Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Robotic prototyping for lightweight façade components

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Abstract

Nonstandard building geometries are typically constructed using customized solutions that generate a significant amount of material waste. However, the exterior of these buildings does not always serve as a structural or functional purpose. Recognizing this inefficiency, this research introduced an iterative process of fabricating a customized module and joint system for load-responsive building components designed for stressed skins. This approach aims to optimize material usage while maintaining the structural integrity and aesthetic appeal of the building. The research outlined the potential of physical prototyping in an iterative, dynamic integrated workflow between design, to fabrication. In this research, Robotic Incremental Sheet Forming (RISF) was employed with a Universal Robot (UR) 10 as the fabrication technique, with aluminium sheets serving as the material for the fabrication of components. This paper discussed the sheet metal-formed components and the 3D-printed joint system, which facilitated the efficient utilization of materials in fabricating customized parts for a nonstandard shell structure.

Keywords: Robotic Incremental Sheet forming, Prototyping, Stressed Skins, lightweight structure, Joint design, customization

1. Introduction

The relationship between architecture and technology is evolving into a mutually dependent symbiotic relation. The emergence of computational design tools is reshaping the design and fabrication process, fostering collaboration between humans, computers, and robots. The role of computational design tools has changed from how things look to how things behave [1]. In this dynamic interaction, designers make decisions based on evaluations from computational models, while robots, serving as fabrication agents, transform digital models into physical parts, creating a synergy between these phases. However, there are opportunities for further integration of these capabilities into design-to-fabrication workflows, particularly through the incorporation of material properties into robotic fabrication. The main challenge associated with computational design tools is a lack of through materialization. Even though material properties are incorporated into the structural evaluation, they cannot be fully simulated in the digital model [2]. The physical prototype functions as a model representing the geometrical structure and material properties [3]. Prototyping plays a crucial role in connecting the physical and digital realms. Forming parts provides researchers with valuable insights into the physical aspects of the design, enabling evaluation and updates. In this research, prototyping process of stressed skin panels improved the performance and aesthetics of components and joints.

Employing robots for prototyping processes streamlines the parametric design workflow by integrating computational models of generation and manufacturing into a paperless process. [4] This integrated workflow incorporates the knowledge produced during the process of designing, developing [5] and prototyping. The objective of this study was to comprehensively analyse the properties of the materials, determine the robot's capacity to create complex geometries with different material stiffnesses, and establish the maximum depth achievable during the forming process. The iterative process of prototyping played a crucial role in enhancing performance of both components and joints designs, as well as the assembly process, thereby making a significant contribution to the overall development of design and fabrication of stressed skins.

2. Background

Cold metal forming creates plastic deformations that result in a reduction in material thickness and an enhancement in strength, leading to significant advancements in the domain of lightweight stressed skins. Robotic Incrementally Sheet Forming is widely used due to its ability to create complex geometries at high speed, without the need for intricate moulds or casts [6]. Existing studies have explored design and fabrication of building components such as stressed skins employing a combination of computation-based optimization methods and advancements in digital fabrication [6-9]. Stressed skin [6], Bridge too Far [10] and Copper Cladding [11] are some examples of the research conducted by Centre for Information Technology and Architecture (CITA) that investigated RISF for architectural application. Upon reviewing the research conducted to date, there has been a noticeable gap in exploring single-point incremental sheet forming (SPIF) without a supporting bed for ultra-thin aluminium sheets. Additionally, the design of joints for stressed skin shells, particularly using discrete components rather than traditional continuous inner and outer skins, has not been investigated. This modular approach aims to facilitate straightforward assembly and disassembly, a concept yet to be fully integrated into the RISF workflows.

This experimental research explored the potential use of UR 10 for fabrication of material-efficient customised façade modules in different scenarios. These scenarios involved testing different materials (such as aluminium with thickness of 0.3 mm, 0.7 mm and steel 0.3 mm) and prototyping different joint systems (including folded steel plates, 3D printed linear faceted, and 3D printed triaxial faceted nodes).

