A CASE STUDY ON STRUCTURAL MORPHOLOGY OF BAMBOO WOVEN STRUCTURE

Formal and Structural Integration in Weaving

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Abstract. This paper examines the incorporation of morphological principles and structural behaviour in Kagome weaving, a form of triaxial weaving, and investigates its possibilities for generating larger-scale architectural structures. The research endeavours to comprehend how the bamboo woven structure can efficiently withstand applied loads through its form as well as how the manipulation of singularities within regular grids can affect the topological forms that result. While there have been studies on employing straight, pliable bamboo strips and manual weaving techniques in creating grid shell structures, there is insufficient research on inducing various curvatures and creating a self-supporting architectural artifact through the incorporation of singularities into the design of bamboo woven structures. This research examines a case utilizing a computational physics engine to simulate the behaviours of bamboo weaving structures. Additionally, to evaluate the precision of the digital simulation in depicting the actions demonstrated by Kagome weaving, a tangible prototype will be constructed. The findings of this study propose that manipulating singularities within regular grids enables formally and structurally rational woven grid shell structures for certain scales of construction. Furthermore, this study enhances innovation in the design of bamboo architecture and broadens the applications of bamboo weaving craft into previously unexplored domains.

Keywords. Craft, Triaxial Weaving, Singularity, Computational Design, Bamboo Architecture

1. Introduction

1.1. TRIAXIAL WEAVING AND SINGULARITY- INSERTION OF SINGULARITIES IN HEXAGONAL MESH TOPOLOGY AND INDUCTION OF POSITIVE AND NEGATIVE GAUSSIAN CURVATURE

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In this research, the forms of bamboo woven hexagonal grid shells and their relationship to their structural stiffness will be investigated using a case study of a simple bamboo shell structure composed by the Kagome weaving technique, one of the traditional bamboo weaving methods in bamboo basketry handicrafts in Asia. The Kagome weaving is a triaxial weaving method that involves interweaving equilateral triangles and regular hexagons in a trihexagonal pattern. Triaxial weaving has the advantage of creating self-bracing objects by tightly interweaving long, pliable bamboo strips without fasteners (except at open edges), thus holding the potential to produce economical structures that conserve materials.

Kagome woven objects display inherent formal and structural properties that facilitate self-bracing capabilities, allowing for the creation of various curvatures through different strip arrangements. In Kagome weaving, the interlacing and self-bracing properties of the object are controlled by the size of the hexagonal cells. Diverse curvatures are achieved through the combination of different strip arrangements and material properties. It is recognized that a single curvature can be attained by directly bending the woven surface, while the introduction of geometric singularities allows for the generation of a positive or negative Gaussian curvature; double curvature (Martin, 2015). Introducing a singularity in a polygonal cell with fewer than 6 edges produces a positive Gaussian curvature, whereas introducing a singularity in a polygonal cell with more than 6 edges results in a negative Gaussian curvature (Ayres et al., 2018). While previous studies have explored the impact of singularities on inducing topological changes in woven structures (Ayres et al., 2018; 2021), there is a lack of research on incorporating singularities into the weaving process to induce different curvatures while integrating morphology and structural features using bamboo strips.

1.2. MORPHOLOGICAL PRINCIPLES AND STRUCTURAL BEHAVIOURS IN KAGOME WEAVING

The research aims at comprehending how the bamboo woven structure can efficiently endure applied loads through its form and how the manipulation of singularities within regular grids can influence the resulting topological forms. The study focuses on a shell-like structure composed by the insertion of pentagons and heptagons, which act as singularities, into the hexagonal grid pattern of Kagome weaving using bamboo strips, with an emphasis on the rationality of the form to create a stable structure. Research questions are: How can a bamboo woven structure effectively withstand applied loads through the insertion of singularities? How can the morphological principles and structural behaviour be integrated into Kagome weaving?

