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BamX: Rethinking Deployability in Architecture through Weaving

Abstract: Deployable gridshells are a class of planar-to-spatial structures that achieve a 3D curved geometry by inducing bending on a flat grid of elastic beams. However, the slender nature of these beams often conflicts with the structure's load-bearing capacity. To address this issue, multiple layers are typically stacked to enhance out-of-plane stiffness and prevent stability issues. The primary challenge then lies in deploying such multi-layered systems globally, as it requires significant shaping forces for actuation. This paper presents an alternative design approach that involves strategically connecting compact-to-volumetric gridshell components using weaving principles to shape a thick segmented shell. This innovative approach allows for an incremental construction process based entirely on deployable modules with volumetric configurations that locally provide the necessary structural depth for the entire system. To demonstrate this principle, we present the realization of BamX, a research pavilion constructed using deployable cylindrical components made from raw bamboo slats. These components are interconnected at carefully optimized interlocking woven nodes, resulting in a bending-active structural frame that is both strong and exceptionally lightweight. To determine the optimal topology and geometry of the pavilion, we employ an integrative computational approach that leverages advanced numerical optimization techniques. Our method incorporates a physics-based simulation of the bending and twisting behavior of the bamboo ribbons. By finding the ideal locations for ribbon crossings, we ensure that all external and internal forces are in global equilibrium while minimizing the mechanical stress experienced by each ribbon. BamX exemplifies how a symbiosis of refined weaving craft and advanced computational modeling enables fascinating new opportunities for rethinking deployability in architecture.

1 Introduction

Elastic gridshells are material- and structure-efficient systems that achieve 3D curved geometries by globally inducing bending and twisting on a flat grid of elastic beams. Based on the magnitude of shaping forces, external mechanisms such as cranes or inflatable cushions are needed to transform the flat grid as a whole into its final 3D shape. Slender beam profiles and materials with high strength and low bending stiffness are required to reduce the magnitude of shaping and residual forces. In practice, these characteristics of slenderness and flexibility generate stability problems even after finding a suitable geometric configuration. To counterbalance this condition, additional

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grid layers need to be superimposed to create sufficient out-of-plane stiffness together with bracing elements to diagonalize the grid and increase in-plane shear strength.

The research presented in this paper showcases an alternative approach for elastic gridshells in architecture. The aim is to develop an integrative computational design framework for double-layered segmented shells built from deployable units. This approach was formed by the adaptation of elastic gridshell principles at the local level of components and from the application of basket weaving principals at the global level of the segmented shell. The design framework built the basis for the development of the BamX Research demonstrator.

2 Related work

2.1 Deployable Gridshells

Elastic gridshells are quad-grid structures shaped from continuous beams connected at nodes by revolute joints. During erection, beams deform elastically and rotate around the joints to achieve the desired geometry. The shape is then locked by diagonalizing the grid, blocking joints' DoFs, adding restraining elements, or a combination thereof. Gridshells are typically classified according to the lengths of their edges within the grid. Traditionally, elastic gridshells are considered to be regular grids that bend as a whole from a flat state (Lienhard and Gengnagel 2018). Irregular gridshells, in turn, require an incremental assembly process since elements need to be individually bent and connected. Recent studies are leveraging the geometrical incompatibilities of irregular grids for deployability and shaping purposes. X-shells (Panetta et al. 2019) are generalized types of irregular gridshells in which the key concept is to encode the 3D curved geometry into the planar state of the irregular grid. Similar studies were conducted by (Soriano et al. 2019; Pillwein and Musialski 2021) based on the design space of geodesic grids. In contrast to previous studies that have mainly concentrated on global deployment, our work addresses the notion of local deployability at the component level.

2.2 Bamboo

Bamboo has emerged as a viable and sustainable alternative to composite materials in the ongoing research on elastic gridshell structures. Previous studies by (Lienhard 2014) have indicated that bamboo exhibits a comparable ratio between Young's Modulus and permissible bending stress to that of Glass Fiber Reinforced Polymers (GFRP), thereby positioning it as a suitable material for both static and kinetic applications involving active bending. In particular, bamboo poles have been utilized in several built examples such as the ZCS Bamboo pavilion (Crolla 2017) or the Pantographic Bamboo Hybrid Amphitheater Structure (Seixas et al. 2021). In contrast to complete poles, our approach necessitated enhanced material flexibility, which we achieved by using thin slats obtained by splitting bamboo poles into thin slats.

