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Conformal 3D printing on bending-active formwork - exploring a new approach to the fabrication of wide-spanning structures

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Abstract
This study introduces a novel methodological framework that combines bending-active structures with conformal 3D printing to address current limitations in architectural-scale additive manufacturing. Traditional horizontal slicing and planar layer deposition present inherent constraints for fabricating large-span elements such as roofs and floor slabs, while conventional approaches to curved forms typically require resource-intensive formwork. We propose an integrated approach that utilizes bending-active structures as material-efficient substrates for 3D printing, potentially serving dual roles as both formwork and supplementary reinforcement. The methodology incorporates a multi-axis robotic platform alongside preliminary design, software, and hardware adaptations to enable material deposition that follows structural force vectors. Through initial experimental studies at various scales, we examine the fundamental aspects of this approach – including material testing, formwork registration, and toolpath adaptation – establishing a foundation for further exploration. This paper presents the conceptual framework and preliminary findings, while specific technical aspects such as toolpath generation algorithms and structural simulations are addressed in a companion paper. By introducing this methodology, we aim to contribute to the discourse on more sustainable fabrication techniques for wide-spanning architectural elements with reduced material consumption and environmental impact.

Keywords: bending-active structures, concrete gridshells, conformal 3D printing, elastic formwork, robotic fabrication, sustainable construction

1. Introduction
This research is positioned in the context of two critical global challenges: the worldwide housing crisis and construction's environmental impact. Forecasts predict that 1.6 billion people – over 20% of the world's population – lack access to affordable housing [1], while in the United States alone, between 3.8 and 7.2 million homes are needed to meet current demand. However, blindly building more housing isn't viable since buildings and building materials account for nearly 34% of global CO_2 emissions, with cement production alone accounting for 7% of all human-caused emissions globally [2] [3]. Industry decarbonization roadmaps emphasize that improving material efficiency can significantly reduce emissions from concrete construction [4], yet current adoption remains limited due to expensive, iterative design processes.

Large-scale 3D printing is emerging as a crucial step towards minimizing CO_2 emissions by optimizing material use and reducing construction waste. Pioneering projects worldwide demonstrate this technology's potential, with companies like PERI and ICON printing residential buildings [Fig.1] [5], contributing to a rapidly growing market valued at USD 18.2 million in 2022 with projected growth rates exceeding 100% annually [6]. Most projects utilize 3-axis gantry systems, which offer scalability and precision but are limited to horizontal layer deposition with minimal overhang, constraining applications to vertical walls. Essential building elements like foundations and roofs typically require conventional construction methods due to their large spans, often making them the most expensive project components. These limitations raise the question: Can roof structures and floor systems be manufactured using the same cost-effective and material-efficient 3D printing technology?

Figure 1: Current 3D printing approaches in construction, limited to vertical elements and requiring conventional methods for roofs and spanning structures [5].

2. Proposed fabrication method - conformal 3D printing on bending-active formwork

To address current 3D printing limitations, this study explores combining bending-active formwork with conformal 3D printing for manufacturing roof and floor structures. This method aims to expand large-scale 3D printing capabilities while maintaining additive manufacturing's environmental and economic benefits.

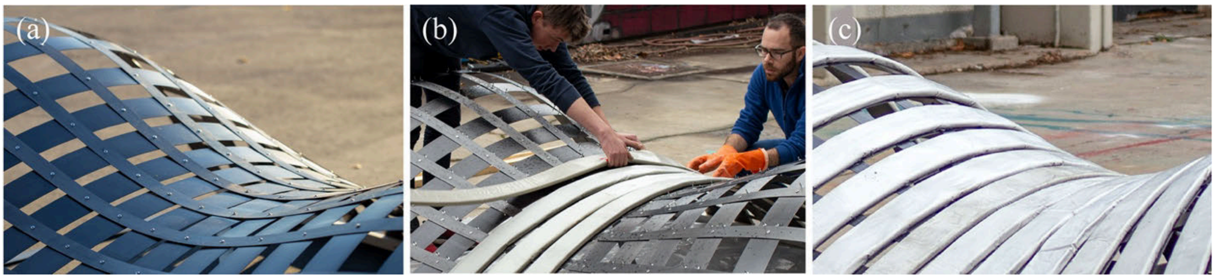

Figure 2: Bending-active formwork approach showing (a) elastically deformed 1.2 mm CFRP strips and (b) conformal concrete application resulting in hybrid structural system [13].