In previous study, "DIATOMA - A Biomimetic Fabrication-Aware Lightweight Pavilion" [12] biomimetic design of a multi-component, load-responsive structure developed for Robotic incremental Sheet Forming (RISF) was elaborated. The design workflow enabled the comprehension of the correlation between the values and the relevant parameters, facilitating modification and calculation of the optimal settings for a lightweight structure. A computational design framework was utilized at the digital materiality level to facilitate the process of form finding for lightweight structures. This current research extends the previous work by evaluating the physical materiality through an iterative prototyping process. The study aims to bridge the gap between digital simulations and physical reality, ensuring that the designed structures perform as expected under real-world conditions. By integrating physical testing with computational modelling, this research provides a more comprehensive understanding of the material behaviour and structural performance of the designed pavilion.

3. Methodology

3.1. Digital prototyping

Digital Materiality is considered as digital processes of materialization that contribute to new types of digital tectonics [13]. Considering architecture solely as a surface disregards the exploration and examination of function, assembly and tectonics. Computational design tools that generate comprehensive digital models, do not easily enable designers to thoroughly examine assembly and tectonic issues [14].

In this research, the computational design process consisted of two main components: scripting a parametric workflow to define the desired solution and the iterative process of adjusting the parameters within the framework to explore different variations of designs. The refinement process updates the solution space in both the scripting code and the visual display at the same time [13].

The design workflow comprised of inputs and generative design algorithms. The computational design was developed in Rhino and Grasshopper environment, along with necessary plugins such as Octopus, Karamba, and Kangaroo. The design process was entirely computational allowing the designer to continuously monitor quantitative metrics such as deflection, span length, number of joints and components, size and depth of components, and weight, as well as qualitative aesthetic aspects of the design. The generative model enabled the understanding of the relationship between values and relevant parameters, facilitating the calculation of optimal settings.

The Diatoma structure was composed of 34 pairs of components to span 1.5 meters. The design of the components consisted of two bilateral convex halves, with their bespoke form determined by the load distribution across its discretized shell. The undulation of the components' surfaces was influenced by their proximity to the load paths, causing regions closer to these paths to experience greater displacement in the intended direction. After developing several digital prototypes, the next step involved transitioning to physical prototyping (Figure 1).

