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Integrative structural design methods for bamboo woven deployable structures: The BamX! Research Pavilion

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Abstract

Bamboo deployable structures take advantage of the high elasticity of the naturally grown material to achieve substantial shape change beyond mechanical deployment. The deployability maximizes prefabrication while maintaining transportation compactness. The BamX! Pavilion investigates the deployability of cylindrical bamboo components and the embedded locking mechanism through geometry. The interlocking weaving pattern stiffens the cylinders by connecting selective points between the deployed cylindrical components, forming a static load-bearing structure. The inconsistency of the mechanical properties of raw bamboo, together with the complexity of the system required an integrative structural design approach. The method includes material characterization, structure system conceptualization, and multi-scale structural analysis. Calibrations are performed both on the component level and the material level. Physical testing on single cylinders facilitates a simplification on the initial form-finding FE into a strut-represented model for rapid iterations on global topology. Once the global topology optimization is accomplished, the characterized mechanical properties from material tests allow for a more sophisticated simulation of the final woven geometry. This paper evaluates the non-standard material and the required multi-scale sampling and analysis workflow towards designing and fabricating a bamboo woven deployable structure: the BamX! Pavilion.

Keywords: Deployable structures, bamboo woven architecture, computational design, integrative design, material characterisation, mechanical testing, non-standard material, structural design

1. Introduction

The BamX! Pavilion represents a bamboo woven deployable structure developed through collaborative research involving weaving artist Alison Martin, the Geometric Computing Laboratory (GCM) at EPFL, and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart. The structure's global geometry closely approximates a spherical cap, achieved through a truncated icosahedron representation, from which 36 deployable gridshell cylindrical components are generated at the edges. These cylindrical gridshells made from thin bamboo slats seamlessly interconnect at 21 nodes, resulting in a double-layered segmented shell (Figure 1). The structure's overall form gradually emerges through the sequential deployment and interconnection of these cylindrical units, employing weaving principles. The systematic interlacing of ribbons permits breaking the quad topology of the cylindrical grid layouts, introducing triangulations that lock the scissor mechanism of the cylinders. The system achieves stabilization through its inherent topological characteristics without the need for external elements to restrain the diagonals of the gridshells.

This investigation encompasses an exploration of the material properties and feasibility of working with raw bamboo, alongside an examination of geometric configurations. These configurations are designed not only to achieve structural stability in the final erected state but also to facilitate a flat, undeployed state during module fabrication and transportation. The transition from a dynamic to a static state is intricately woven into the design of the weaving pattern, wherein individual components are interlinked, completing the locking mechanism and ensuring structural integrity.