2.3 Segmented shells

Segmented shells are a different type of discrete shell offering a simpler construction process than elastic gridshells. The fundamental principle is to connect prefabricated components in a step-by-step process to create a unified shell structure. The connection between components is crucial since any compromise in material continuity can reduce the structure's stiffness. Significant efforts have been conducted on segmented timber shells based on double-layered plate components with finger joint connections to increase in-plane stiffness (Li and Knippers 2015; Alvarez et al. 2019). Elastic bending has also been used to create double-layered components using custom-laminated beech plywood and sewing techniques to establish the connection between components (Sonntag et al. 2017). Other works deal with modular tubular fibrous morphologies produced through coreless filament winding technology (Pérez et al. 2020). Our research aligns with this study concerning the cylindrical typology of the component. However, the primary differentiation lies in the conceptualization of individual components as elastic gridshells and their interconnection through weaving principles.

2.4 Weaving

Basket weaving involves interlacing thin flexible ribbons in regular patterns to create a stable lattice structure. By alternating over- and under-crossings, the interlacing principle creates the necessary friction for holding ribbons in place (Martin 2015). Woven structures commonly utilize bi- and tri-axial arrangements of straight ribbons. In such cases, introducing topological singularities becomes crucial for inducing curvature Ayres et al. (2018). However, the combination of straight ribbons and topological singularities tends to produce kinks in the woven structure. Ren et al. (2021) presented an alternative approach to attain smooth free-form woven surfaces based on injecting in-plane curvature into the ribbons. An optimization-driven process is employed to accurately calculate the curved planar geometry of each ribbon, enabling the interwoven structure to approximate a specified target surface closely. In our work, we rely on straight bamboo ribbons but apply a similar optimization scheme to determine the ideal lengths and crossing locations to best approximate the desired target shape while minimizing stress.

3 Design principle

The presented study was conducted under the assumption that combining fun- damental principles from segmented shells, elastic gridshells, and basket weaving can lead to large-scale architectural applications. The realization of the BamX research demonstrator serves as a proof-of-concept of the above. The structure is an ultra-lightweight dome shaped from 36 deployable cylindrical components. When deployed, the cylinders connect seamlessly at 21 woven nodes to globally form a double-layered segmented shell (Fig. 1). Cylindrical components are designed as compact-to-volumetric gridshell units made from thin flexible bamboo slats. While deployable components can be highly compacted for transport and storage, they also facilitate the construction process of the entire structure. By sequentially deploying cylindrical units and connecting them using weaving principles, the global geometry of the structure progressively emerges. The introduction of weaving principles at the level of nodes allows the cylinder's scissor mechanism to be locked, gradually stabilizing the entire structure without adding external elements.

Fig. 1: BamX research demonstrator.

4 Computational framework

The design, modeling, and simulation of segmented shells composed of deployable gridshell modules entail considerable complexity. The kinematics of deployable components and the overall structural behavior of the shell are significantly affected by

