EXPANDING BENDING-ACTIVE BAMBOO GRIDSHELL STRUCTURES' DESIGN SOLUTION SPACE THROUGH HYBRID ASSEMBLY SYSTEMS

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Abstract. This paper discusses the development and testing of a novel design method for the low-tech construction of bending-active bamboo gridshell structures. It expands this typology's current design solution space by combining and building up on two common production methods for light-weight shell structures: 1) the "lay-up" method, typically used in bamboo architecture in which members are added one at a time, and 2) the "flatbed" method, in which a prefabricated equidistant flat grid without shear rigidity is propped up and deformed into its final doubly curved shape. The novel methodology expands the system's design solution space by incorporating singularities within the grid topology and by layering multiple separate grids. This allows for spatially radically different building geometries without loss of implementation workflow efficiency. A demonstrator design project, tested through a large-scale prototype model, is described to illustrate the possible spatially engaging architectural design opportunities presented by the novel approach.

Keywords. Bending-active structures; Bamboo architecture; Shell structures; Low-tech fabrication; Form finding.

1. Introduction

The combination of bamboo construction and digital design technology enables radically unique and spatially versatile architectural solutions rooted in local culture and sustainable building practices. This design research project builds on earlier fundamental research on the digital design and implementation of bending-active bamboo shell structures and expands its concept design methods, leading to more diverse design outcomes. The study combines research in architectural design with digital physics-simulation engines and prototyping for low-tech, light-weight construction systems and uses demonstrator design studies as proof of concept (see Fig. 1, 11).

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Figure 1. Close-up of the 1:20 scale demonstrator physical prototype.

Bamboo is a material of high environmental and socio-cultural importance. It is one of the fastest growing, widely available, low-cost, carbon-sequestering natural resources suitable for direct implementation in construction. It has globally been part of vernacular construction for centuries. Expanding its design solution space with contemporary answers will positively impact the development of the built environment.

Bending-active shells are amongst the most material-efficient, hyper-light-weight structures. They rely for strength and construction implementation on the overall geometrical double curvature and elastic bending properties of their components. Their nonstandard geometries provide unique spatial design opportunities, and their material efficiency results in a reduced need for natural resources. Two types of bending-active gridshell structures exist. 1) "Flatbed" structures employ initially flat, prefabricated, regular grids with no shear rigidity, and elastically deform and brace those into place. 2) The "lay-up" method additively bends and joins individual members into a final shape onsite. Both types present important opportunities and restrictions. Prior research illustrates that computational tools considerably facilitate their development (Crolla, 2017, 2018); yet, no scholarly study exists on further typologies or hybrid structures, and limited research exists on bamboo applications.

This study illustrates that a wider and spatially more versatile and practically applicable solution space exists for this eco-friendly mode of construction.

2. Background

2.1. BENDING ACTIVE GRIDSHELL STRUCTURES

Bending-active gridshells are material performance-driven structures defined by a doubly curved grid with a shell-like behaviour. It requires minimal amounts of materials for making large spans. Applications typically use the rapid and cost-effective deployable flatbed construction method, in which an initially flat regular grid with no shear rigidity is elastically deformed and braced (see Fig. 2). The advantages of this shaping process are savings in construction cost and erection time, as the structural members do not need individual bending and the grid can be prefabricated flat on the ground. Yet, few bending-active shell structures have been built outside of academic research lab environments. This can be ascribed to two issues. Firstly, the related design-analysis processes are historically notoriously cumbersome. Until recently, only analogue form-finding methods were available to define a specific geometry's appropriate boundary conditions, grid patterns, and bearing positions (Bächer et al., 1978). Today, parametrically controllable digital design simulation tools absorb most of this heavy lifting in form-finding (Tamke and Nicholas, 2013), allowing architects to focus their attention on other design criteria, such as spatial development and programmatic or contextual response. Secondly, flatbed grid systems leave very little room for geometry deviation, heavily restricting the architectural designs flexibility required by professional design practice. To capitalise on the system's benefits, expanded typologies need to be explored in search of more flexible spatial solutions that include appropriate methods for efficient onsite implementation.

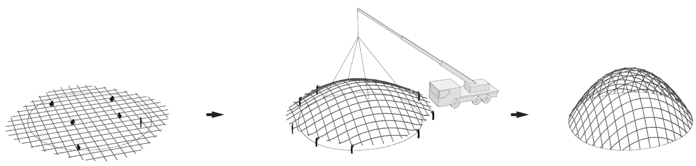

Figure 2. Deployable "flatbed" structures prefabricate an initially flat regular grid with no shear rigidity and elastically deform and brace it into place.