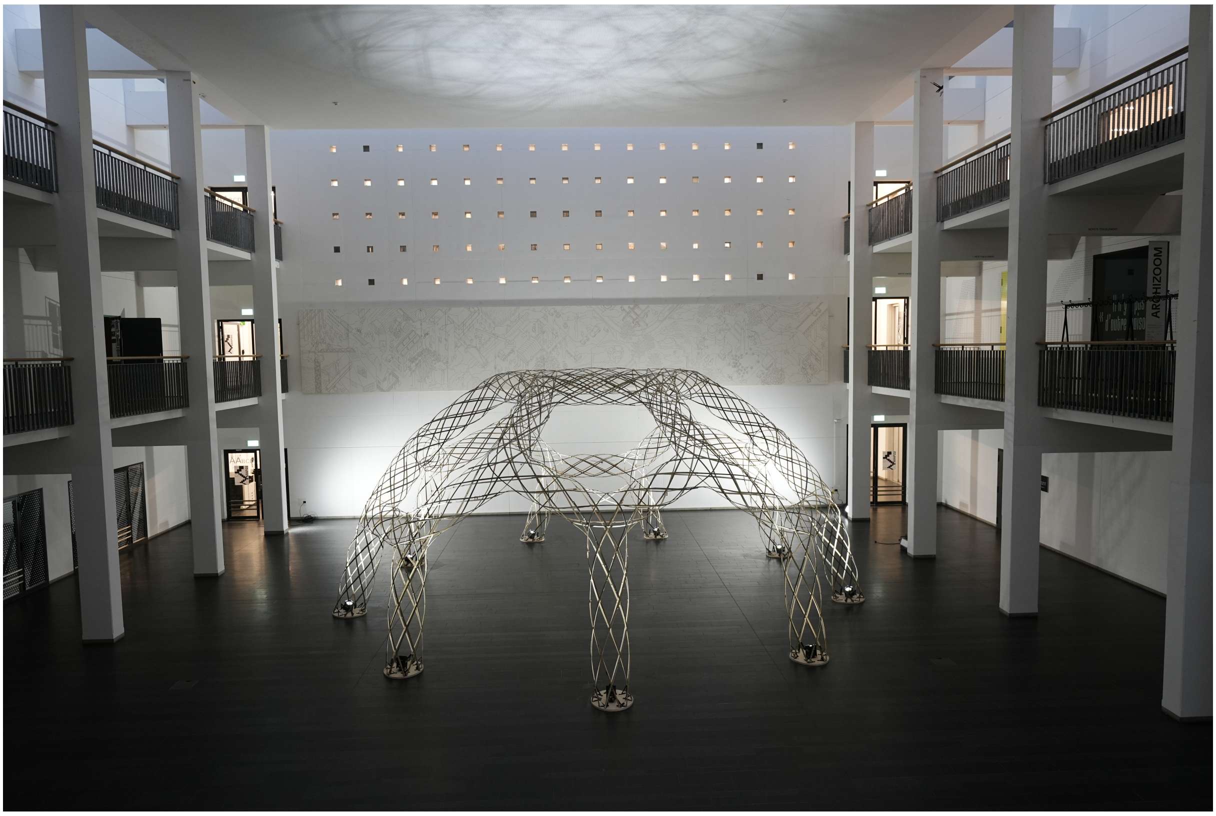

Figure 1: BamX! Bamboo pavilion, Sep. 2022, EFPL campus.

2. Related Work

Our work falls within the topic of elastic gridshells, which are discrete shell structures shaped from a grid-like arrangement of elastic beams. The selection of the grid pattern significantly influences the global behavior and structural performance of the resulting structure. An overview of the various patterns of elastic gridshells is provided in [1]. Elastic gridshells have been traditionally designed using regular grids [2], following the principles of discrete Chebyshev nets. Such grids consist of equilateral quadrangles, facilitating the connection of thin beams with revolute joints, similar to a scissor linkage. Beams can deform elastically while rotating around their joints, permitting the linkage to transition between different equilibrium states. However, the regularity of these scissor linkages restricts their deployment to the plane, necessitating the imposition of boundary constraints to facilitate deformation into a 3D curved shape. More recent studies, exemplified by X-shells [3], C-shells [4], G-shells [5, 6, 7], and A-shells [8], adopt a different approach by arranging flexible beams into non-regular grids. This departure leads to kinematic incompatibilities during deployment, compelling the structure to buckle out of plane. Such buckling behavior is essential for achieving the desired transformation from a planar state to a 3D curved state without the imposition of boundary constraints. This way, the target shape is directly encoded in the planar layout of the grid by fine-tuning the distances between joints.

The modular system developed in our work is based on a special type of deployable grid-shell cylindrical units. These units are interconnected using weaving principles, where ribbons from different units are interlaced to form a stable lattice structure. This interlacing technique relies on the alternation of over- and under-crossings to generate the necessary friction for securing the ribbons in place ([9]). Introducing topological singularities into the pattern is crucial to break the regularity of the grid and induce curvature [10]. However, the combination of straight ribbons with topological singularities often results in the appearance of kinks in the woven structure. To address this issue, Ren et al. [11] proposed an optimization-driven process to achieve smooth woven surfaces using curved planar ribbons. In our work, we employ straight ribbons but utilize a similar optimization process to determine the ideal grid layout.

3. Multi-scale system characterization

Bamboo, being a naturally occurring material, exhibits mechanical properties that remain contingent upon the unique composition of individual slats. Due to its nonstandard nature, conventional design methodologies prove inadequate for its structural assessment. Consequently, the design methodology for an elastic bamboo structure necessitates a multi-scale approach for system characterization. [12][13]This method entails delineating the structure system into three distinct scales: global, component, and material (see Figure 2). To account for the uncertainty brought by the material system, corresponding physical tests were conducted informing the digital models of various parameters across these scales.