2.1. Bending-active formwork

Current architectural-scale 3D printing with viscoplastic materials relies on slicing elements into planar layers with predefined heights and thicknesses, typically producing vertical elements like walls and columns with minimal overhang (17.5° from vertical or less [7]) due to large part sizes, high material viscosity, and extended curing times. Printing inclined surfaces results in stair-stepping effects, while larger cantilevered spans often cause material collapse under self-weight, challenges that traditional concrete construction addresses using supporting scaffolding and formwork as temporary molds. Although formwork in concrete construction has been extensively studied, limited research exists combining formwork with large-scale 3D printing, with previous studies primarily examining temporary formwork using soil, meshes, or textiles [8] [9] [10]. This study proposes using bending-active structures as formwork for conformal 3D printing, utilizing large elastic deformations of originally straight elements to construct complex curved load-bearing geometries [11]. A distinctive advantage is that the bending-active formwork can either be removed after concrete curing or retained to serve dual roles as both formwork and supplementary reinforcement. Recent studies by Cuvillier et al. [12] and Schleicher and Herrmann [13] developed hybrid systems with bending-active formwork supporting concrete layers, demonstrating remarkable load resistance [Fig.2], with the important finding that as concrete cured, initial layers bonded with the formwork and reinforced the system, allowing more material to be added as the formwork became stiffer over time.

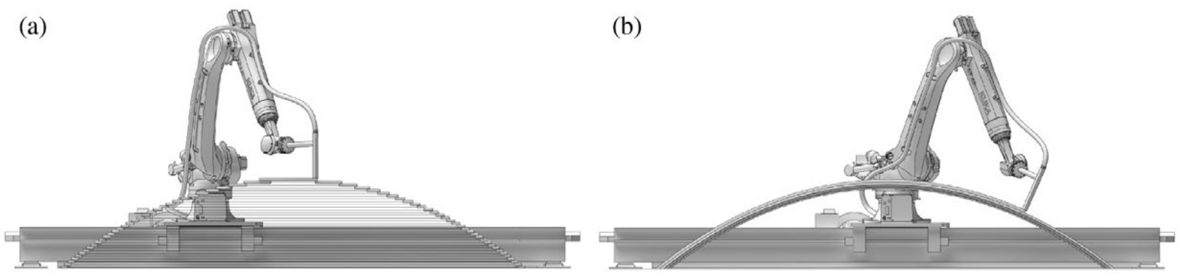

Figure 3: Comparison of (a) conventional planar 3D printing requiring support material and creating stair-stepping effects versus (b) proposed conformal 3D printing on bending-active formwork eliminating support material through multi-axis deposition.

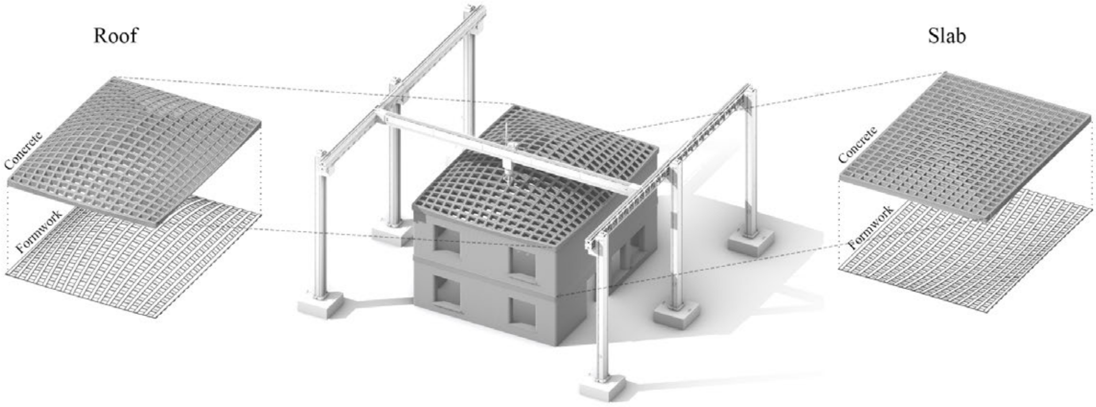

Figure 4: BarkBeetle toolpath examples showing continuous conformal printing on bending-active formwork for curved roof geometry and flat slab with curved bottom surface.