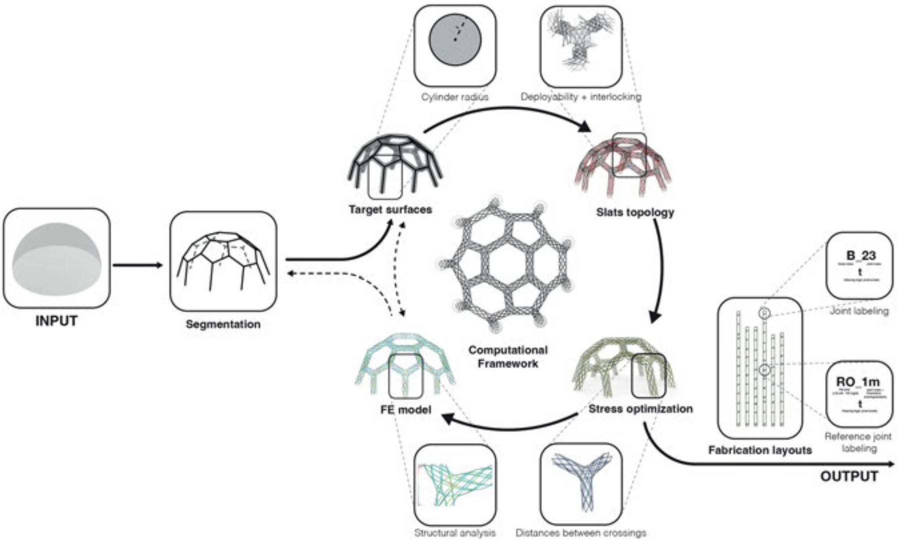

Fig. 2: Computational framework combining several models with different levels of detail.

geometric and topologic features at different scales. In addition, it is also necessary to incorporate materialization principles at conceptual design stages to ensure the viability of the design. A consistent digital approach was formulated, combining an iterative design process with diverse computational models that vary in detail (Fig. 2). These stages comprise simplified global models of segmented surfaces and detailed models encompassing all deployable grid layouts.

4.1 Modeling

A *segmented shell* is modeled using a valence 3 n-gon topology created from a structural free-form surface representing a desired geometry. The edges of this topology are used to create cylindrical surfaces that are interpolated at incident vertices to develop the surface of nodes. A simplified FE model based on a strut representation is then used to calibrate the diameter of cylinders and define material quantities. The results obtained from this model are in turn utilized to create the curve network of cylindrical components.

A *cylindrical gridshell component* is developed from a curve network consisting of two families with an equal and even number of spiral curves. Two construction planes positioned at the ends of the corresponding edge and aligned with the normals to the global surface are used to create spiral curves with precise control over their starting/ending points and tangent directions. The number of turns around the edge determines the number of crossings along the cylinder and its deployment.

A *woven node* is shaped from the connection of adjacent cylindrical gridshell components, wherein spiral curves are carefully paired and linked by alternating family types (Fig. 3). The connection is geometrically modeled by extending one of the curves using tangent directions and incorporating an overlap between connected curves. Materialization constraints based on the dimensions of the available bamboo rods are enforced at this point to restrict the maximum length achievable by those curves. Consequently, a tessellation containing triangular tiles is generated on the surface of the node through the connection of spiral curves. Triangular tiles are a desired feature to lock the kinematic behavior of the scissor linkage of the deployable cylinders. Since the resulting topology contains vertices with a valence greater than 4, interlacing principles need to be carefully defined to connect these curves at the level of the node.

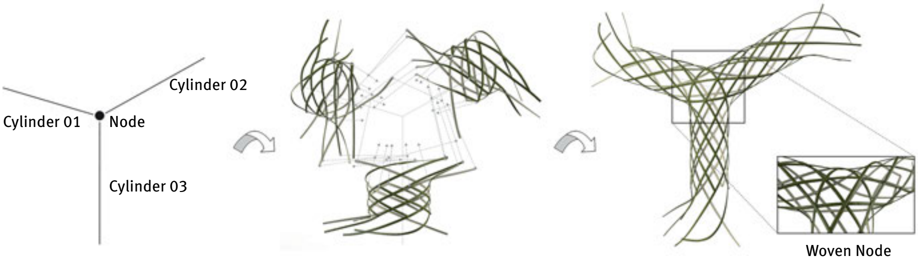

Fig. 3: Woven node created from the connection of deployable cylinders.

For the design of the BamX research demonstrator (Fig. 4), the geometry of a spherical cap was approximated by using part of a truncated icosahedron. The structure spans 10.3 m and has a height of 4.60 m. Deployable gridshell cylinders have a diameter of 40 cm. Curve networks are created with 8 spiral curves per family and one turn around the corresponding edge-axis. In total, 432 bamboo slats were used to build the structure, with a total weight of less than 160 kg.