At the global scale, a simplified finite element (FE) model was constructed, employing equivalent beam elements to represent components. This facilitated iterative global design processes without imposing excessive computational demands.

Conversely, at the component and material levels, a detailed ribbon model was employed in the FE analysis, delineating each segment of the bamboo strips into beam elements. Material properties derived from small-scale tests were incorporated into the cross-section properties. Additionally, large-scale component tests were instrumental in calibrating joint stiffness within the ribbon model.

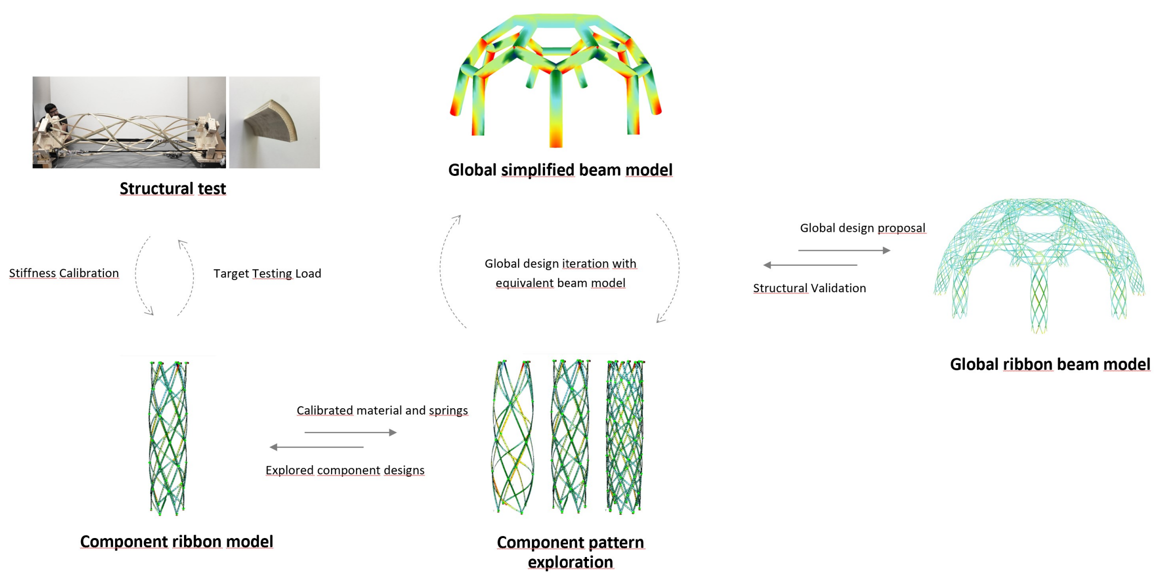

Figure 2: Multi-scale structural system calibration

3.1. Material Characterization

The bamboo slats utilized in this study were sourced through a non-industrialized procedure, exhibiting variations in age and diameter. Selection criteria were based on cross-sectional size and length, with manual sorting of bamboo poles. Following several days of air drying, bamboo poles underwent processing using a six-bladed bamboo splitter, a conventional tool in bamboo processing. The width of split strips depended on pole diameter, contributing to material property variability, including dimensional variations and mechanical properties inherent in natural materials. Consequently, a preliminary material investigation was undertaken.

Bamboo samples were categorized roughly into thicker and thinner cross-sections, the former typically wider due to originating from larger-diameter poles. Six samples from each group were selected for testing. Bamboo slats were sectioned into 50 cm-long specimens and subjected to standard 4-point bending tests using the Zwick Z100 material testing machine. Due to inherent cross-sectional irregularities (slightly arched shape, see Figure 3 left), resulting flexural stiffness values were adjusted using respective specimen cross-section geometries to obtain equivalent stiffness values with rectangular cross-sections. As depicted in the material test outcomes (see 3 right), the conducted tests yielded a 10% variation in stiffness and an 8% variation in density across specimens. Thicker bamboo samples exhibit a higher material density, as well as higher bending stiffness. In the sample set, the increase in stiffness correlates proportionally with the increase in material density. Varying stiffness values for the component ribbon model were approximated based on the density of the later assembled strips and subsequently incorporated as inputs for determining the material properties of the detailed ribbon model.