2.2. Conformal 3D printing

Conformal 3D printing represents a significant departure from traditional layer-based approaches. While conventional printing relies on horizontal slicing where z-coordinates remain constant within layers, conformal printing allows continuous z-axis changes, enabling non-planar toolpaths that conform to complex surfaces [14]. This addresses fundamental limitations including poor mechanical properties and surface finish from weak interlayer connections and stair-stepping effects [15]. In architectural-scale manufacturing, conformal 3D printing addresses constraints of traditional horizontal slicing for large-span elements. The unique advantage is that printed layers can directly follow curved formwork geometry without additional support material [Fig.3-4]. This alignment of material deposition with structural force vectors represents a fundamental shift from conventional approaches requiring resource-intensive formwork. Integration with bending-active formwork presents technical challenges requiring design, software, and hardware adaptations. Precise formwork registration demands accurate surface knowledge through reference point registration, robotic construction, or 3D scanning. This study employs a multi-axis robotic platform combining a six-axis industrial robot with linear motion track, creating a seven-axis system enabling precise nozzle alignment perpendicular to target surfaces for optimal print quality and material bonding.

3. Methodological framework and research goals

This research establishes a novel methodological framework that integrates bending-active structures with conformal 3D printing to overcome current limitations in architectural-scale additive manufacturing. The core innovation lies in utilizing elastically deformed structural elements as both fabrication substrates and potential reinforcement systems, enabling the production of wide-spanning elements that traditional layer-based printing cannot achieve. The methodological approach operates on three fundamental principles: bending-active structures serve as material-efficient formwork that can support concrete deposition while following complex curved geometries, conformal 3D printing enables non-planar material deposition that aligns with formwork geometry and structural force vectors, and multi-axis robotic platforms provide the necessary degrees of freedom to maintain perpendicular extrusion angles across complex surfaces. The integrated system addresses three primary technical challenges – material interaction, formwork registration, and toolpath adaptation – through experimental studies at various scales from material-level testing to larger prototypes. The research goals focus on establishing fundamental understanding and initial validation while identifying key technical challenges, material interaction behaviors, and workflow requirements to establish preliminary guidelines for formwork geometry, printing parameters, and material specifications. Through this exploratory work, we aim to chart new territory by documenting successful and unsuccessful implementation strategies, revealing critical areas requiring further investigation, and providing a foundation for future research teams to advance this approach toward sustainable, material-efficient construction of complex architectural elements.

4. Digital and physical prototyping

To validate the methodological framework and explore the feasibility of using bending-active formwork for conformal 3D printing of wide-spanning structures, we implemented a systematic three-tiered experimental approach through material tests, small-scale experiments, and full-scale prototyping to identify fundamental challenges, establish preliminary design guidelines, and develop a coherent workflow for architectural-scale applications.

4.1. Material tests

The first series investigated timber-concrete composite beams, building upon prior research on CFRP-concrete hybrid systems [16], evaluating the feasibility of using softwood elements as bending-active formwork for printing concrete layers. The composite system utilized fir timber as the primary tension element and Sikacrete-752 3D micro-concrete as the compression layer, bonded with Sikadur 32 Hi-Mod epoxy adhesive. Individual material characterization included tensile and bending tests on softwood specimens following ASTM D143-23 and compressive strength testing of 7-day concrete cylinders per ASTM C39/C39M-24. Composite beams were fabricated through both 3D printing and conventional casting, then tested under four-point bending. Test specimens comprised Group A (3D printed), Group B (cast concrete with 9-inch spans), and Group C (cast concrete with 18-inch spans). Group B specimens were designed using back-calculated section properties targeting 84.6 kN ultimate load capacity, while Group C used the same concrete thickness without additional recalculation. As a result, the Group C beams were not structurally optimized for their longer span and higher expected bending moments. However, this was intentional: the 18-inch specimens were included to explore the shear behavior of the composite system under increased span and load.

Material characterization revealed significant performance differences between fabrication methods. Timber testing showed average tensile strength of 63 MPa with elastic modulus ranging from 5,581 to 9,852 MPa. However, significant discrepancies emerged between cast and 3D printed specimens, with cast specimens achieving only 9 MPa compressive strength compared to 29.6 MPa for 3D printed specimens, suggesting material degradation due to concrete age differences.

Structural testing revealed unexpected failure modes across all specimens. Despite design intent for flexural failure, all composite beam specimens failed in diagonal shear through the concrete layer. Group A specimens achieved maximum loads of 28.7-35.8 kN, while Groups B and C exhibited lower capacities of 9.5-12.8 kN, both significantly below predicted capacity. Load-deflection responses demonstrated initial linear elastic behavior followed by sudden brittle failure, with diagonal cracks propagating at approximately 45-degree angles from supports toward loading points [Fig.5]. This failure pattern indicated insufficient concrete shear strength rather than interface failure, as epoxy bonds remained intact throughout testing.