This study gained insights from multiple factors. Firstly, it is a practical response to the decline of bamboo weaving crafts observed in various regions of Asia. Its aim is to establish a design methodology that expands the application of bamboo weaving to the field of architecture. Additionally, there is theoretical significance in the field of architecture. Semper (1989) views weaving as one of the origins of architecture, albeit limited to enclosures. This research strives to offer fresh outlooks on the architectural discourse by exploring the possibilities of weaving as a structural element. Consequently, this study contributes to the discourse on material/ form, challenging hylomorphism (Thomas, 2022).

2. Methodology

2.1. DIGITAL SIMULATION FOR FORM FINDING

The goal of this research is to explore the logical connection between the design and structure of woven shell structures that incorporate singularities in their grid shell formation. This investigation will be conducted through the utilization of physics simulations and physical mock-ups, with the focus on examining a scenario where singularities are combined to create both positive and negative curvature. This allows for topological transformations in the form, aimed at enhancing the structural properties of the designed object through its shape. The case study centres on the design of a gate-shaped structure constructed from bamboo strips, resembling a woven shell. The design is conceived as a temporary structure intended to define a human-scale space, large enough to accommodate a low table with four cushions, suitable for installation in an indoor environment. The design assumes the use of locally sourced bamboo materials that can be easily procured from the local market and hand-woven by multiple adults with average physical capabilities.

The form of a structure is greatly influenced by the cross-sectional shape of the material used, which determines the properties of the material along with the fabrication method, in this case, weaving. Furthermore, there will be differences in the structural behaviour of a small-scale, handicraft-level structure and an architectural-scale structure that exceeds the size of a human and produces a shelter. First, we investigate different forms of a prototype design by digitally simulating the behaviours of the woven object using a computational physics engine. In this research, a grid shell will be constructed using a hexagonal pattern through three axial weaving. The mesh size is adjusted based on the cross-sectional profile of the material, ensuring manual weavability and shape retention through material interlacing, eliminating the need for fasteners at strip intersections. Consequently, the initial step involves determining the grid size through testing with the actual material to be used. Subsequently, by using the grid size as a base module of the hexagonal grid and incorporating singularities (pentagons and heptagons) while maintaining the regularity of the grid, plain “mesh blocks” are combined to form a gate-shaped woven shell structure. Rhinoceros 3D and Grasshopper are utilized as the modelling and visualization platforms, and the Grasshopper add-on Kangaroo is employed to simulate the physical properties of bamboo weaving and generate forms. For the digital representation of Kagome bamboo weaving, the Mesh Block Combination System (Shinohara & Chan, 2024) will be adopted. Triangular mesh is transformed into Kagome weaving with vertices representing the centres of hexagons that tessellates the geometry. The flow of modelling and digital simulation is illustrated in Figure 1 below.

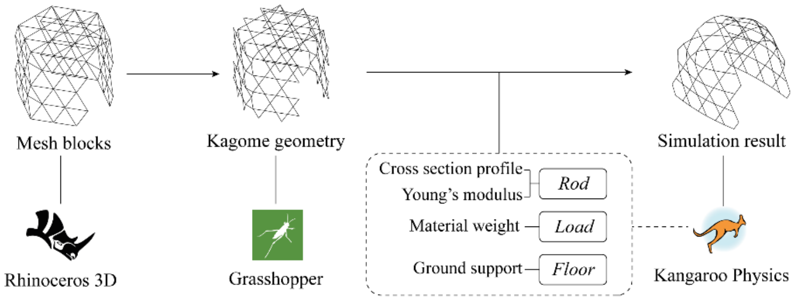


Figure 1 Flow of modelling and computational physics simulation

2.2. MOCKUP AND DIGITAL SCANNING FOR AS-BUILT MODEL

Digital scanning is employed to generate a digital model of a built physical prototype for comparison with the designed models. The chosen shell form, determined through simulation examination, will be fabricated into a physical prototype using actual materials. This allows for the observation of actual material behaviours and the scrutiny of the structural characteristics. A prototype is produced using bamboo strips with specified cross-sectional dimensions of approximately 3 mm in depth and 30 mm in width for comparative analysis.