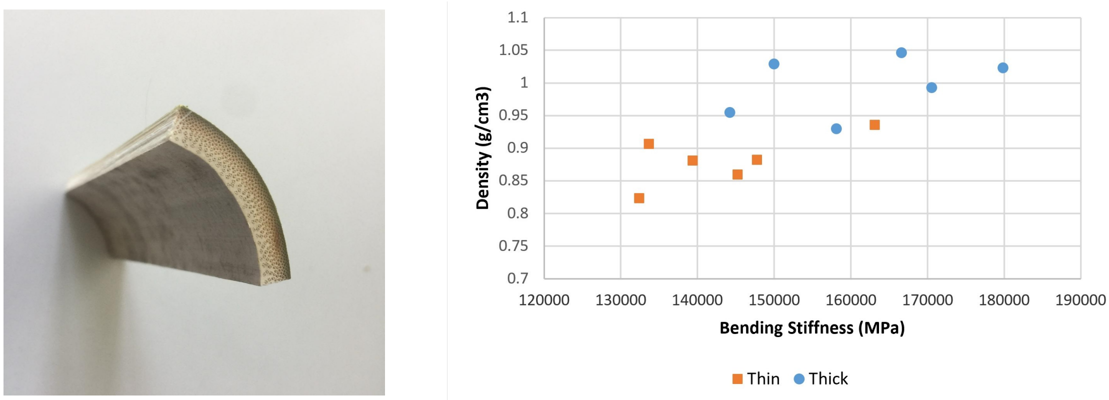

Figure 3: Bamboo slat sample (Left) and material test results (Right)

3.2. Component Characterization

Component characterization entails conducting a 1:1 scale compression test on six distinct configurations of woven cylinders. The test is executed horizontally, with two load cells positioned on opposite sides of the cylinder (See Figure 4) One end of the cylinders is securely fixed, while the other end is supported by rollers. Compression is achieved through gradual shortening of the straps connecting the two ends, with subsequent measurement of deformation. Synchronization of the shortening process for the two straps is achieved by aligning readings from the load cells. Each step of load incrementation is set at 100N.

The five configurations of cylinders are categorized into two groups: three elastic-patterned and three reinforced-patterned. Elastic-patterned cylinders are designed to calibrate the geometrical stiffness of the component, considering various joining methods and friction accumulation among woven slats. In

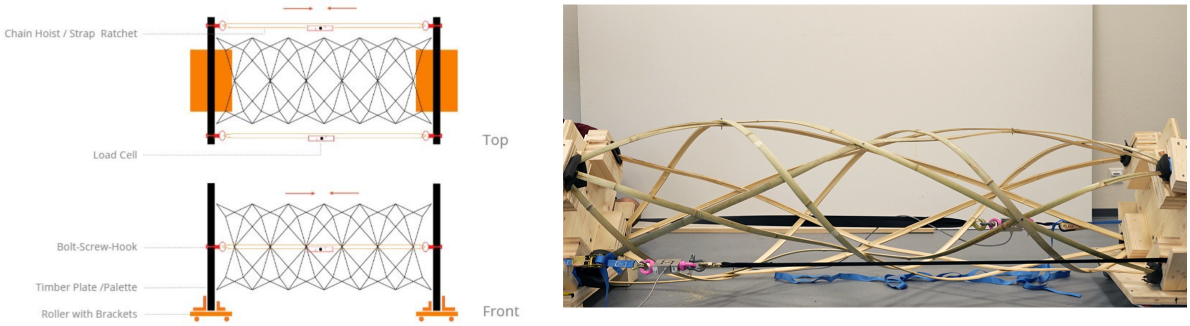

Figure 4: Horizontal load test setup

contrast, reinforced-patterned cylinders aim to explore methods for securing the deployed structure in shape. The two elastic-patterned cylinders were configured as follows: 1) single slats with pinned joints, 2) double slats with thick-tied joints. Meanwhile, the three reinforced-patterned cylinders were configured as follows: 1) single-pair spiral reinforcement 2) double-pair spiral reinforcement, and 3) steel cable reinforcement (See Figure5.)

Test results indicate that the cylinder reinforced with steel cable exhibits superior performance compared to other reinforcement methods (See Figure 6). However, through the systematic exploration of weaving techniques, a novel approach has been devised to incorporate reinforcement patterns as interlocking mechanisms within the joining process of two components. Specifically, extended bamboo slats are strategically affixed to neighboring components during assembly, thereby triangulating the quadrilaterals within the cylinder to establish a stable configuration. This method seamlessly integrates spiral reinforcement patterns into the woven structure of adjacent components, thereby facilitating a monolithic material solution.