The findings establish critical design considerations for future applications. The consistent shear failure mode revealed that while the adhesive interface maintained composite action effectively, the absence of mechanical shear connectors concentrated all shear resistance demands on the concrete alone, creating stress concentrations that initiated premature diagonal cracking. The successful epoxy bonding validates the composite concept, but enhanced shear resistance through mechanical connectors or increased concrete thickness is essential for achieving design capacity. The study highlights the importance of transitioning to 3D printing fabrication methods, which appear to improve material properties and construction precision compared to manual casting.

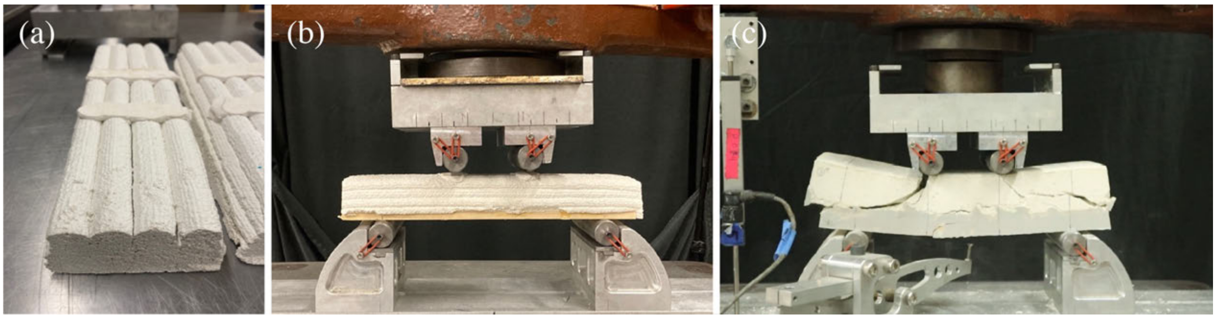

Figure 5: Flexural testing of hybrid timber-concrete specimens with (a,b) 3D printed concrete layers and (c) cast concrete layer, showing diagonal shear failure modes.

4.2. Small-scale experiments

The second series of studies built upon material test insights by introducing physical and digital experiments aimed at identifying key challenges, limitations, and opportunities for conformal 3D printing on bending-active formwork. Three progressive tests were conducted to explore basic printing scenarios. First, clay was printed on 30cm long, 1mm thin veneer strips to test fundamental toolpath designs and infill patterns [Fig.6a]. Second, concrete printing was scaled up to single plywood strips comprising two glued 3mm plywood layers (2000mm length, 100mm width) bent to different curvatures with midspan heights of 222mm, 305mm, and 375mm [Fig.6b]. Third, concrete was printed on three longitudinal plywood strips connected by six transverse elements, forming a simplified single-curved gridshell [Fig.6c]. All formwork was mounted on timber frames to maintain fixed support distances. For experiments two and three, concrete was 3D printed in two 15mm layers using Sikacrete-752 3D micro-cement with an IMER Small 50 mixer and pumping system, while a KUKA KR16-2 robotic arm controlled nozzle orientation to remain perpendicular to the curved formwork.

Figure 6: Small-scale conformal 3D printing experiments on bending-active formwork: (a) toolpath patterns on single strip, (b) concrete printing on single strips with varying curvature, and (c) multi-strip gridshell configuration.

Toolpath design and formwork registration were developed through a two-phase digital workflow. Initial curve creation used Rhinoceros 3D, Grasshopper, and our self-developed BarkBeetle software [17], a Grasshopper plugin for conformal 3D printing on bending-active formwork. The curved formwork strip geometries were digitally form-found using Rhino's Kangaroo Physics engine, while toolpaths and infill patterns for concrete 3D printing were generated in BarkBeetle. Accurate formwork registration followed through 3D scanning to capture the imperfect geometry of the physically constructed formwork. Our registration process involved attaching a touch probe to the extrusion nozzle and moving it to multiple locations on the formwork surface, using the collected data points to digitally reconstruct the formwork geometry and maintain constant distance between the nozzle and formwork during printing.

The printing process implementation required careful sequencing to manage formwork deflections. The process began with precise mixing of Sikacrete-752 3D micro-concrete with 18.5% water by weight. To optimize material deposition, strips were divided into four passes considering the 20mm nozzle width and 100mm strip widths, with print layer spacing established by offsetting toolpaths 30mm. Since the thin formwork was particularly susceptible to deflections from asymmetric loading during initial stages of material deposition, we implemented a sequenced 3D printing approach, starting with the center strip followed by adjacent strips from both sides to ensure even weight distribution and mitigate buckling risks. Calibrations for all prototypes proved successful, as evidenced by uniform distance between nozzle and formwork throughout printing, proper material adhesion, and consistent width of print paths and layers.