2.2. BAMBOO ARCHITECTURE

The demand for eco-friendly architectural practice is continuously increasing. Sustainable, regionally accessible and renewable materials play an essential role in reducing the overall carbon footprint of global building production, particularly in the world's most rapidly urbanising regions. Bamboo is one of the fastest growing natural construction materials, locally available in most of the developing world (Hidalgo-López, 2003). It is becoming increasingly popular amongst contemporary architects. Certain giant bamboo species can be used in their raw form in construction, grow up to a metre a day, and can be harvested in three-to-five-year cycles, making bamboo far more sustainable than any wood species. Yet, despite its century-old use in vernacular architecture, natural unprocessed bamboo is hardly incorporated as a viable structural material in today's construction.

The plant's unique cellular build-up results in a highly efficient section profile very suitable for use not only in compression or tension, but also when bent. Yet, when used in construction, bamboo is most commonly used in its processed form or as a replacement for traditional wood or steel members (Minke, 2012). Common bamboo architecture rarely fully absorbs the plant's most unique natural bending properties. Limited research has been done on the applications of bamboo as a structural material in bending-active gridshells from the viewpoint of professional practice. This knowledge gap has only recently begun to be addressed.

David Rockwood's book "Bamboo Gridshell" presents fundamental work on bamboo gridshells using the 'flatbed' method (Rockwood, 2015). Building on work by the Institute for Lightweight Structures (Dunkelberg, 1985), he touches on the design and construction challenges when using bamboo in gridshells produced with the flatbed method in an academic context. Typical 'flatbed' methods turned out to be ill-suited for e.g. traditional Cantonese bamboo craftsmanship, which involves building structures one stick at a time in a lay-up method (see Fig. 3). This traditional way of working was successfully combined with a computation-driven design and implementation methodology in the ZCB Bamboo Pavilion - a thirty-seven-meter spanning temporary pavilion built in Hong Kong in 2015 using this method (Crolla, 2015). This method provides more geometric design freedom, allowing better architectural response to site, context, and programme. However, its challenges are its labour-intensive nature, and the management of errors and deviation associated with manual construction.

This study seeks to advance knowledge towards implementation of a hybrid system that combines benefits of both the flatbed and lay-up approach.

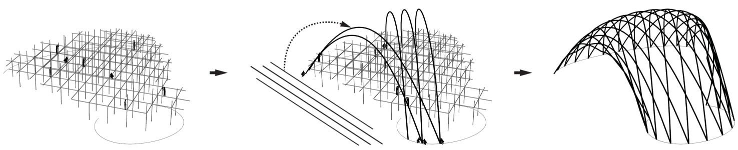

Figure 3. The "lay-up" method additively bends and joins individual members into the final shape onsite. Both types present important opportunities and restrictions.

3. Computational Design System

This study was driven by the development of a series of digital and physical bending-active bamboo gridshells prototypes aimed at iteratively increasing the typology's spatial variety and overall geometric complexity. The bamboo models operated as analogue form-finding computers relying on material properties and physical model constraints. The digital computation models mimicked this approach in McNeel's 3d NURBS modeller Rhinoceros 6® with procedural modelling plugin Grasshopper®, interactive simulation live physics engine Kangaroo®, and parametric structural engineering engine Karamba 3D®. The physics simulation engine abstracts forces at play in the analogue material prototypes by applying corresponding vector forces to discretised curve networks represented by a spring-particle system. Each curved member in this interconnected network aims to maintain its original length and attempts to straighten itself by pushing against its anchor points. Macrolevel behaviour can then be perceived similar to what is found in physical models and comparable geometries emerge as all virtual forces balance out in equilibrium.

Further data can be derived from these digital setups. Geometry data, such as member curvature, can straightforwardly be derived and structural engineering engines can apply actual material properties and real-world physical loading scenarios to extract structural performance properties like overall displacement and compression or tension forces. Additional building model information can be extracted to facilitate construction: the equidistant parts of the curve network can be relaxed into their respective orthogonal flat grids, while the laid-up members can be individually unrolled into straight lines with their intersection points with other members mapped out onto them. Such notational information becomes crucial in facilitating a straightforward and low-tech construction and/or fabrication of the prototypes.