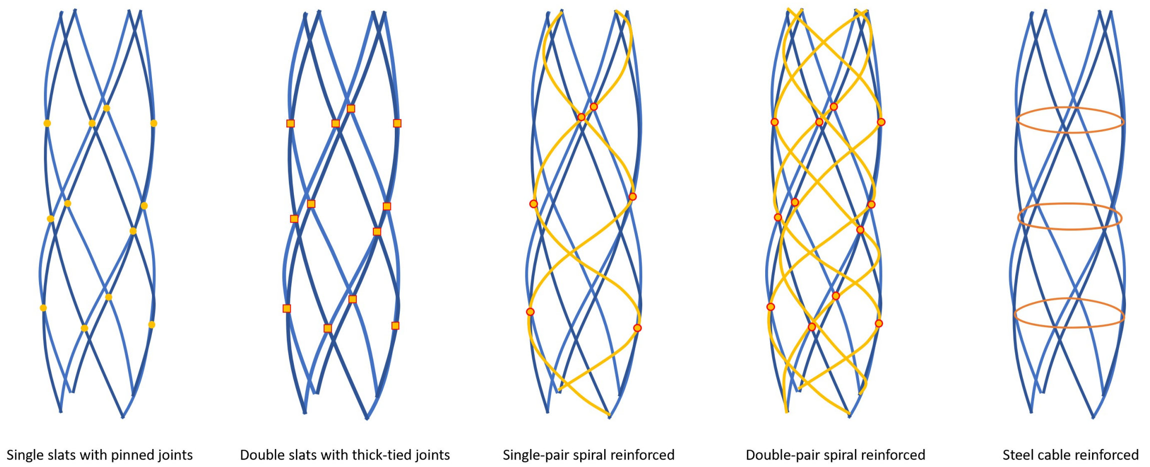

Figure 5: Cylinder configurations for full-scale test

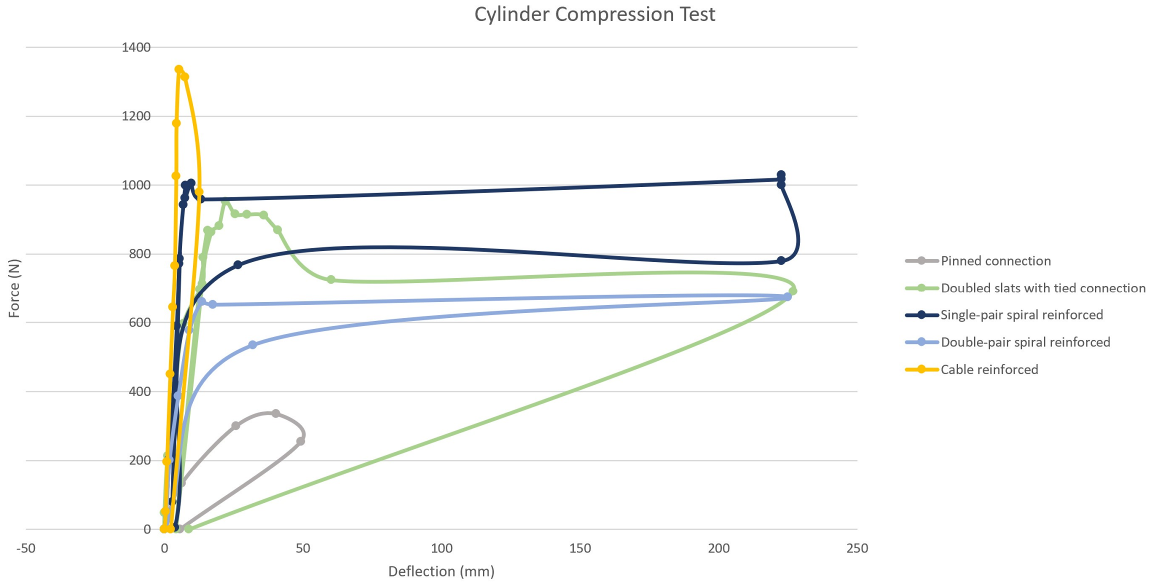

Figure 6: Cylinder compression test results

4. Geometrical exploration

4.1. Simplified component representation

Following the calibration of materials and joints through physical tests, a digital exploration of diverse woven configurations was undertaken to ascertain target global stiffness and optimal material utilization. This approach facilitated an expanded comprehension of potential woven patterns and their corresponding performances, extending beyond the confines of materialized configurations (see Figure 7).

