WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

World's First Bamboo-Timber Composite Gridshell: Design, Construction and Full-Scale Experimental Analysis

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ABSTRACT: This paper presents the design, construction, and structural analysis of the world's first full-scale bamboo-timber composite gridshell. The structure combines laminated bamboo's tensile flexibility with softwood timber's compressive strength, using active bending for form generation without requiring prefabricated curved elements. A parametric design-to-build process is developed, followed by a full-scale prototype construction (12.4 m × 12.4 m). The structure was evaluated through physical load testing under 3-ton local area loading. The results offer insights into structural behaviour, specifically highlighting creep, residual deformation, and in-plane stiffness. 3D cloud point models were built to illustrate the global deformation response further. This study demonstrates the feasibility and performance of composite bamboo-timber gridshells, offering a sustainable and structurally efficient alternative for architectural applications.

KEYWORDS: *bamboo-timber composite, post-formed gridshell, design to construction, load-displacement response*

1 INTRODUCTION

Growing interest in sustainable and material-efficient construction has revitalised attention toward gridshells-lightweight spatial structures composed of slender, initially straight elements that are actively bent into double-curved configurations [1-6]. This structure typology enables material-efficient usage while achieving architecturally expressive forms.

The concept of elastic gridshells was pioneered by Frei Otto in the 1970s, leading to the construction of the Multipurpose Hall in Mannheim [7], which demonstrated the feasibility of actively bent timber elements for large-span enclosures. Since then, several notable gridshells such as the Japan Pavilion [8], the Downland Museum roof [9], and the Savill Building [10] in Windsor Great Park have gained attention from architects and structural researchers.

Timber remains the dominant material in gridshell construction due to its high flexibility, low torsional stiffness, and renewable characteristics. While alternative materials such as steel, aluminum, and glass fibre-reinforced polymers (GFRPs) have been explored, timber offers a superior balance of structural efficiency and sustainability.

Bamboo presents a compelling alternative. It is fast-growing, naturally renewable and exhibits a high elastic

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https://doi.org/10.52202/080513-0083

limit stress-to-Young's modulus ratio (f_m/E), making it suitable for bending-intensive applications. Bamboo related research has attracted significant attention in recent years [11-14]. Moso bamboo (phyllostachys edulis), for instance, can store up to two times more carbon per hectare compared to spruce [15]. Engineering bamboo, produced by transforming bamboo stalks into laminated bamboo panels, offers enhanced structural performance and reliability for gridshell applications [16]. However, previous studies on single-material bamboo active bending structures have limitations, including reduced lateral stiffness and excessive out-of-plane deformations in large-scale applications [17]. Recent research has demonstrated that by combining engineered bamboo and wood, high-performance bamboo-timber composite materials can be developed [18]. This approach has been validated in prestressed bamboo-timber beams, where material interaction enhances structural efficiency [19].

To explore this potential, a multi-layer bamboo-timber composite gridshell was developed, comprising two layers of laminate bamboo and two layers of softwood. This hybrid system exploits bamboo's tensile strength and flexibility while utilizing timber's compressive and shear resistance. A 12.4 m ×12.4 m full-scale prototype was constructed, validating both structural feasibility and architectural appeal (Fig. 1.1).

Despite increasing research on gridshell, existing research has primarily focused on case studies and computational form-finding of the statically driven geometry. Full-scale experimental validation remains limited due to construction complexity and cost. Discrepancies between simulation and as-built geometry further highlight the need for physical testing. This study addresses these gaps by detailing the design-to-build process, construction methodology, and experimental analysis of a bamboo-timber composite gridshell.

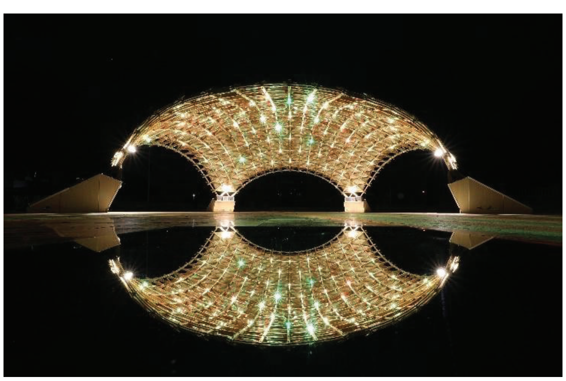

Figure 1.1. Night view of illuminated Bamboo-timber composite gridshell.