4. Design Research

4.1. DEMONSTRATOR 1: HYBRID SYSTEM

The design study started with the production of a basic shell structure to test the concept of a hybrid system between both flatbed and lay-up methods. Its design consisted of a half-elipsoid-like shell made from a triangulated bamboo grid. From this grid, 2 of the 3 member directions defined an equidistant bent grid that was "popped" into place using the flatbed method. The third member direction was added using the lay-up method (see Fig. 4).

A 1:6 scale model was built from bamboo splits and metal wire to first test the implementation strategy. Following this, a larger prototype was built at 1:1 scale using 2.5mm diameter round bamboo sticks and plastic zip ties. In both prototypes, the flat, equidistant, rectilinear grid was first pre-assembled and then converted into a domed-shaped surface by pushing the centre point upwards while pulling the edges down and anchoring them onto a ringbeam. For the full scale prototype, the digital design model accounted for properties like material thickness and stick overlaps, and the orientation of the connection ties was predefined to allow for easy hinging in the predicted digitally-simulated direction.

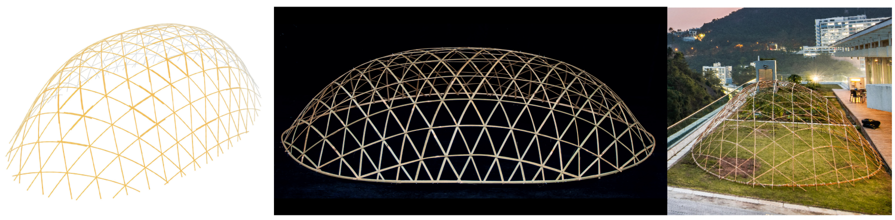

Figure 4. Tectonic study model: digital model, 1:6 scale prototype (1.6m x 1.0m x 0.4m), 1:1 scale prototype (9.6m x 6.2m x 2.8m). .

The final emerged geometry of both prototypes deviated slightly from the digital model as variables like uneven forces during the pop-up process, variations in bamboo diameters, inaccurate joints locations, etc. couldn't be anticipated precisely in the digital simulation engine. This, however, was allowed for and seen as an inherent part of the system. The overall behaviour and outcome of the demonstrator successfully proved its concept.

4.2. DEMONSTRATOR 2: EXPANDED DESIGN SOLUTION SPACE

A second demonstrator was then developed with as main goal to expand the design solution space associated with the workflow tested in demonstrator 1 and to a bring this beyond the typical "bubble" shaped architecture solutions found in projects like the Mannheim Multihalle (Otto et al., 1975). The approach relied on the precise and strategic inclusion of singularities within the continuous grid to allow for directional changes in the grid and overall geometry (see Fig. 5).

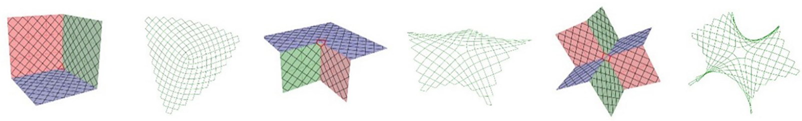

Figure 5. 3, 5, and 6-sided singularity inclusion into a continuous, equidistant, quadrilateral bending-active system.

To this idea, a multi-layered system of different grids was added, recomposing the system's primary structural tectonic layer from three distinct quadrilateral grid layers. The outer layers from this system could then be "peeled-off" from the primary layer to become single-layer grids that define stiffening geometries, like a support column structure or an upward "eye-lid" that could allow light to come down into the structure (see Fig. 6). To allow for this, three pentagonal singularities were inserted into the quadrilateral grid system around the points of deflection. This flexible system expanded the design solution palette of further project designs (see Fig. 7).

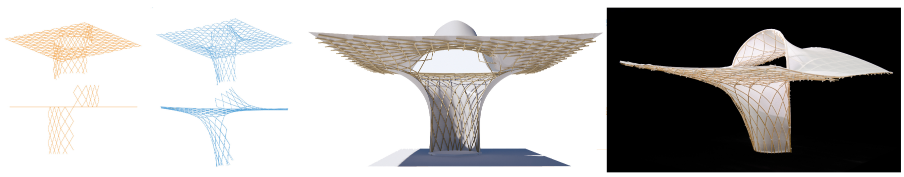

Figure 6. Topology, digital simulation, and 1:20 physical prototype .

In further design developments, an additional layer was added to the central rectangular grid to form a hexagonal grid system. This further expanded design opportunities, as the rectangular nature of the earlier central grid constrained the orientation of columns and openings. A multi-axial symmetric topology instead permits rotating column and eye-lid features in multiple directions, allowing spatial alternatives underneath while simultaneously further reinforcing the structural system. In this hexagonal system, openings were also six-sided and relied on the inclusion of two heptagon singularities around the points of deflection.