The subsequent phase involves transforming the outcomes of the component ribbon model into equivalent beam cross-sectional properties. Each configuration within the ribbon model is translated into an equivalent component axial stiffness by aligning the applied force and deformation with those of a simplified beam subjected to axial force. These stiffness values, representing various configurations, are integrated into the list of material options available for utilization in the simplified global model (see Figure 8).

Subsequently, global geometrical exploration is conducted to assess and evaluate diverse design proposals, characterized by variations in support counts, dome topologies, and overall structural height. Within this simplified beam finite element (FE) model, both component joints and supports are depicted as rigid connections. At this juncture, preliminary estimations of structural stiffness and global deformation are feasible, enabling swift design iterations and decisions. Nonetheless, actual stress levels and material utilization remain indeterminate.

4.2. Computational workflow

The complexity of the design process arises from the intricate relationship between the kinematics of deployable components, the grid topology, and the overall structural behavior. This relationship is influenced by factors such as the connectivity and number of slats per cylinder, as well as the connectivity of cylinders and their diameters. To address this complexity, a unified computational pipeline has been developed to integrate various geometric and numerical models of varying detail, facilitating the exploration and optimization of design concepts [14].

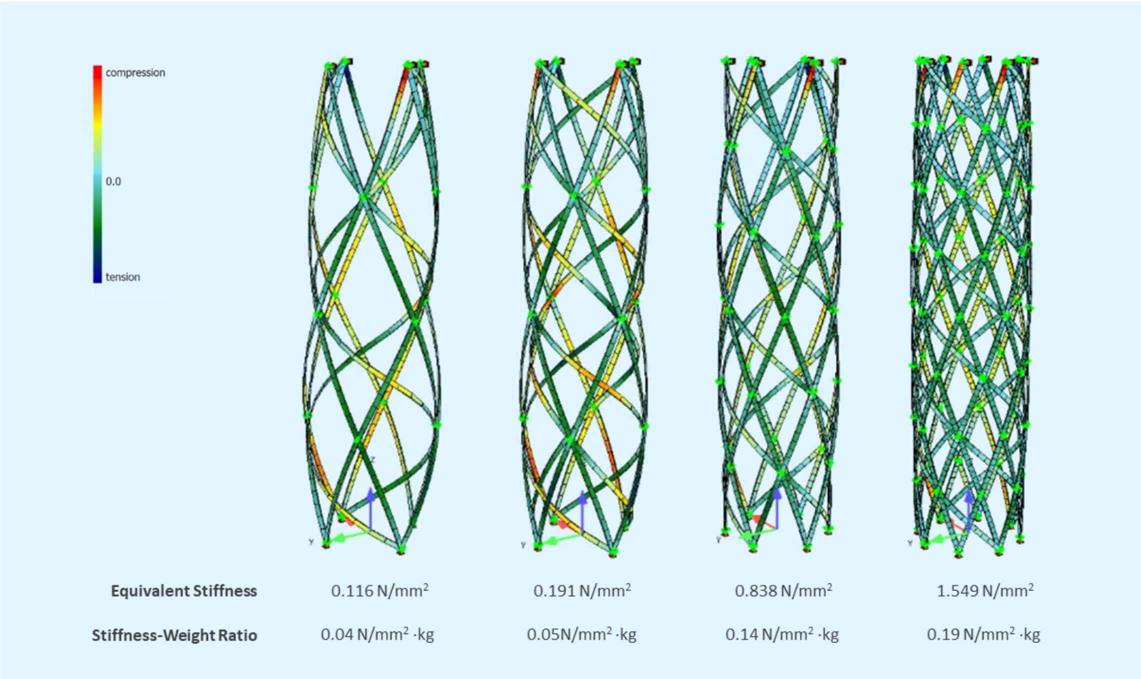

Figure 7: Component design iteration and geometry stiffness determination

The entire structure is modeled in its deployed state using results from previously conducted component characterization. A geometric approach based on geodesic tracing and curve intersections is employed to extract grid topologies and geometric quantities such as the lengths between joints. On this basis, equilibrium states are modeled by simulating the bending and twisting behavior of flexible slats. The Discrete Elastic Rods model [15], combined with a reduced joint model representation [3], is utilized for this purpose. Forward simulation processes are conducted iteratively to model both the equilibrium states of global structures and the deployment process of individual cylinders. Simplified global models are employed to evaluate the overall form and structural behavior.