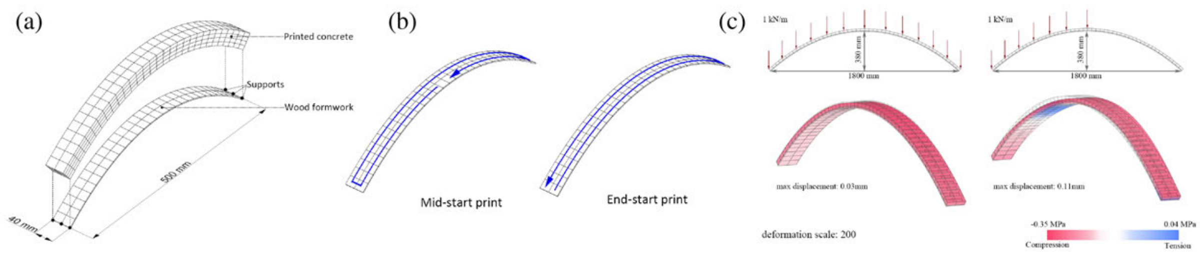

Figure 7: Digital simulation analysis showing (a) mesh representation of hybrid strip, (b) printing sequence scenarios comparing end-start and mid-start approaches, and (c) stress analysis under symmetric and asymmetric loading conditions.

Digital simulations supplemented the physical experiments to validate the observations on structural performance and are described in more detail in a companion paper [18]. Using Alpaca4D, which integrates OpenSees finite element software within Grasshopper [Fig.7], distinct material properties were assigned to both the timber formwork and printed concrete layers while representing the physical bonding between components. The simulations revealed that formwork is particularly susceptible to early-stage deflections when concrete is deposited asymmetrically and cannot yet contribute structurally, requiring fine-tuned print path sequencing and strategic printing pauses. The composite performance analysis generally confirmed the hypothesis that timber formwork can be used to handle tension while concrete manages compression, though performance depends on deflection direction, with detailed computational insights presented in our companion structural simulation paper.

Key findings confirmed the feasibility of the fabrication method while identifying areas for improvement. These tests validated the effectiveness of achieving hybrid composite structures through concrete 3D printing on bending-active formwork. However, several challenges emerged requiring further development. The formwork registration process, while effective, proved time-consuming with numerous steps that may compound with more complex geometries. Toolpath generation for intersecting cross-members was initially cumbersome, becoming streamlined only through development of our custom BarkBeetle plugin. The critical finding from earlier material tests that diagonal shear stress represents a crucial failure mode for these composite cross-sections is not yet adequately integrated into the current design and analysis process. Future work should focus on developing more efficient registration methods to scale this approach, optimizing strip patterns and toolpath generation for complex geometries, and conducting comprehensive cross-sectional investigations to better address typical failure modes.

4.3. Full-scale experiment

Our third series of experiments validated fabrication methods, material behavior, and structural performance at the target scale of architectural interventions such as building roofs and floors. This test aimed to address the previously identified need for improved registration methods and optimized strip patterns and toolpath generation for complex geometries. Building upon previous investigations using parameter sensitivity analysis of hybrid gridshells with bending-active formwork to optimize designs through target shape geometry and varying strip pattern arrangements [19], this experiment focused on applying this knowledge to fabricate a full-scale wide-spanning structure, enabling assessment of practical feasibility and identification of proof-of-concept challenges.

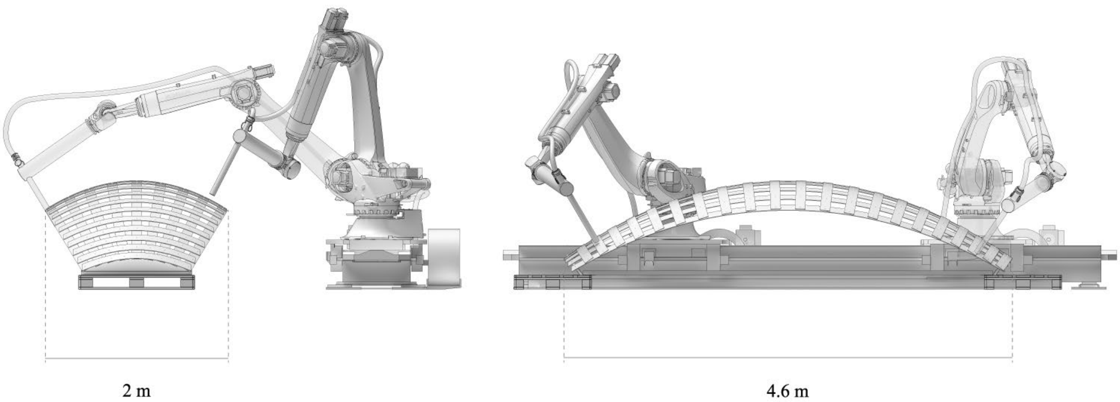

Figure 8: Seven-axis robotic system combining six-axis industrial robot with linear track, enabling comprehensive reach and perpendicular nozzle alignment to bending-active formwork surfaces.

