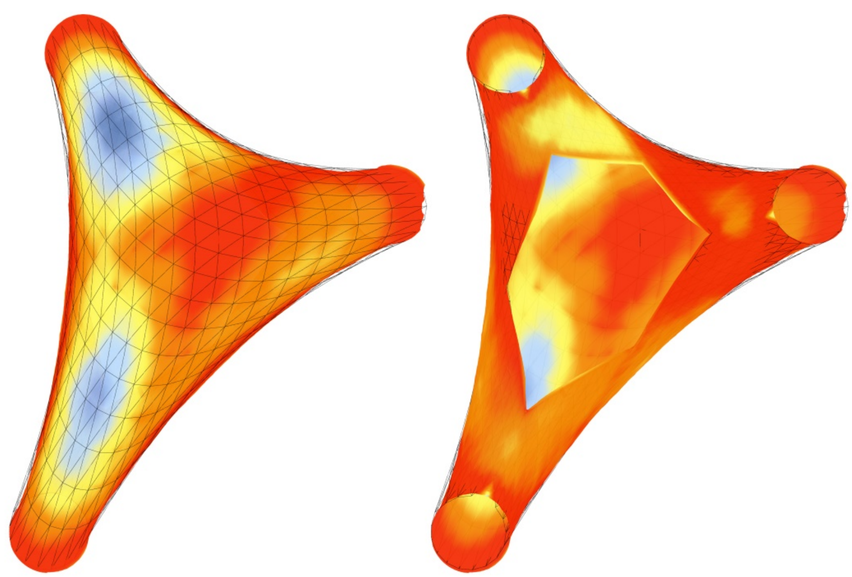

Figure 5. 3D scanned fabric vs. originally designed fabric: red = less than 50mm deviation, blue = more than 1000mm deviation; Top view (left); bottom view (right)

## 5. HONG KONG'S BUILDING CODE & BIM PROTOCOL

The 'ZCB Bamboo Pavilion' presents a variety of challenges in order to comply with the Hong Kong building code. Given the relative complexity and innovative nature of the design and materials, the pavilion construction proved to be especially ambitious given the strict nature of Hong Kong's regulatory bodies. Calculating the structure with a safety margin was also difficult given the variation between material samples with respect to age, origin, species, diameter, and diaphragm variation. The traditional approaches to bamboo scaffolding assembly employed made structural calculations difficult, and relied heavily on the experience of licensed Bamboo Masters.

In response to the variety of material unknowns, the structural model was simplified into continuous members of a single size (constant diameter and thickness) and without overlapping elements. Bending forces were also not calculated into the system. Instead, the entire pavilion was treated as a steam-bent structure with no residual internal force. Since the majority of structure is based on triangulation, a large number of load paths exist allowing redundancy and local structural failures to occur without a total system collapse. These simplifications, in conjunction with a safety factor, ensured that the overall system remained within reasonable safety limits. Subsequently, results from structural analysis were left out of the comprehensive digital information model given the simplified system approach.

In order to achieve a fully detailed and one hundred percent accurate BIM structural model, the entire built pavilion would have needed to be accurately measured in detail and subsequently recalculated to prove structural stability. This would have included measuring the length, diameter, and initial curvature of every bamboo pole. Further embedded into the model could have been an ongoing monitor to display abnormal undesirable deflection or degradation of material due to environmental factors such as UV exposure, humidity, heat and biotic attack. This level of specificity, however, is not practical or cost effective and is ultimately not necessary when developing a flexible system entirely based on unpredictable and indeterminate factors stemming from building materials.

### 5.1 Hong Kong vs. Regional Standards

The current general attitude toward BIM in Hong Kong is rather optimistic. However, in the most practical situations of the design and construction industry, BIM is advancing in very small steps. Local client interest in the adoption of and financial investment in an emerging approach toward developing architecture is much delayed and has only shown special interest in full use of BIM at the highest and most visible levels. These would include high profile government projects that require levels of transparency and accountability due to pressures beyond a conventional client contractor relationship. As an example, M+, in West Kowloon is a museum for visual culture currently under construction in Hong Kong that is adopting a high level of BIM.

In Hong Kong, the current demands for the implementation of medium to high resolution information models are lower compared to other communities throughout Asia (Singapore, Korea, etc.) According to the Singapore BIM Road Map, issued by the Building and Construction Authority, Singapore mandates all projects with GFA above 5000 square meters to use BIM as of 2015, whereas the HK equivalent does not have such projected requirements. This has much to do with the low government standards and requirements being set for building construction documentation. The BIM industry has generally adopted the use of such tools to quickly develop 2D documentation, but with the exception of extraordinarily high profile public projects, the more sophisticated aspects of a data transaction based 3D model (dynamic collision detection, building maintenance) are not being adopted as part of the culture by management, client, architect, or contractor unless specifically requested to be part of the scope of contract.

Some of these benefits can only be found in more detailed BIM models (Level 3 and above). However, the most popular BIM tools are not developed to accommodate the variety of material inaccuracies, tolerances, and indeterminacies that contractors and architects face on site during assembly. Although BIM models are iteratively updated to achieve an “as built” model, the information flow does not incorporate the pipeline of indeterminate dimensions back into the design process. This can result in a final model with potentially dramatic differences from the original design intent.