2 Design to construct

2.1 Parametric Form-Finding

The design of the bamboo–timber composite gridshell was guided by a parametric form-finding approach, beginning with a flat grid configuration and progressing toward a doubly curved shape, as shown in Fig. 2.1.

Key design constraints—including joint behaviour, boundary conditions, and mesh density—were integrated into the process.Form-finding was performed using Kangaroo, a physics-based simulation engine within Grasshopper® for Rhino. The simulation modelled the elastic bending of the flat grid under predefined boundary constraints, enabling prediction of the final equilibrium shape.

Kangaroo's dynamic relaxation algorithm iteratively adjusted the geometry to simulate structural equilibrium. The model accounted for material stiffness, connection constraints, and external supports, allowing for accurate evaluation of potential grid densities and curvature patterns. By optimising the initial geometry and boundary conditions, this approach supported real-time exploration and refinement of the gridshell topology, ultimately leading to a more efficient and constructible design.

2.2 Construction Process

A full-scale prototype measuring 12.4 m × 12.4 m was constructed using five layers of laths with a cross-section of 68 mm × 25 mm. The configuration consisted of two lower layers of softwood, two upper layers of laminated bamboo, and a final diagonal layer of laminated bamboo for bracing and in-plane stiffness on the top.

The construction began by assembling nine panels in a flat configuration (Fig. 2.2(a)), which were lifted to form the final double-curved shape using an upward erection strategy (Fig. 2.2(b-d)). The lifting strategy was informed by the positioning of upward forces during the form-finding stage, ensuring that the structure deformed as predicted. Four nodes (Fig. 2.2(a-b)) and another four nodes (green line in Fig. 2.2(c-d)) of the gridshell were raised using a pulley system on a central scaffolding tower, along with cables and hand hoists. The structure bent and rotated due to its self-weight when pulled to a certain height. The designed shape was achieved through the process shown in Fig. 2.2(a-d).

Bolts were left untightened during deformation and tightened after achieving the final shape to secure rigidity. The boundary edges were restrained using four prefabricated wooden supports, secured with sandbags. The fifth layer of diagonal laths was installed on top (Fig. 2.2(e)) to maintain shape and ensure in-plane stiffness.

The structure was completed by placing the roof membrane on top for shelter and other functions, with a simulated version shown in Fig. 2.2 (f).

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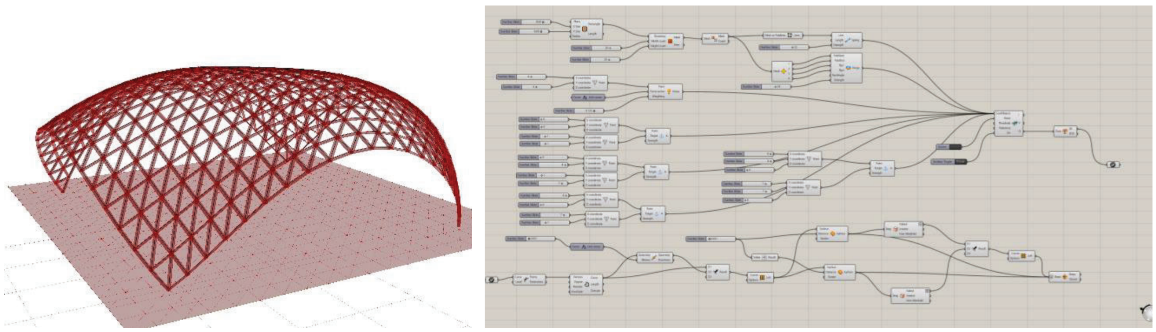