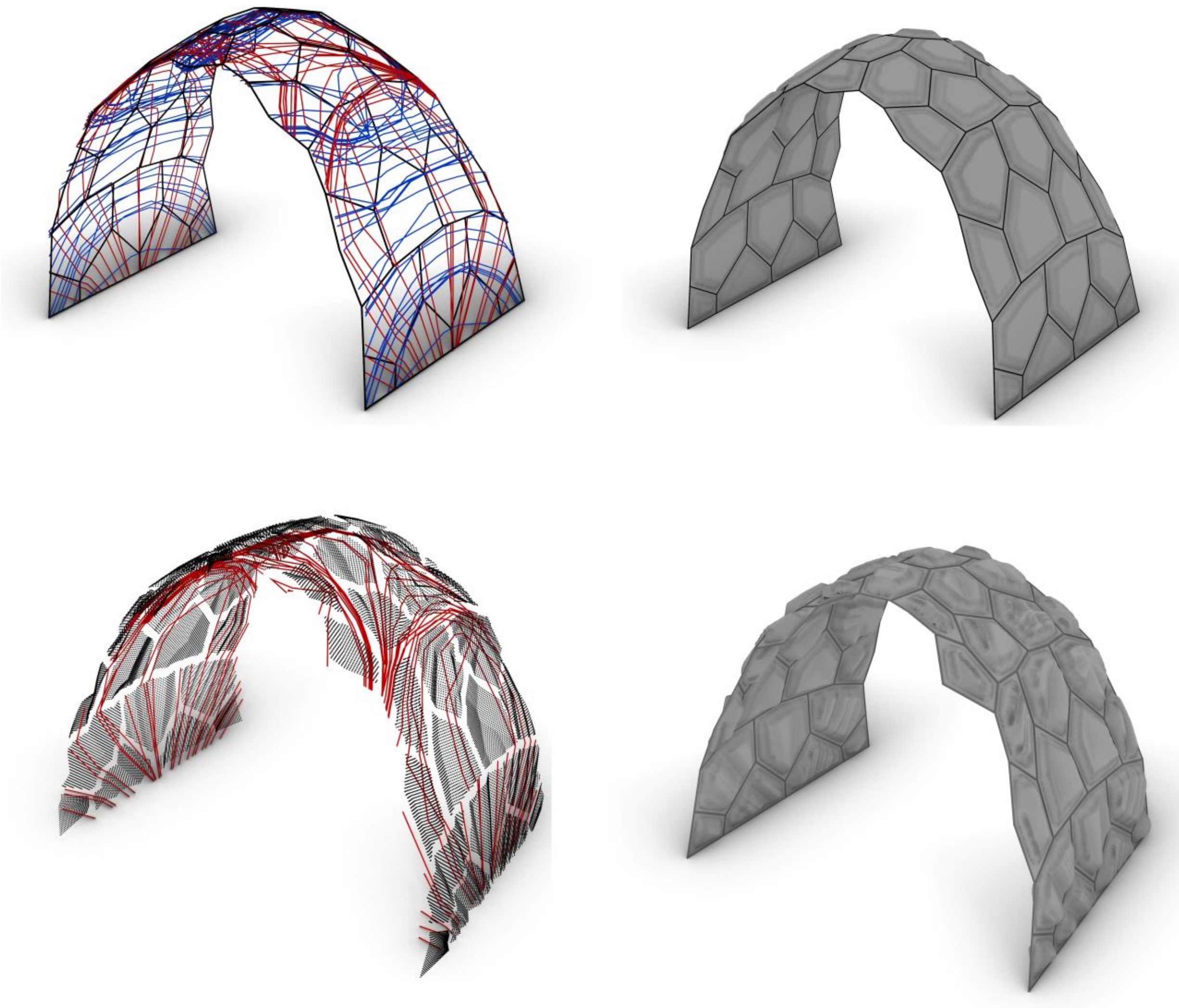

Figure 1 Components form generated based on the density and the location of load paths

3.2. Physical prototyping

3.2.1. Components

A UR 10 with a 4mm dapping punch tooltip was utilized for RISF of aluminium parts. Due to the pressure-based shaping process, a setup was necessary to firmly hold the aluminium sheets in place during robotic formation. To provide support against the applied pressure during the forming process, a table like frame was utilized (Figure 2). The aluminium sheet was cut to the required lengths, and then the sheets were affixed to the table-like frame using two clamps and two strips of timber on each side, totalling eight strips and clamps altogether. These strips of timber securely sandwiched the edges of the aluminium sheet, fastening it to the frame underneath with the clamps.