To examine the mock-up, a scanned digital model will be compared with the design model for a comparative analysis, with a specific attention made to the amount of displacement. The digital scanning model are generated by RealityCapture, photogrammetry software, using video image data captured by an iPad. Video images are shot to cover as much of the mock-up as possible in all directions. Through the comparative analysis, factors such as simulation accuracy and constructional concern will be discussed.

3. Findings

3.1. DIGITAL SIMULATION: GRID SHELL FRAMES WITH POSITIVE AND NEGATIVE GAUSSIAN CURVATURE

For this case study, we randomly selected six pieces of bamboo strips to conduct a basic bending test and assess their stiffness. The bamboo we used was Moso bamboo, harvested in Fujian, China. We calculated the Young's modulus of the bamboo as 9469 N/mm^2 based on the test and used it as input for the digital simulation. Additionally, we conducted a trial weaving with the same bamboo, setting the grid size to approximately 100mm.

Figure 2 presents the outcomes of simulating the hexagonal weave of bamboo strips using Kangaroo, and the line drawings illustrate the geometric pattern and topological variations of the Kagome bamboo weaves. The figure on the left depicts weaving with only hexagonal grids of uniform size, resulting in a flattened woven surface. In contrast, the figure in the middle demonstrates a topological transformation centred around the inserted pentagon, leading to a convex woven surface within the hexagonal grid. The figure on the right depicts a concave woven surface configuration pivoted on the inserted heptagon, which acts as a singularity. This results in a curvature that shifts in the opposite direction compared to when the pentagon was inserted. Furthermore, in both cases involving the pentagon and heptagon, it is evident that the curvature is most pronounced at the singularity and gradually flattens as it moves away from it.

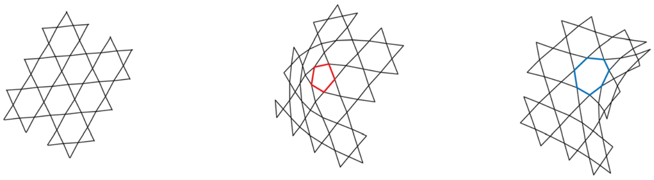
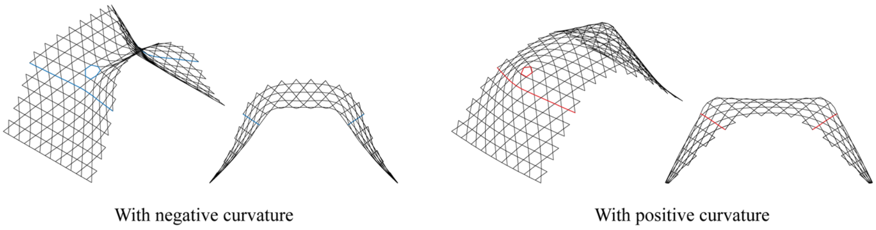


Figure 2 Morphological effects on woven surfaces by insertion of different singularities

This case study utilized the insertion of singularities and their resulting topological changes to shape a gate-shaped shell structure. Figure 3 demonstrates the digital simulation results of inserting pentagonal singularities into the edges, where the hexagonal grid surfaces, forming the vertical elements corresponding to the wall, connect with the hexagonal grid spanning the space horizontally. This gave rise to the formation of a shell-like frame with a cross-sectional shape that bent inward like the letter "n" and exhibited a positive Gaussian curvature. In contrast, when heptagons were inserted, as depicted in Figure 3, a shell frame with a negative Gaussian curve and a cross-sectional profile bent outward resembling the letter "U" was formed.