Figure 2.1. Parametric design of gridshell within Rhino Grasshopper®

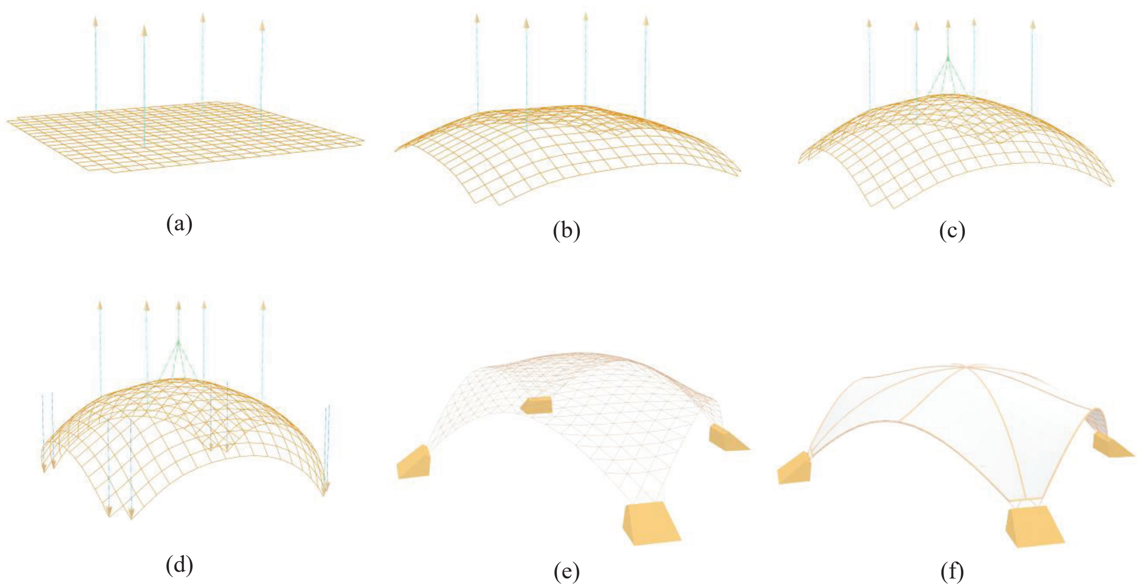


Figure 2.2. Construction process: (a-d) The central nodes are pulled up from flat to final shape; (e) Restraining the shape and structure; (f) Adding the roof membrane on top.

2.3 Connection

As illustrated in Fig. 2.3, five types of joints were developed to accommodate the structural behaviour and assembly requirements of the composite gridshell:

1) Layer-to-Layer Connection: To allow sliding and rotational movement between layers during bending, a slot-joint system was used. Layers were connected using M8 threaded bolts, nuts, and washers (Fig. 2.3a).

2)End-to-End Connection: Adjacent panels were connected using finger joints, secured with three M8 bolts and washers on each side (Fig. 2.3b), ensuring continuity along the laths.

3)Diagonal-to-Diagonal Connection: In the higher regions of the gridshell, longer diagonal laminated bamboo laths were required. These were joined by nailing additional segments together to form continuous members. The completed diagonal elements were then integrated with the underlying layers using the same M8 bolt system, ensuring structural continuity and stiffness.

(a) (b) (c)

Figure 2.3. Connection design: (a) Layer Connection; (b) Panel Connection; (c) Diagonal Connection

4)Edge-to-Support Connection: The four corners of the gridshell were anchored to prefabricated timber supports using pre-drilled steel plates. One end of each plate was bolted to the gridshell corner; the other was nailed into the timber support.

5)Membrane-to-Top Connection: The roof membrane was fixed to the top layer using stainless steel bands, providing a secure and weather-resistant enclosure.

3 EXPERIMENTAL METHODOLOGY

3.1 Prototype and Load Setup

To evaluate the structural performance of the bamboo–timber gridshell, on-site load testing was conducted. Nine representative joints (labelled 1 to 9) were selected as measurement points, as shown in Fig. 3.1. These joints were positioned along the gridshell's quarter lines (highlighted in blue), capturing areas of maximum curvature and deformation, and allowing analysis of load propagation through the structure.

To capture displacements in three orthogonal directions at each structural joint, three draw-wire displacement sensors (1000 mm range) were installed per measurement point. The initial positions of both measurement points and sensors were recorded using a total station survey. During loading, the actual position (X, Y, Z) of each joint was calculated based on the geometry between the sensor and joint positions using the following equation:

$$(X,Y,Z) = f(x_i, y_i, z_i, s_i, Disp_i) \tag{1}$$

For each sensor group (i.e., three sensors per joint), the equations can be expressed as:

$$\begin{cases} (X-x_1)^2 + (Y-y_1)^2 + (Z-z_1)^2 = (s_1 + Disp_1)^2 \\ (X-x_2)^2 + (Y-y_2)^2 + (Z-z_2)^2 = (s_2 + Disp_2)^2 \\ (X-x_3)^2 + (Y-y_3)^2 + (Z-z_3)^2 = (s_3 + Disp_3)^2 \end{cases}$$

(2)

where (xi, yi, zi) are the known coordinates of the i-th sensor; si indicates the initial slope distance between the measurement point and the i-th sensor; and Dispi is the measured displacement from the sensor during the loading process.