4.2 Optimization

To model the equilibrium state of the entire structure, it is necessary to simulate the bending and twisting behavior of flexible beams shaping the cylindrical gridshells and woven nodes as well as the forces occurring at the joints. Using volumetric FEM with continuous collision detection to model the beams is a non-trivial and computationally expensive approach that can compromise design exploration. Instead, we adopt the Discrete Elastic Rods model (Bergou et al. 2008) to simulate the physical behavior of beams. We employ a reduced joint model to constrain such beams at their intersections (Panetta et al. 2019).

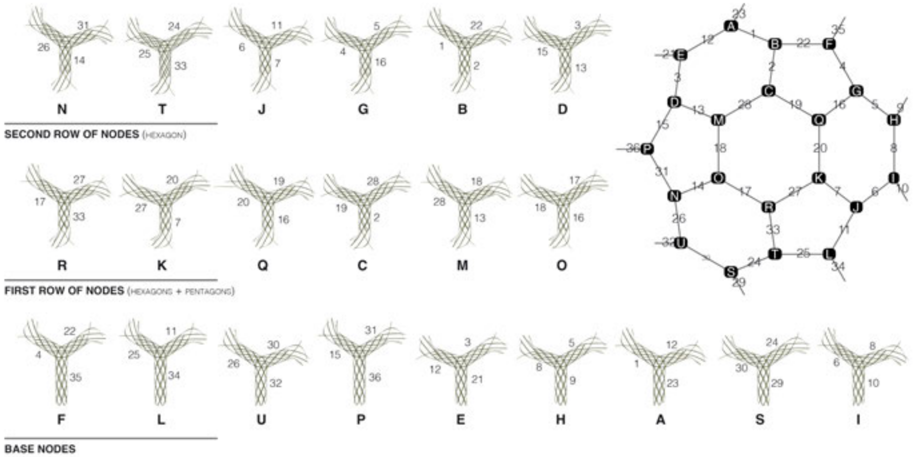

Fig. 4: Typologies of woven nodes and cylindrical gridshells in the structure.

The numerical model is constructed from the curve networks generated for each cylindrical unit. The required inputs are the topology defined by the crossings originated from the intersection of curves and the spacings between these crossings. While crossings with valence 4 are modeled as revolute joints, crossings with higher valences are modeled as fixed joints. Additional information regarding the offsets along the normal direction at crossings is also required to define the under-and-over logic for interweaving. On this basis, the 3D equilibrium state of the entire assembly can be computed. To better approximate the interpolated surface generated from cylinders and nodes, it is important for the simulation to keep joint positions close to the surface while also permitting them to glide along it. This objective can be formulated using closest point projection from a point to a 3D surface. Since the input topology is fixed to respect the weaving pattern on nodes and the deployability of cylindrical modules, the main design parameters are the spacings or “rest-lengths” between joints. Given a set of length parameters, the forward simulation can be run to compute the 3D joint positions and then evaluate the objective function. Using the adjoint state method and sensitivity analysis, a gradient-based optimization method is implemented to find the optimal length parameters while tracking the equilibrium state of the structure at each iteration. This design optimization permits to minimize stresses on the beams. More details about the method can be found in Panetta et al. (2019); Ren et al. (2022).

4.3 Analysis

Structural analysis is integrated into the framework at different stages, with models varying in their level of detail. Physical tests on cylindrical gridshell components were conducted to construct an FE representation of screw connections between flexible beams. The testing result of the cylinder prototypes also serves to inform the global design with an accumulated stiffness of the components. This step largely simplifies the initial FE analysis into a strut-represented model for rapid global topology iteration. Once the global topology optimization is accomplished, the characterized mechanical properties from material samples allow for a more sophisticated simulation of the detailed woven geometry.

An important consideration for developing the BamX research demonstrator was the utilization of raw bamboo slats. Up-scaling a structure built out of raw bamboo requires a calculation process that considers the material properties derived from test results. This is because raw bamboo has substantially varying mechanical properties and cross-section dimension along the axis, unlike more standardized and graded building materials such as steel, concrete, or timber. Hence, integrating structural information into the design loop requires the characterization and evaluation of the acquired batch of material. Multi-scale calibration on the material, component and global levels provides an understanding of the range of scalability the structure can achieve.