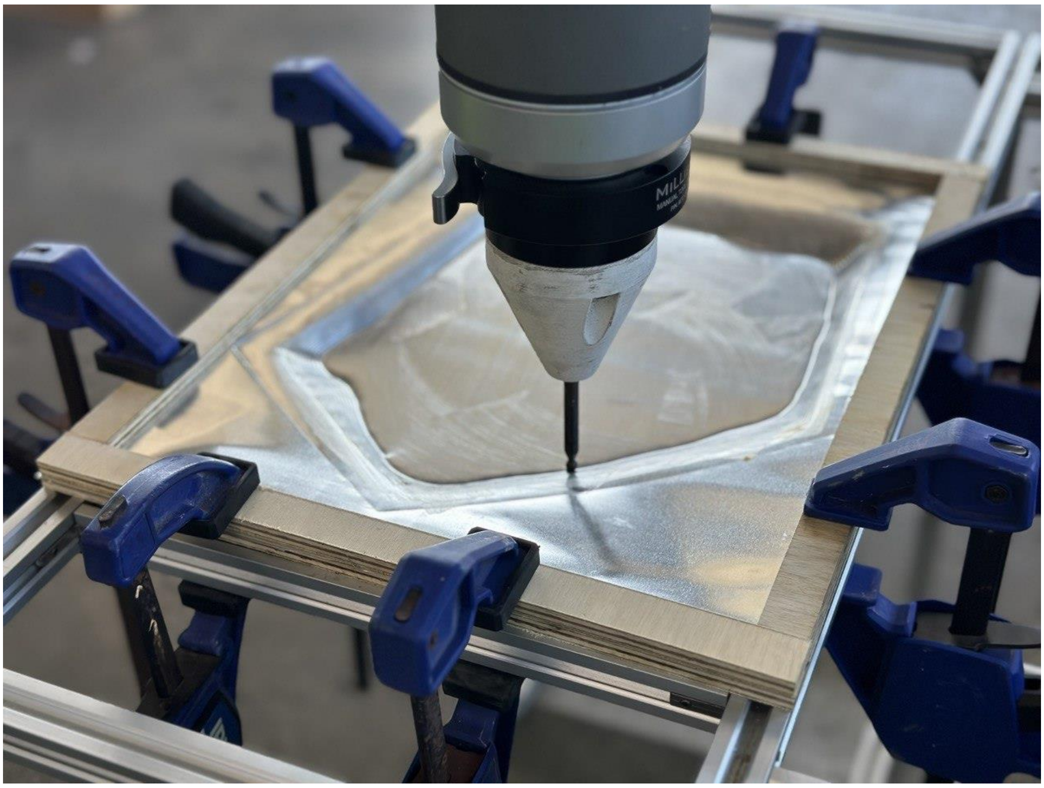

Figure 2 RISF Setup

For the RISF process, the digital models of the components were contoured in Grasshopper to create toolpaths for the robot. The prototyping of components commenced with the formation of several initial pieces to evaluate the suitability of a 0.3 mm thick aluminium sheet for forming different geometries with varying depths (Figure 3). Although the complex forms were produced without difficulty, the ultrathin material bent easily during transportation and cutting, leading to undesired deformations in some parts. Consequently, a second test was conducted using a thicker aluminium sheet with a 0.7 mm thickness.

Figure 3 forming 3 sets of components with aluminium 0.3mm

The robot's capacity was exceeded by the pressure required to form the thicker aluminium sheets. To address this, the number of robot paths was doubled, reducing the tween distance and allowing for a more gradual forming process. While this solution effectively mitigated the pressure issue for shallow parts, it proved ineffective for parts with more depth. Additionally, this approach resulted in doubling the duration of the forming process (Figure 4).

Figure 4 Unsuccessful tests for geometries with steep inclines using 0.7 mm aluminium

The thickness of thin aluminium sheets was limited to either 0.3 or 0.7 mm. To test a more rigid material than aluminium 0.3 mm, steel with a thickness of 0.3 mm, was selected for another test. The same geometry was selected for forming to enable a direct comparison between the different approaches. However, in this test, the low formability of steel, compared to aluminium, became evident. The robot encountered difficulties and halted in the forming process, resulting in unsuccessful forming of the parts (Figure 5). Subsequently, the prototyping was continued with the 0.3 mm thickness sheets.

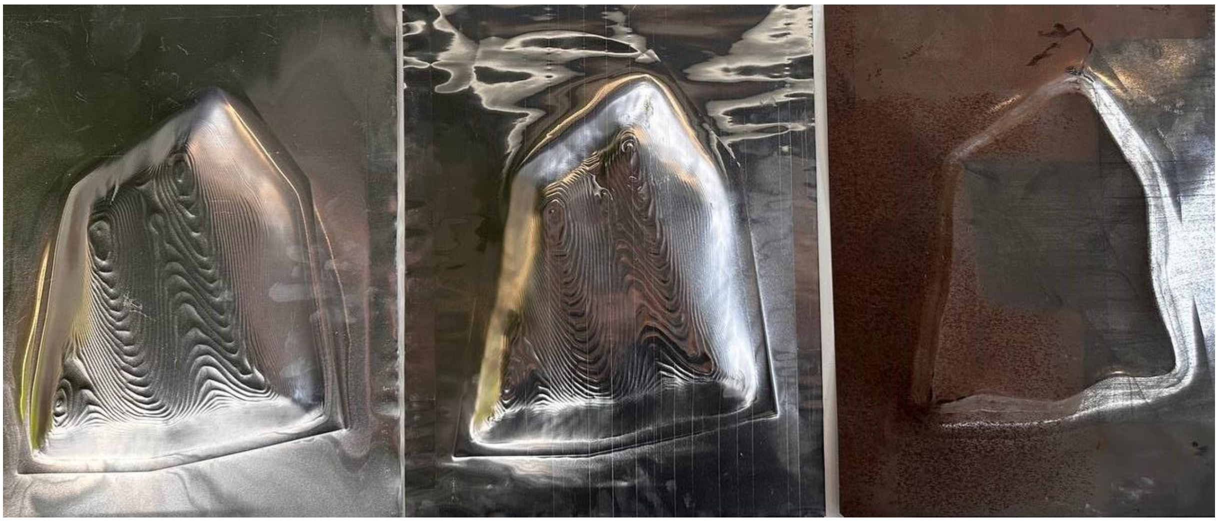

Figure 5 11 forming same geometry with A) aluminium 0.3, B) aluminium 0.7 mm, C) steel 0.3 mm