Sensors were connected to the structure using extension cables: one end was fixed to the designated joint, while the other was connected to the sensor. All sensors were mounted on holders attached to steel base plates, which were magnetically secured to the ground.

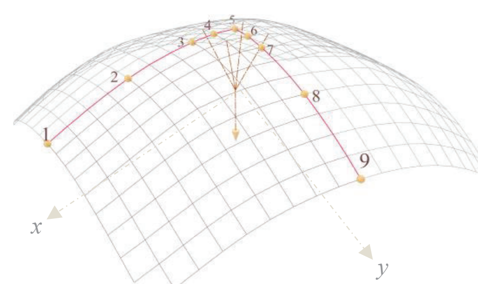


Figure 3.1. Arrangement of measurement joints and loading points on the bamboo-timber gridshell.

Four joints around the gridshell centre were chosen as the loading points to ensure balanced load distribution and to assess the global structural response. At each loading point, a flexible lifting webbing sling was securely looped around the intersecting structural members and connected to a red load-bearing nylon climbing rope via an M12 stainless steel eyebolt/shackle for load application. The red rope was threaded through the four eyebolts, with sufficient slack to converge at a single point beneath the highest point of the gridshell. The rope ends were lap-jointed and secured with multiple rope clamps, forming a closed-loop system to ensure uniform load distribution. The rope was connected to a load cell, which was linked to the external load through an intermediate eyebolt, a bow shackle, and a certified

 https://doi.org/10.52202/080513-0083

lifting sling. The lifting sling supported a weighted steel hanger filled with calibrated steel plates. All loading components were rated for safety and certified for structural testing.

The complete loading setup is shown in Fig. 3.2. The final suspended weight-approximately 3 tons-generated a concentrated local area load of around 29.85 kN distributed across the four central joints.

Prior to testing, all loading components- including bolts, eyebolts, rope clamps, and ropes-were individually tested for reliability and load capacity. The load cell and displacement sensors were also calibrated to ensure accuracy.

The loading scheme, illustrated in Fig. 3.3, was executed in two controlled stages using an electric chain hoist. First, the load was gradually increased to 20 kN at a rate of 2 kN/min and held for 30 minutes to allow the structure to stabilise under sustained loading. Subsequently, the load was increased to a peak value of 29.85 kN at the same rate and maintained for 40 minutes. This was followed by a gradual unloading phase.

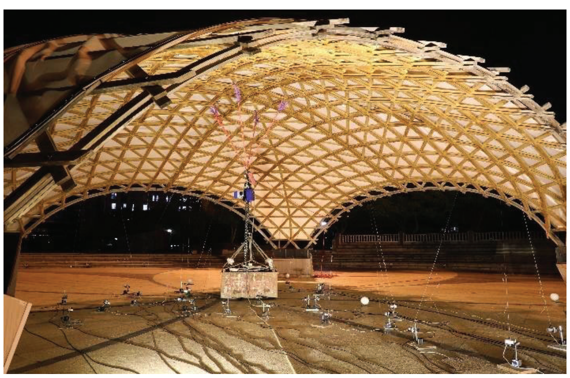


Figure 3.2. Bamboo-timber gridshell loading experiment set-up

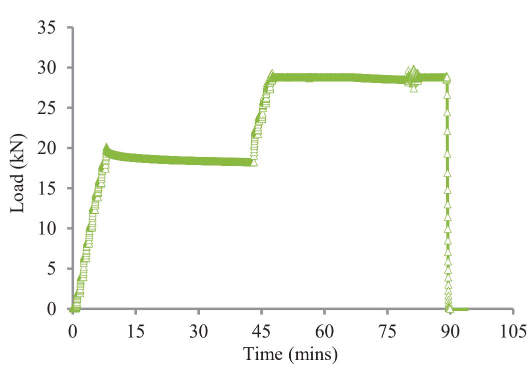


Figure 3.3. Loading-time curve

4 RESULT & DISCUSSION

4.1 Load-Displacement Behaviour

The load-displacement response of two representative joints—point 1 (at the edge) and point 5 (at the geometric centre)—is shown in Fig. 4.1. In these plots, the Y-axis represents the applied load, while the X-axis shows displacement in the three spatial directions.