Calibrations are done on the component scale and the bamboo slat scale. 4-point flexural tests were carried out on 70 cm slat specimens. Wide and thin specimens were extracted respectively from the pole's root-end and tip-end. In total, 12 air-dried specimens were tested, and 2 sets of mechanical properties were characterized. In the final FE model, both stiffnesses were applied to check the maximum deformation under the lowest stiffness scenario and the maximum stress state under the highest stiffness scenario.

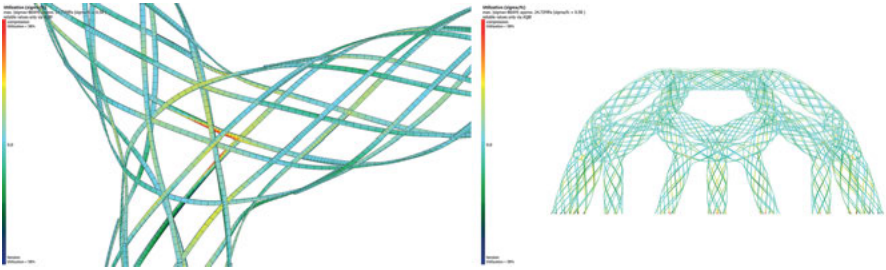

Fig. 5: Calibrated FE model. Left: Beams close up; Right: Detailed model with deformations.

5 Materialization

The computational process simplified construction instructions, making them independent of advanced fabrication technologies and industrial materials. The con- struction was divided into two phases: preparing bamboo slats and pre-fabricating cylinders in the first phase and transporting and connecting the cylinders at the construction site to form the structure in the second phase.

5.1 Off-site pre-fabrication

The final structure relies solely on raw bamboo slats and basic hand tools for construction. The bamboo was sourced from the Tuscany region of Italy, belonging to the Phyllostachys family, with a maturity of 3–4 years. The bamboo poles utilized on this project had a cross-section diameter of 5 cm from which 6 slats, each with a width of 2.5 cm and a thickness of 7 mm, were split using a traditional bamboo splitting device. To the greatest extent possible, it was important to maintain a consistent cross-section along the splits to ensure surface smoothness and material continuity. For this reason, only the central part of the plant was utilized to minimize the difference in diameters between the upper and lower part of the poles. The total amount of material came from 50 bamboo poles of 5 meters and 20 poles of 3 meters.

During pre-fabrication, a peer review system was instituted to ensure that manual measurement of the joints and label information precisely aligned with the data of the digital model. A custom-designed labeling system was adopted to include, in each bamboo slat, the required weaving information for assembly. Holes are then manually drilled and slats are cut to length with a hand saw. Finally, slats are connected with 3 mm screws to create the cylindrical components, which were stored in their compact state.

5.2 On-site assembly

Once pre-fabrication was done, cylinders were transported to the construction site to assemble the entire structure (Fig. 6). The general assembly principle involves the interweaving and connection of slats from three deployable cylinders that converge at a node. After weaving the slats through the node, the connection is finalized by overlapping slats of different cylinders, as defined in the computational model. The overlap between slats is always fastened by one pin joint and two cable ties attached at both ends (Fig. 7). Consequently, cylinders are joined seamlessly at nodes since the overlap between slats permits maintaining material continuity.

The assembly sequence of the entire structure was carefully planned by taking into account the maneuverability of cylinders and avoiding scenarios where slats can be over-stressed while weaving. A top-to-bottom strategy (Fig. 8) was adopted, which involved assembling the top hexagon on the ground and then lifting it up using tension cables. This enabled adding the remaining parts of the structure and weaving the nodes always at the floor level. From the initial hexagon, the remaining cylinders of the nodes

Fig. 6: Undeployed cylinders on the construction site.