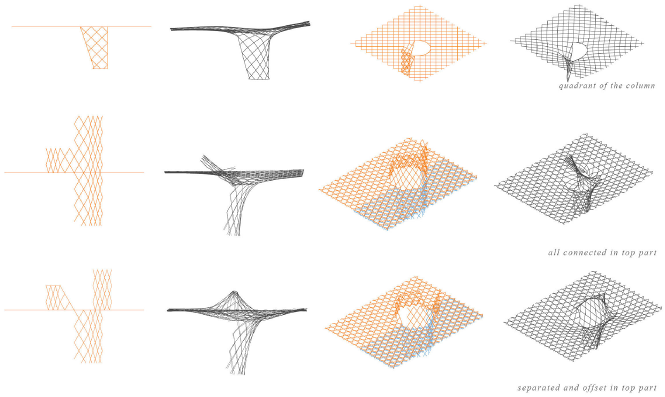

Figure 7. Variations on input grid layering and topology producing various opening & column strategies.

4.3. DEMONSTRATOR 3: DESIGN APPLICATION

Finally, applicability of the overall tectonic system was tested through the conceptual design of an architectural intervention. The selected design brief and programme requested a temporary outdoor music performance space cover with three stages and a central bar area.

The design's primary structural tectonic system consisted of a hexagonal grid that overlapped with the quadrilateral grids of three bent half-columns and one large column placed in the centre (see Fig. 8, 11). The multiple overlaid structural systems were designed and linked together to work in symbiosis, strengthen one another, and secure overall structural integrity. Grid layouts were positioned and combined to allow the generation of a continuous, undulating roof surface that was distorted and pulled down at points of de- and inflection created around the support columns. These features were then link to the architectural programme and specified stage and bar areas.

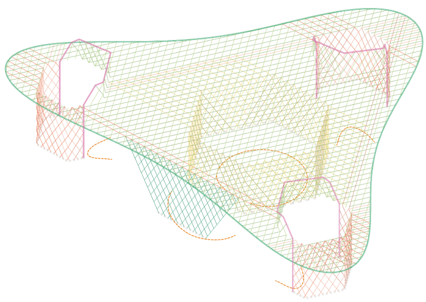

Figure 8. Design topology input diagram.

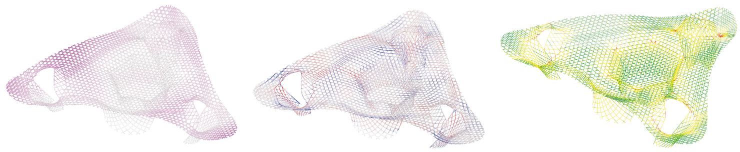

Figure 9. Simulation and analysis: displacement under gravity, structural utilisation, and curvature.

Once activated, the digital simulation setup allowed for the real-time evaluation of properties like displacement under gravity and loading, material utilisation, and curvature analysis (see Fig. 9). Constructability of the demonstrator was then tested through the production of a large 1:20 scale bamboo study model that was assembled following a process similar to a possible actual large-scale construction sequence (see Fig. 10, 11). Round bamboo sticks with a 2mm diameter were used for their behaviour was deemed comparable to bamboo culms at full-scale. To represent the manual ties found in traditional bamboo architecture, standard zip-ties were used as these allow for a similar level of flexibility and rotation. The first fabrication step involved the production of the several equidistant quadrilateral flat grid layers Three half-columns were bent into shape and joint to the main top grid, to which the skylight openings and central support column were added. An edge ring beam was added to stiffen the perimeter. Then, additional diagonal members were added using the lay-up method to turn the top grid into a hexagonal grid, adding stiffness to the overall shell by locking the quadrilateral grid into place. Overall, the geometry gradually formed and stiffened up as different layers of the structure were joined. Finally, the model was covered in a translucent elastic fabric as a representation of a glassfibre-reinforced membrane cover as found in the ZCB Bamboo Pavilion.

Figure 10. Fabrication process of physical model.

5. Discussion and Evaluation

5.1. ARCHITECTURAL DESIGN EVALUATION

The final design outcome portrayed a dramatic departure from the typical bubble-shaped geometries often associated with bending-active gridshell structures, or from the typically planar geometries found in traditional bamboo architectures that use the straight members as column, beam, or screen elements. Instead, a fluid and elegant continuous surface emerged from the setup in response to all the internal forces finding their equilibrium. The system allowed a spatially unique design response to site and programme, while maintaining the material's high environmental and socio-cultural importance and benefits.