Under vertical loading, the structure exhibited three distinct behavioural phases. In the initial loading phase, displacement increased proportionally with the applied load, indicating linear elastic behaviour. During the sustained loading stages at approximately 18 kN and 28 kN, displacements continued to grow slowly over time, suggesting time-dependent creep. Upon unloading, the displacement followed a nonlinear descending path and did not return to its original state, stabilising at a residual displacement. This residual deformation reflects permanent set due to stress relaxation within the structure. Comparison

4.2 Comparison of Joint 1 and 5

Joint 1, located at the edge, showed greater horizontal displacements than joint 5, due to its position (more flexible along the positive x-axis compared to joint 5). Lateral displacement at joint 1 reached about 22 mm in the x-positive direction. Both joints showed minimal movement in the y-direction, indicating high in-plane stiffness. Interestingly, joint 1 also exhibited a greater vertical displacement (~17 mm) than joint 5, despite the latter being at the loading centre. This suggests notable load redistribution from the centre toward the edge regions.

A notable observation is the nearly parallel alignment of the load-displacement curves during the unloading phase (from 28.5 kN to 0 N) across both tests, indicating a similar path of structural recovery. This indicates a consistent recovery behaviour in the bamboo-timber composite gridshell.

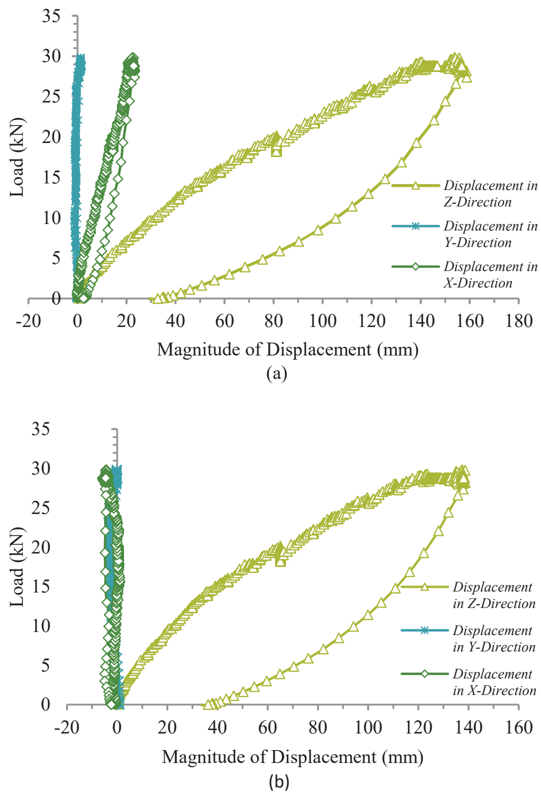
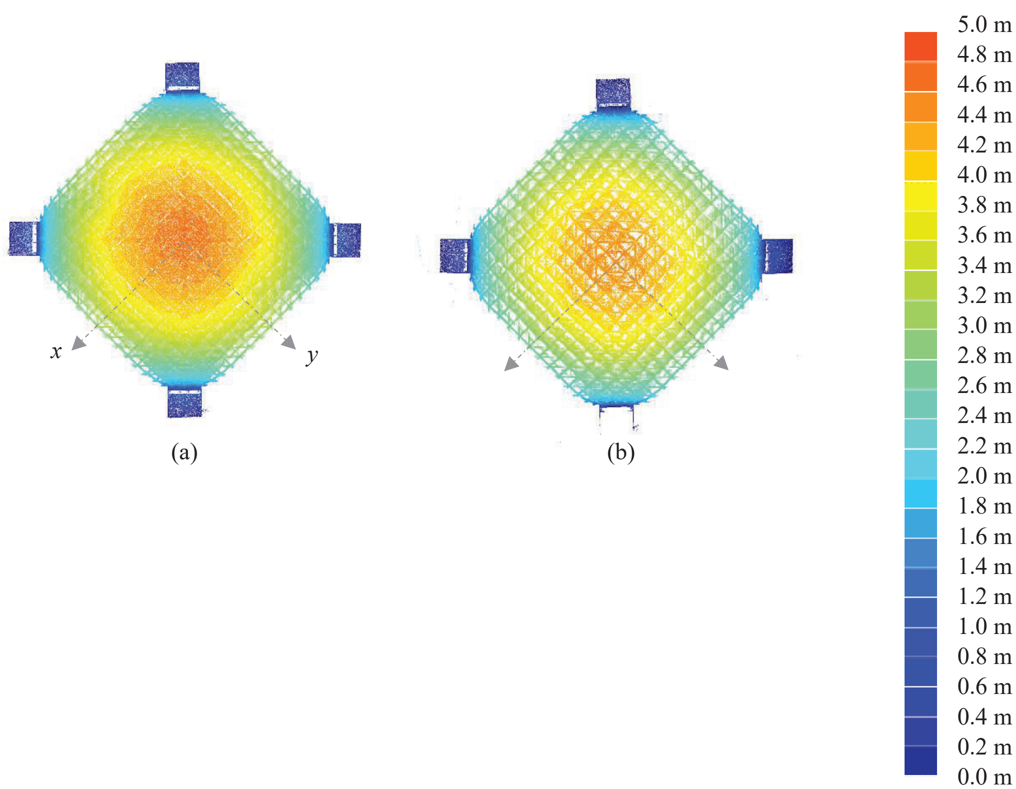