The experimental setup applied the developed method to a full-scale prototype, constructing a wide-span hybrid gridshell measuring 4.6m in length and 2m in width [Fig.8]. To elevate the gridshell and facilitate mobility, it was placed on two timber EURO-pallets fitted with custom-made bulkheads designed to accommodate the timber strips and provide structural support. Given that this scale exceeded the capabilities of our previous robotic and pumping equipment, the research team partnered with

Print4D to utilize their facilities in Prague. Their setup included a larger KUKA KR 210 R3100 robot on a linear track (KUKA KL 1500/3), significantly increasing the 3D printing platform's reach, and an upgraded pumping system (MAI Multimix) that enabled improved print quality and higher volumes using Sikacrete®-752 3D material. The bending-active formwork comprised nine longitudinal spruce strips (100mm wide, 15mm thick) and 22 transverse plywood strips (100mm wide, 6mm thick).

Toolpath design for the complex gridshell utilized our refined BarkBeetle plugin for conformal 3D printing on bending-active formwork, as detailed in a companion paper. This method utilizes user-defined linear networks derived from formwork strip intersection points, which are converted into skeleton graphs representing the printing structure with continuous, non-intersecting paths ensuring process continuity [Fig.9]. The plugin generates multiple printing layers using conformal stacking methods that eliminate stair-stepping effects on curved surfaces while offering various approaches for material deposition control. For the fabrication of this full-scale prototype, the team used a spiral skeleton graph with offset stacking and constant layer heights, demonstrating the system's capability to handle complex geometries while maintaining optimal printing parameters.

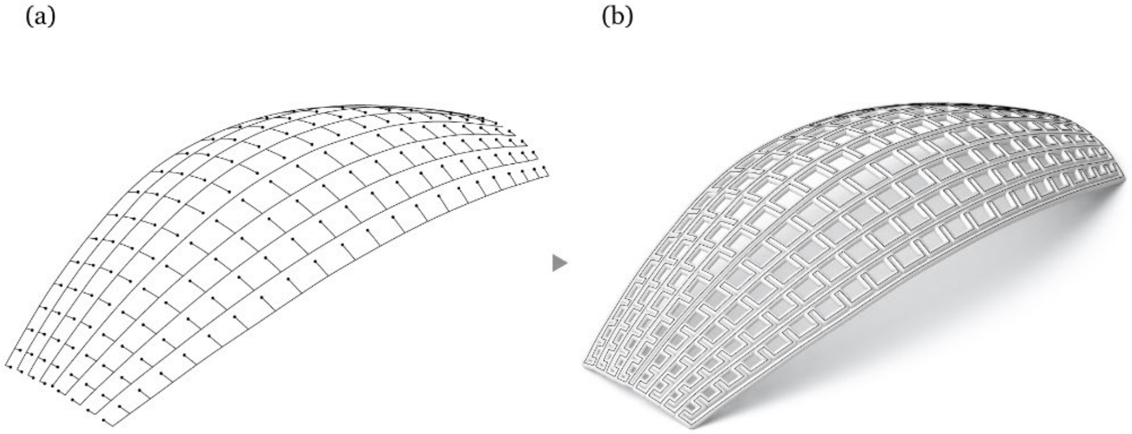

Figure 9: Toolpath design process: (a) skeleton graph generation from strip iso-curves and (b) conversion to multi-layer toolpath with user-defined widths and resolved member intersections.

Formwork registration methods were explored through two alternative approaches to address upscaling challenges. The 3D scanning method employed an Einscan HX handheld scanner combining LED light with blue laser, whose compact size and portability made it suitable for large objects. The resulting 3D scan proved exceptionally accurate and reliable, enabling successful toolpath projection and execution during printing, though the process involved time-consuming steps from initial preparation to importing the mesh into the toolpath design software environment. The second method utilized vision-based position estimation using ArUco markers as reference points [Fig.10-11]. A ZED 2 stereo camera with Inertial Measurement Unit (IMU) was attached to the robot arm, enabling real-time tracking of camera position and orientation in 3D space as it traversed the formwork. While this method occasionally produced duplicate points or inaccuracies due to poor ambient conditions, it proved sufficient for recreating the strip-based formwork surface geometry.