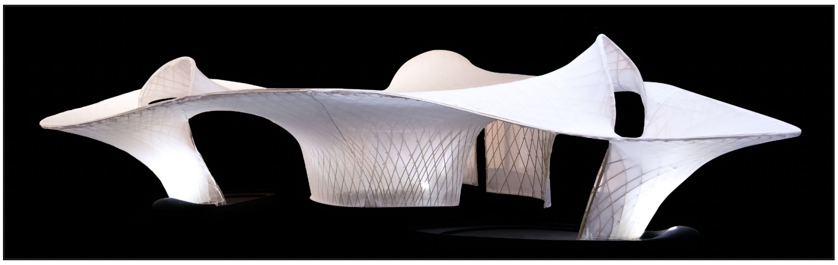

Figure 11. Final 1:20 scale physical prototype (2.4m x 2 m x 0.5m).

5.2. FUTURE CRAFT

Similar to how the ZCB Bamboo Pavilion commenced with a conceptual 1:20 scale bamboo model to inform its novel structural system, here too physical scale models are used as analogue material computers to point towards possible future directions for bamboo architectural construction (Crolla, 2017). While many items and challenges will need to be resolved in far greater detail before the project's actual construction could become possible, a clear and novel pathway is identified.

The demonstrator prototypes showcased that the developed approach can merge complex geometrical form with low-tech construction methods: computational simulation and building information modelling techniques significantly reduced the complexity of construction of the final non-standard building form. Possible future ways to further reduce the construction complexity associated with the developed methodology may involve introduction of new implementation strategies beyond the annotation and labelling systems developed earlier for projects like the ZCB Bamboo Pavilion. Augmented and mixed reality technology provide very interesting opportunities to reduce the complexity of the whole construction process even further, while simultaneously opening doors for continuous information feedback from and into the digital model during construction for further development or analysis. This will be a topic of study for future research projects.

6. Conclusion

This paper demonstrates that the industry has far from reached the limitations of the architectural design and construction solution spaces found in low-tech building contexts without access to advanced computer-controlled fabrication equipment or that employ natural, unprocessed materials like raw bamboo culms. Through the strategic integration of computation and digital simulation in century-old crafts and building traditions, a world of design opportunity can be opened up without substantially increasing construction complexity. In response to the urgent call to find more environmentally sustainable alternatives to our current wasteful methods of construction, this study highlights the vast future potential of bamboo as a construction material.

Figure 12. Physical prototype of bending-active bamboo gridshell.

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References

Bächer, M.a.x., Burkhardt, B. and Otto, F.: 1978, *IL13 - Mannheim Multihalle. Stuttgart*, Institut für Leichte Flächentragwerke.

Crolla, K.: 2017, Building indeterminacy modelling – the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials, *Visualization in Engineering*, **5:15**, -.

Crolla, K.: 2018a, Bending Bamboo Rules: Beyond Century-Old Typologies, *Journal of Architectural Education*, **Volume 72 - Issue 1: A / To Project**, 135-145.

Crolla, K.: 2018b, *Building Simplexity: The*, Ph.D. Thesis, RMIT University.

Dunkelberg, K.: 1985, *IL31 – Bamboo. Bambus als Baustoff Bauen mit pflanzlichen Stäben.*, Stuttgart: Institut für Leichte Flächentragwerke.

Grasshopper3D, : 2019, *Available from www.grasshopper3d.com*, Robert McNeel and associates.

Hidalgo-Lopez, O.: 2003, *Bamboo: The Gift of the God*, Oscar Hidalgo-Lόpez.

Kangaroo, : 2017, *Available from www.food4rhino.com/app/kangaroo-physics*, Robert McNeel and associates.

Karamba3D, : 2019, *Available from www.rhino3d.com*, Karamba3D.

Minke, G.: 2012, *Building with Bamboo*, Basel: Birkhauser.

Rhinoceros3D, : 2019, *Available from www.rhino3d.com*, Robert McNeel and associates.

Rockwood, D.: 2015, *Bamboo Gridshells*, New York: Routledge.

Tamke, M. and Nicholas, P.: 2013, Computational Strategies for the Architectural Design of Bending Active Structures, *International Journal of Space Structures*, **28**(3-4), 215-228.