Forward explorations serve as a foundation for subsequent design iterations, enabling refinement and optimization of the design through feedback loops. Initial results indicate that the geometric initialization is not optimal. Therefore, a gradient-based optimization process was introduced to optimize the geometric model while tracking the equilibrium state at each iteration. This inverse design optimization aims to minimize stresses on the slats by finding the optimal length parameters between joints. Further details about this optimization method can be found in [11].

5. Structural integrity and validation

The conclusive assessment of structural integrity was conducted through a global finite element (FE) ribbon model. This involved comprehensive stress examinations and deformation evaluations for the finalized structural design. SOFISTIK, developed by Sofistik AG, served as the primary tool for these FE analyses (See Figure 9). In configuring the FE model, timber was designated as the foundational material for the woven slats, with its properties adjusted based on stiffness and density data derived from small-scale material tests. Additionally, spring stiffness values between slats were derived from the calibration of the component ribbon model. For modelling purposes, an average bamboo strip with an equivalent rectangular cross-section was utilized.

To ensure adequate safety margins, stress accumulation was assessed. This involved considering vari-

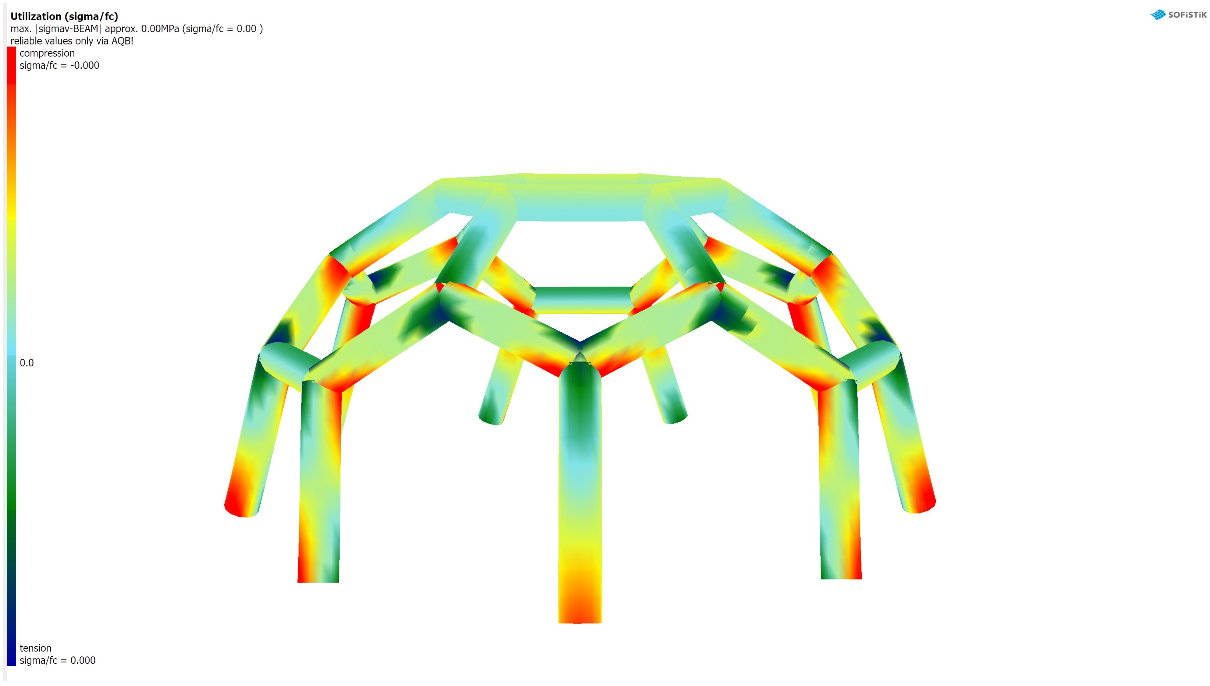

Figure 8: Global FE model with simplified component representation