Figure 10: Completed bending-active formwork with 9 longitudinal and 22 transverse timber strips.

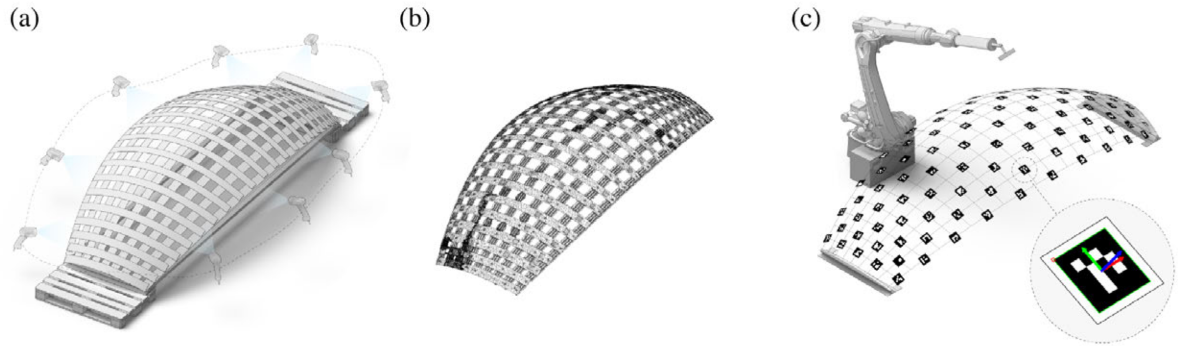

Figure 11: Formwork registration methods: (a) 3D scanning with portable scanner, (b) resulting point cloud and processed mesh for toolpath projection, and (c) vision-based registration using ZED 2 stereo camera with ArUco markers for real-time position tracking.

The printing process encountered critical challenges that provided valuable insights into full-scale implementation requirements. Following formwork registration, the robotic toolpath was projected onto the substrate surface for conformal 3D printing. The MAI concrete pump was initiated, mixing Sikacrete®-752 3D material with high consistency throughout the entire printing duration. The toolpath was designed to apply five consecutive layers of concrete, with each layer strategically sequenced to maintain balanced loading across the formwork structure [Fig.12]. However, the fabrication encountered a critical failure after the third layer when the bolts securing the formwork strips to the bulkhead experienced excessive stress and tore out. This connection failure caused the support conditions to change dramatically, leading to the gridshell formwork's structural collapse under the accumulated concrete load. Despite this setback, the experiment provided valuable insights into load-bearing capacity, as the formwork successfully supported approximately 500 kg of concrete before failure – a significant load considering the material had not yet fully cured.

Figure 12: Conformal 3D printing process showing multi-axis platform maintaining perpendicular nozzle orientation for uniform concrete distribution, creating hybrid gridshell structure for wide-span construction.

Structural analysis conducted after the physical experiment validated our observations and revealed critical design insights that could have prevented the failure. We conducted finite element analysis using Alpaca4D with layered quadrilateral mesh voxels representing both the printed concrete (50mm thickness) and wood formwork (8mm plywood). A uniform vertical surface load of 1 kN/m² was applied across the printed shell to simulate typical roof loading conditions. The analysis of our nine longitudinal strip configuration revealed significant stress concentrations in the central region, with tensile stress in concrete reaching 6.22 MPa and compressive stress in wood reaching 14.4 MPa – both exceeding typical material capacities. This excessive stress concentration resulted from the odd number of strips creating symmetric load accumulation in the middle strip, directly explaining our physical observations of critical loading conditions that led to the connection failure during printing. When we digitally modified the geometry to eight longitudinal strips, force distribution became dramatically more uniform and eliminated the problematic central stress concentration, maintaining both materials within their respective capacity limits [Fig.13]. This computational analysis revealed that using an even number of strips would have prevented the central load accumulation that caused the connection failure, demonstrating how digital analysis can inform design decisions to avoid structural collapse. The combined experimental and computational results establish a foundation for advancing this fabrication methodology toward practical architectural applications while highlighting the critical importance of strip configuration in preventing failure modes.