Moreover, the shell frames with pentagonal singularities and heptagonal singularities induce curvatures in opposite directions concerning the cross-sectional aspect of the frame. Consequently, by alternating the placement of pentagonal and heptagonal singularity, a corrugated form is created. The corrugated configuration depicted in the figure is structurally advantageous by creating a three-dimensional formal effect that enhances stiffness. Table 1 presents a comparison of the formal variations achieved by simulating the gradual changes in grid numbers, both vertically and horizontally, in the shell frames with singularities arranged in the order of pentagon, heptagon, pentagon in the transverse direction. To explore design possibilities and identify the appropriate form for construction, parameters for the number of hexagonal grids on both vertical and horizontal directions are established to facilitate variations in form-finding.

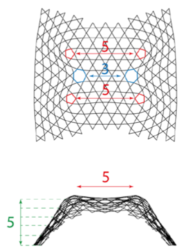
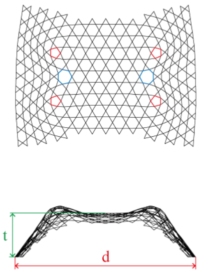
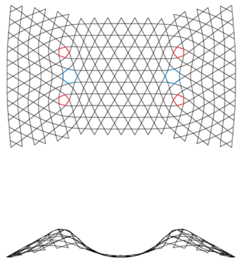
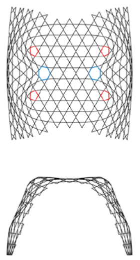
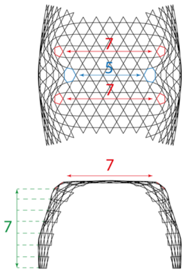
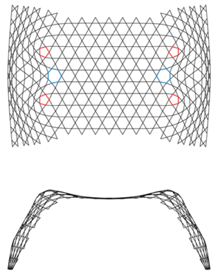
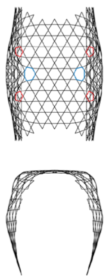
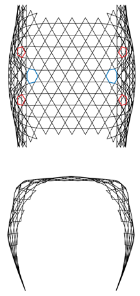
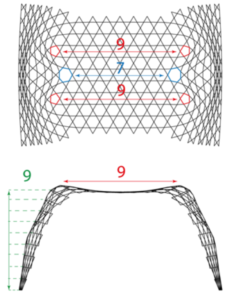


With negative curvature

With positive curvature

Figure 3 Gate-shaped shell frames with different curvatures

Table 1 Comparison of formal variations with changing vertical and horizontal grid numbers

	H1 5 horizontal grids	H2 7 horizontal grids	H3 9 horizontal grids
V1 5 vertical grids	 $\Delta t=0.43$ $\Delta d=0.98$ $s=1.41$	 $\Delta t=0.44$ $\Delta d=1.04$ $s=1.48$	 $\Delta t=1.12$ $\Delta d=1.32$ $s=2.44$
V2 7 vertical grids	 $\Delta t=0.15$ $\Delta d=0.99$ $s=1.14$	 $\Delta t=0.1$ $\Delta d=0.69$ $s=0.79$	 $\Delta t=0.33$ $\Delta d=1.14$ $s=1.47$
V3 9 vertical grids	 $\Delta t=0.09$ $\Delta d=0.15$ $s=0.24$	 $\Delta t=0.08$ $\Delta d=0.08$ $s=0.16$	 $\Delta t=0.27$ $\Delta d=1.23$ $s=1.5$

As shown in Table 1, deformations happened in the simulated structures are measured and quantified as the vertical deformation Δt and the horizontal deformation Δd from comparison between the original and simulated structures, with the value s which is the sum of Δt and Δd. After cross-referencing of the results, as displayed in table 1, value s in column H3 are larger than those in H1 and H2, which indicates that the longer the span, the horizontal woven surface in the middle of the frame gets flattened. This means the singularities inducing the curvature that created the corrugated effect to support the structure is not functioning as the middle part of the frame moves away from the singularities.