Figure 4.1. Load-displacement behaviours under local area loading in three directions of joints: (a) joint-1; (b) joint-5.

4.3 Global Vertical Deformation

To gain a broader understanding of the global deformation behaviour under localised loading, a Trimble X8 laser scanner was used to capture the gridshell geometry in both unloaded and fully loaded states. The resulting 3D point clouds were processed into colour-mapped elevation models, with a gradient scale ranging from 0 m (blue) to 5.0 m (red), as shown in Fig. 4.2. These visualisations highlight the doubly curved form of the gridshell and its symmetrical deformation in response to applied loads.

The colour-mapped elevation models in Fig. 4.2(c-d) offer a detailed comparison of vertical deformation in the quarter gridshell (with nine measurement points on) before and after loading. Upon application of the 3-ton load, significant deflections were observed in two primary zones. Area II, which includes the central loading region (joints 4 & 6), exhibited vertical displacements of 150-160 mm. Area I, encompassing the outer edges (joints 1 & 9), shows slightly greater vertical displacements of 155-165 mm. These patterns, highlighted by the colour gradient, illustrate how the structure deforms (vertically) and redistributes stresses across its geometry.



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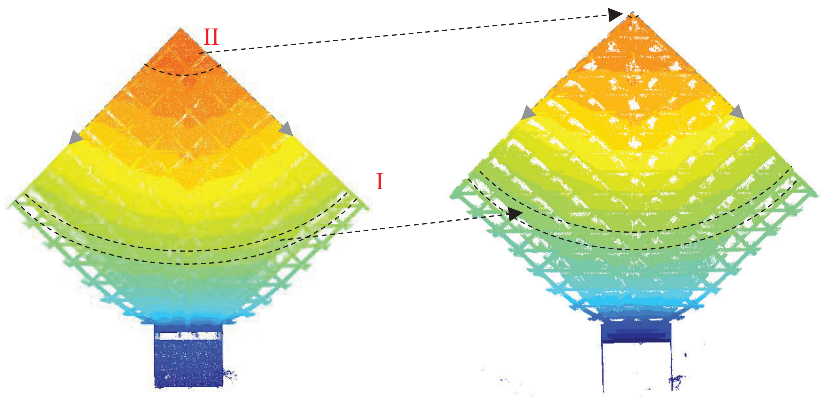

Figure 4.2. Colour-mapped elevation profiles comparing unloaded and loaded states (a) unloaded state; (b) 3-ton loading

The observed displacement distribution highlights the bamboo-timber composite gridshell's flexibility and effective load-sharing behaviour. Despite a self-weight of approximately 2.2 tons, the prototype (after 1.5 years of construction) safely withstood a 3.5-ton local area load without collapse, demonstrating its robust structural performance and effective load-sharing behaviour.

5 – CONCLUSION

This study demonstrates the feasibility of a novel bamboo-timber composite gridshell through a full-scale design-to-build approach. The structure employed active bending to form a doubly curved geometry without relying on prefabricated curved components, demonstrating both material efficiency and architectural versatility. Experimental load testing revealed a three-phase load-displacement response, including measurable residual deformations due to creep and stress relaxation-factors that should be considered in future design models. Laser scanning enabled a comprehensive assessment of global deformation under localised loading, providing insights into the structures' flexibility and load redistribution behaviour.

These findings provide a foundation for further research into sustainable, composite, and actively-bent spatial structures. The successful realisation and performance of the prototype highlight the potential of bamboo–timber gridshells as a viable solution for lightweight, adaptable, and resource-efficient architectural systems.

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