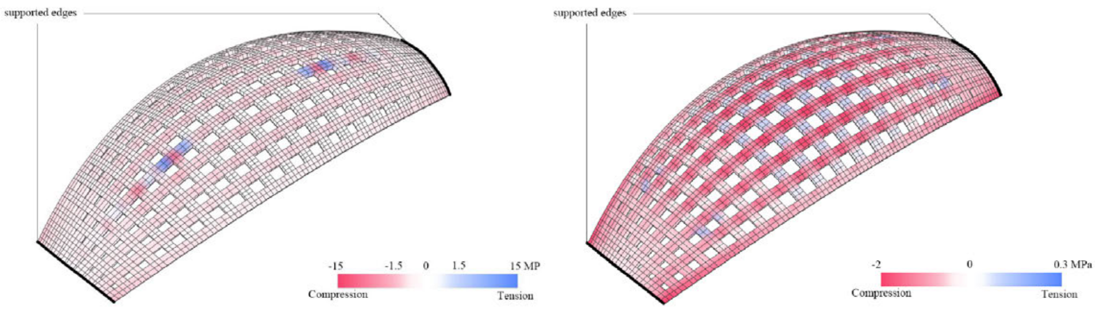

Figure 13: Structural analysis comparing stress concentrations in gridshells with odd (left) versus even (right) numbers of longitudinal strips.

5. Discussion and future research

This research introduces conformal 3D printing on bending-active formwork for architectural-scale additive manufacturing, offering potential to reduce construction waste while enabling long-span roof structures. Our investigation progressed from material characterization through small-scale prototyping to full-scale implementation, revealing diagonal shear failure modes in timber-concrete composites and verifying feasibility while identifying challenges in formwork registration and toolpath planning, leading to development of our BarkBeetle plugin detailed in a companion paper. The full-scale prototype demonstrated connection design challenges – while failing after the third layer due to inadequate fastening, the formwork supported 500 kg of concrete, validating the structural concept. The proposed method offers promising applications in both prefabrication and on-site construction processes, enabling off-site manufacturing of modular structures under controlled factory conditions or on-site responses to unique site constraints while leveraging enhanced quality control and reduced material transportation costs. The methodology's versatility allows integration of functional and structural elements, as envisioned for our planned technology demonstrator [Fig.14], where the hybrid gridshell combines structural and functional performance. Future research must address robust connection details, optimized print sequencing, comprehensive structural testing, and quantitative assessment of material efficiency gains for validating this approach's practical viability in architectural applications.

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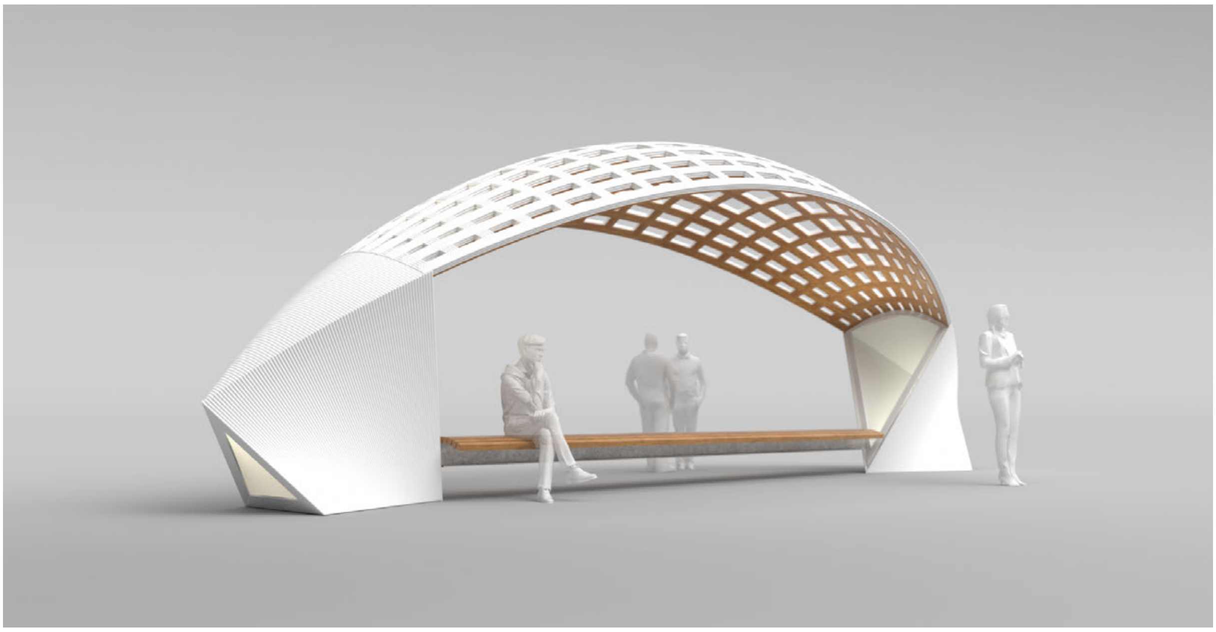

Figure 14: Planned technology demonstrator integrating structural and functional elements.

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