Regarding the number of rows of vertical grids, shown in the V1, V2, and V3, the deformations of the shall frames at the lower portions of the frame tend to bend inward as the number of rows of vertical grids increases. In this case study, there is one singularity to generate negative curvature in-between two singularities that exert positive curvature on each side of the shell frame. As the numbers of rows of vertical grids increase, the bottom part of the frame attaching to the ground moves farther from the singularities and gets flattened while the middle portion of the vertical wall are dominated by the positive curvature generated by the effect of the two pentagonal singularities. With this, which affects in the horizontal direction, together with the bending effect in the vertical direction generated by the same singularities would result in the inward bending phenomenon at the lower portion of the frame as depicted in the Figure 4. This inward bending will be disadvantageous to the structure as it makes a smaller footprint in comparison to the upper portion of the shell frame, making it more vulnerable to lateral load. However, this phenomenon seems less affected in the case of V3-H3 because the outward spreading of the bottom part of the vertical walls, caused by the deformation of the horizontal portion of the shell frame at the top, is superior to the effect of the bending inwards.

For the selection of the prototype to physically construct, a woven shell frame that fulfils the aforementioned spatial requirements as well as the structure with no significant deformation out of the simulation results was chosen. The cases of V2H1 and V2H2 have less deformation visually, however, V2H2 has a larger volume (2.3m wide × 2.2m deep × 1.3m tall) for the conceived activities and performs better in measurement of deformation with the least s = 0.79 among all cases except cases V3H1 and V3H2 that bend inwards, thus selected for the construction.

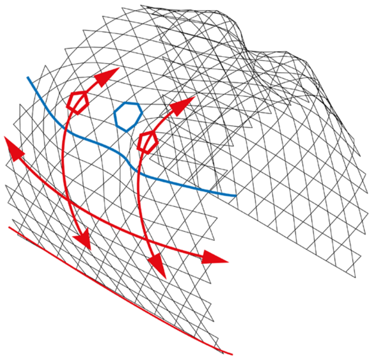


Figure 4 The combination of singularities and the flattening effect

3.2. MOCK-UP AND AS-BUILT MODEL

We extracted the information from the simulation result and constructed the physical mock-up of the case of V2H2, starting from weaving the horizontal top portion and then at the edge weaving the singularities turning the orientation of grids from horizontal to vertical so as to for the side portion of the shell frame. The built model is 2.6 m wide × 2.2 m deep × 1.2 m tall. Table 2 identifies three distinctions between the designed model and the scanned physical mock-up.

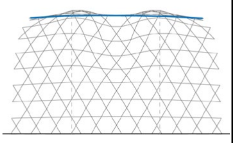
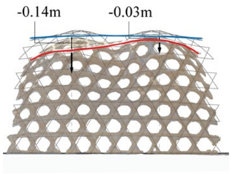
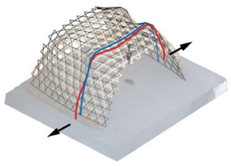
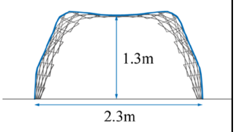
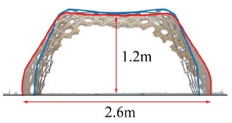
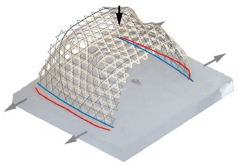
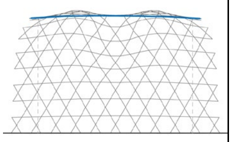
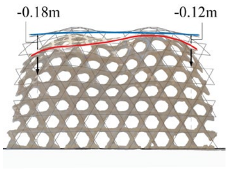
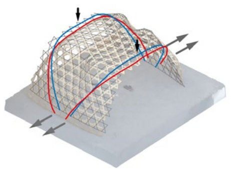
Firstly, the overall height of the mock-up is lowered asymmetrically on the two sides of openings by 0.14 meters for maximum on the one side and 0.03 meters for minimum on the other side in comparison to the simulation result. The distinction could be resulted from the widening of an opening's bottom portion during the construction process. Since the method of constructing the mock-up is to weave two vertical sides of the shell frame from one to the next, the cause of this distinction could be that one vertical portion constructed earlier easily experiences more load and deformation compared to the part constructed later as construction progresses. It brought extra force on the horizontal top part towards one opening side, causing an imbalance in the symmetrical form of the bamboo woven shell frame. The fluctuation on the material properties among bamboo strips could contribute to the asymmetrical deformation as well, while the input parameters of the material properties in computational simulation were based on the average of measured samples and homogenous on every strip in simulation. Secondly, the physical mock-up's footprint is 0.15 meters wider on each side compared to the simulation, with no discernible difference in depth. This should be the deformation of the shell frame linked to the first distinction. The top part of the frame was lowered, and as a consequence, the shell frame slid outward. Thirdly, the top part of both openings of the shell frame drops lower by approximately 0.12 meters. This distinction could be related to the widening of the footprint of the mock-up mentioned in the second distinction. Since the bottom parts of the shell frame were slid outwards, the strips passing at the top of the openings were stretched outward at their ends, consequently, lowering the top part of both openings. Regardless of the observed deformations in the physical mock-up, the digital simulation using a computational physics engine demonstrated the overall form-structure relationship in the bamboo woven hexagonal grid shell, achieved through the combination of singularities.