Fig. 7: Detail of the overlapping between bamboo slats (left); Connections occurring when cylinders start to shape nodes (right).

were added to form the first row of woven nodes. Note that the structure was raised gradually as deployed cylinders were added. The next row of woven nodes was created by adding the remaining two cylinders per node, which also served to close the first level of pentagons and hexagons. The third row of woven nodes was completed after adding the cylinders in contact with the floor. The structure was then carefully released from the tension lines with the end cylinders attached to the base, thereby becoming load-bearing.

6 Limitations and future work

The design and construction of the final pavilion posed a significant challenge for the proposed structural system and design framework. Several digital models with different

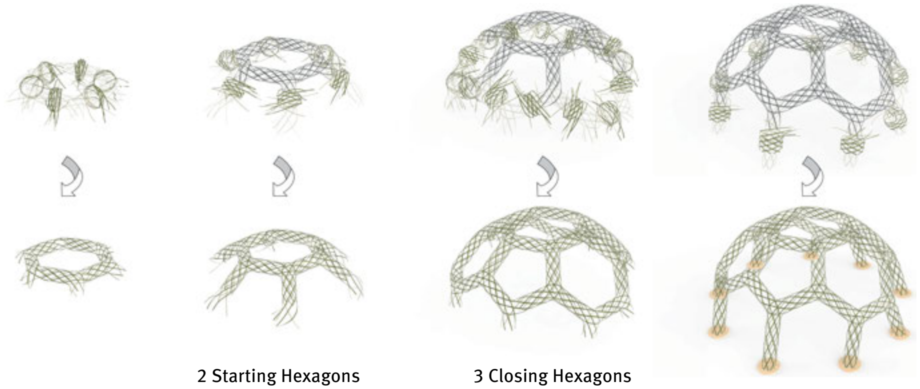

Fig. 8: Assembly sequence.

levels of detail incorporating physical behavior and materialization constraints have heavily informed the entire design process. The segmentation of the spherical cap modeled as a part of a truncated icosahedron was intended to facilitate our large-scale testing. However, the design framework can use different types of structurally stable free-from surfaces but some special features are always required. The segmentation of the target surface needs to only contain interior vertices of valence 3, with nearly symmetrical edges. At this stage, symmetrical edges secure the creation of triangular tiles on the surface of the node while maintaining the continuity of curves connected from two different cylinders. Further studies are required to include nodes with higher valence and accommodate more variation between the angles of adjacent edges.

Currently, cylinders showed a straight deployment path which forces curvature to be accumulated at the level of the woven nodes. While it is possible to develop positive and negative curvature with this deployment, smoother results on the target surface could be obtained by incorporating cylinders exhibiting a curved deployment path. As shown in preliminary studies, it is possible to obtain deployed curved cylinders by enforcing geometric incompatibilities on the curve network. Curvature can then be distributed at the level of woven nodes and along edges. However, this raises further problems regarding the woven connection of cylinders and the generation of triangular tiles. Future studies are needed to explore computational strategies for incorporating curved cylinders.

7 Conclusion

This paper introduces a computational framework to design, optimize, and fabri- cate double-layered segmented shells made of elastic gridshell components. The fundamental principle is to create rigid woven nodes by connecting compact-to- volumetric cylindrical components. The use of volumetric components creates sufficient out-of-plane stiffness to stabilize the entire structure with a similar effect of a double-layer grid. Triangular tiles are created on the surface of woven nodes by carefully interweaving curves from adjacent cylinders. This topologic feature permits to lock cylinders' kinematic behavior and stabilize the entire structure without adding external elements.

To demonstrate the effectiveness of the design framework, a dome structure with a span of 10.3 m was constructed using raw bamboo slats. The structure shows the enormous potential that the combination of segmented shells, deployable units, and natural materials has in architecture. Deployable cylindrical components can be pre-fabricated off-site and kept in their compact state for transportation and storage. Based on an incremental assembly process, components can then be deployed and interconnected without requiring external mechanisms due to their small weight and magnitude of shaping forces. The optimized geometric and topologic features are the only factors determining the stability of the entire structure. Additionally, the strategy presented here combines high-tech and low-tech strategies by using computation for the design and simulation of the material behaviour but relying on an intuitive manual fabrication process that takes advantage of traditional bamboo processing knowledge.

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