ations such as employing a thinner cross-section with a higher material density. Such variations were crucial for verifying the robustness of the structure built with biomaterials under various loading scenarios. Furthermore, the supports were simulated as pinned connections located at the foot ends of the bamboo strips within the FE model. This modelling method attempts to narrow the gap between the inherent variability associated with designing using biomaterials and an accurate representation of the structural behaviour under real-world conditions, aiding in the comprehensive assessment of its integrity and performance.

6. Conclusion

This paper delineates the methodologies employed in the structural design and material-aware design-to-assembly workflow of the BamX! Pavilion. Through a combination of multiscale physical testing and digital analysis techniques, the project exemplifies the feasibility of crafting a deployable bamboo woven structure, which was realized in an architecture scale in 2022, EPFL campus (see Figure 1). Furthermore, it also highlights the gap between existing building standards/codes/design methodologies and the burgeoning use of renewable biomaterials. This prompted a project-specific structural design approach and a bespoke experimental testing regimen. Nonetheless, the BamX! pavilion demonstrates an alternative paradigm for envisioning bamboo structures. It elucidates how computational methods can enrich design ideation, facilitating the transformation of conceptualization into tangible realization.

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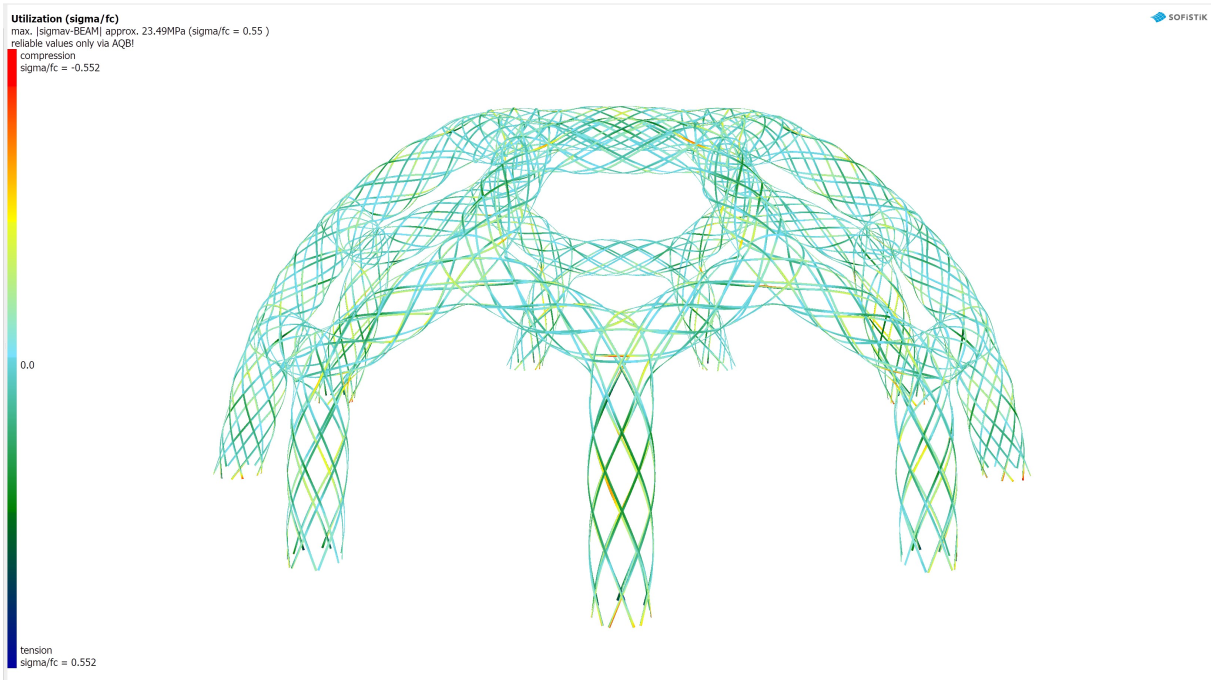

Figure 9: Global FE model for validation of structural integrity

volunteers: James Pauly and Hannah Pauly.

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