4. Discussion

The morphological principles and structural behaviour can be integrated into Kagome weaving by appropriately allocating polygonal grid cells containing fewer than 6 edges that produce a positive Gaussian curvature and polygonal grid cells comprising more than six edges that induce a negative Gaussian curvature acting as singularities, and creating combinations and repetitions that make morphological effects to articulate structural characteristics.

Furthermore, a woven surface with a pentagonal or heptagonal grid cell in the hexagonal grid acting as a singularity tends to flatten as the hexagonal grid moves away from the singularity. Since structural stiffness will be enhanced through the three-dimensional morphological effects by the combination of positive and negative curvatures, distances between the singularities should be controlled within the range that curvatures do not recede into a flat surface. In the studied case of gate-shaped woven shell frames, as a woven surface spanning between inserted singularities gets longer, the frame deforms more significantly in the middle of the woven surface where the predominant gravity load applies. When the height of frames increases by the number of rows of hexagonal grids composing the side surface of the frame, the bottom parts of the frame get distanced away from the singularities and become weak against lateral loads. Bamboo woven structure loses morphological effect to structural stiffness where the woven surface is flattened. Therefore, for a bamboo woven structure to effectively withstand the applied load, its form should maintain combinations of curvatures that avoid the surface being flattened.

Table 2 Comparison and analysis of the simulation results and physical mock-up

	Simulation result	Comparison with mock-up	Analysis
Distinction 1			
Distinction 2			
Distinction 3			

5. Conclusion

In this case of gate-shaped grid shell frames using Kagome bamboo weaving, the structural stiffness of the Kagome bamboo woven structure can be enhanced by manipulating the allocation of singularities. Through the production of a mock-up and comparison with the simulation models, we determined that the digital modelling approach utilizing computational physics simulations enables an assessment of the overall form of shell structures to some degree, taking into account the materiality and fabrication method of bamboo strips. As additional consideration, evaluation of the structural performance regarding morphological effect of the woven structure can be further developed with measurement of the bending curvature of the strips in the simulation. Furthermore, the digital method of designing bamboo weaving structure could be applied for other types of weaving technique such as bi-axial weaving with additional studies.

Nonetheless, it is essential to note that the physics simulation possesses certain constraints as a result of incorporating uncertainties such as property variations of natural material and the intricacy of taking into account numerous structural factors when producing architectural artifacts with form/structure integration. This study omitted details regarding the connections where the bamboo strips overlap and phenomena, including twisting of bamboo strips when they form three-dimensional curves. The comprehension of the distinctive restorative force of bamboo strips, attributed to the weaving process, is also limited. Hence, additional research in structural engineering is mandatory for more precise and quantitative configurations with the structures, such as bending curvature and stress of material.

Acknowledgments

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