### 5.2 Variability and BIM

The possibility of incorporating materials with naturally variable shapes is not yet possible with conventional BIM tools. Such unpredictable aspects can also include human error, material responses to environmental factors such as thermal expansion, or reaction to extreme conditions. These gaps between computer-controlled design environment and as built construction inevitably require the additional attention of architects or other experts in order to interpolate an appropriate and detailed solution.

The ability for BIM technology to move forward and improve in areas such as indeterminacy exists in two key areas. Firstly, the tools need to adopt a more open source application program interface (API). Such an interface can allow for greater direct access to database fields and tables – in order for the designer to take greater direct control of their model data. This open interface will allow direct access to the software for autonomous development of more accurate tools. Such tools can be configured with greater sensitivity toward material attributes, and structural behavior beyond convention. This API is already somewhat available in the form of scripting languages such as Python®, Visual Basic® and graphical versions such as Dynamo®, and are definitely steps in the right direction, albeit somewhat proprietary in nature.

Secondly, designers, certifiers, and trainers need to gain further literacy into these scripting languages. An open-source attitude whereby the appropriation and sharing of content and approaches toward building design at a certifiable level will greatly enhance the versatility of BIM managers in the areas of design, allowing them to more comprehensively introduce solutions to construction indeterminacy by developing their own ad-hoc solutions. Current Autodesk® Revit Architecture® certification courses held via the Certiport® Authorized Centers remain within the limited scope of modelling and documentation and withhold areas of computation and open source from the scope of their courses and examinations.

## 6. FUTURE RESEARCH

A variety of future research can grow from the challenges found during the design and construction of the 'ZCB Bamboo Pavilion'. Further structural investigations into bamboo will greatly reduce the levels of indeterminacy. This will allow for higher levels of accuracy in understanding of the material's structural behaviour and narrow the gap between design and as-built construction models. Throughout the design and construction process of 'ZCB Bamboo Pavilion', many assumptions were made based on the traditional expertise of the licensed Bamboo Master. This knowledge can be formalized into investigations furthering regional understanding and legitimization of bamboo as a sustainable construction material.

Once delivered to site, the overall supply of treated materials was categorized by factors such as condition, natural curvature, and diameter. However, this valuable detailed information concerning the total amount individual pole characteristics was not fed back into the digital information model and was simply used as an indexed stockpile of pre-selected members for assembly. By developing a streamlined method for the evaluation, recording, and tracking of unique materials, assembly times would be reduced. The appropriate deployment of poles based on their unique capacity to bend, would further reduce the risk of individual member failure.

Ongoing scanning is taking place in order to monitor the condition of materials and identify any areas of deflection throughout the structure. This continued investigation will reveal valuable information concerning a prolonged ability to withstand extreme and temperate environmental factors. The current high resolution 3D scanning can only be done intermittently. Regular visual inspections are also conducted to evaluate the state of individual connections, poles and footings. More advanced and sensitive tools for measuring geometry and behaviour may be deployed in the future to monitor structural activities in real-time, giving a more comprehensive reporting at a multitude of scales. This data of increased sensitivity could be incorporated into future 'live operational BIM models' to signal replacement of degrading material

Finally, a controlled series of destructive tests could ultimately assist in verifying the accuracy of initial structural calculations. This destructive physical analysis is aimed to commence when the pavilion is decommissioned. Live load will be added to selected nodes throughout the structure until failure occurs. This direct investigation will quickly reveal information that can be tested against digital simulation models relating to how and when the pavilion might deflect, buckle, or break under extreme load conditions.

## 7. CONCLUSION

The relationship between absolute accuracy and a system with indeterminacy will remain open as the adoption of unconventionally used materials and construction practices are further explored. Through the innovative use of computational tools, comprehensive building information models can adopt an ad-hoc approach toward balancing risk, probability, and ambiguity against an idealized overall design. The 'ZCB Bamboo Pavilion' was an experiment in the ability to manage expectations based on an initial set of unknowns within a construction system. Through time, investigation, refinement, and redevelopment, these gaps in design were clarified and inserted into the digital design model. This new information became part of a system of ongoing real-time digital simulations, capable of anticipating system behaviour and greatly assisted in advising design decisions for an optimal outcome.

Paramount to the success was a digital configuration capable of flexibility with respect to materials and assembly techniques. The overall design needed to accommodate a design input cycle from the field and be rapidly deployable. Documentation and reference material needed to achieve a level of simplicity capable of transcending language and skill barriers that would have otherwise made the assembly process impossible.

With the end goal of achieving a sustainable and viable architecture, the use of unrefined, fast growing natural materials will continue to be a critical part in reducing the construction industry's impact on the environment. The adoption of digital tools needs to be applied sensitively, in order to accommodate and take advantage of a widening array of raw materials and regional labour skills.

Figure 6. Aerial view of ‘ZCB Bamboo Pavilion’ by day

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Construction Team: Main Contractor: W.M. Construction Ltd.; Bamboo Construction: Sun Hip Scaffolding Eng. Co., Ltd.; Fabric Contractor: Ladden Engineering Ltd.; Lighting: CONA Technology Co. Ltd. & Brandston Partnership Inc.

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