3.2.2. Joints

A crucial step in fabricating the structure was to evaluate how the formed components would be connected. The components were comprised of two symmetrical convex halves, each with irregular hexagonal perimeters and flat edges. The two halves were joined by aligning their flat edges and fastening them together. Given that the components at the edges are flat, the positioning of joints became a critical consideration for enhancing structural integrity of the overall shell structure. Moreover, the design accounted for a high number of components, emphasizing the significance of joint design not only for structural robustness but also for facilitating ease of assembly and disassembly. To rigorously evaluate joint effectiveness, four distinct types of joints underwent physical testing. With each test iteration, the designer refined the digital model, implementing necessary adjustments based on observed outcomes. The rationale behind the joint design was to accommodate various arrangements and configurations of components and facilitate connections between the upper and lower parts of each component, as well as between adjacent components.

The first type of joints utilized bent steel straps, with each joint custom-designed to match the size and orientation of its corresponding component. These joints served to connect the edges of neighbouring components. The length of each joint was tailored to match its corresponding edge, while the width was standardized at 1.5 cm, consistent with the width of the flat edges of the components.

The geometry of the joints and the bending angles were determined based on the digital model. Three specific joints were selected, unrolled from the model, and then cut using a guillotine. Following this, they were bent using a Hydraulic Panbrake machine. The angles of the bent parts were subsequently measured using an angle-measuring calliper to compare them with the angles predicted by the model. Due to the spring back of the material and the small degrees of the angles (< 2°), the results were not accurate. The entire process, including cutting, bending, and drilling holes in the parts, required intensive manual labour (Figure 6).

Following the evaluation of the first series of prototypes, the design of the second series of joints was initiated. To enhance precision and speed in fabrication, the joints were 3D printed. The geometry remained largely unchanged, except for the addition of a third side to increase the thickness and create a flatbed for 3D printing. This series featured joints with a triangular section that were 3D printed using PLA Filament, 1.75mm, with the Luzbot PRO S (Figure 6).

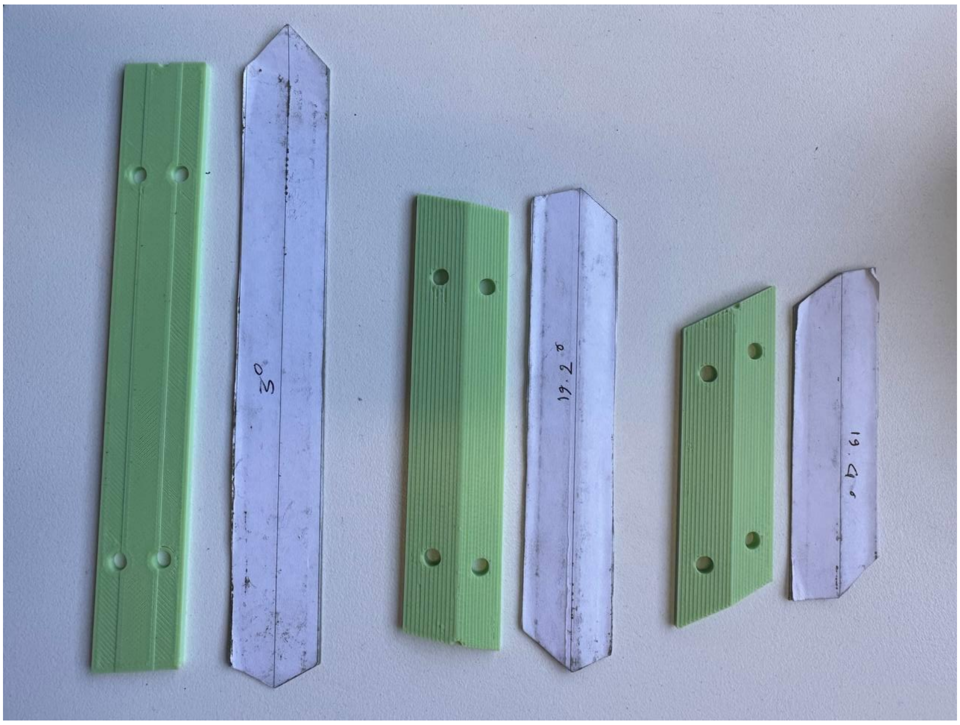

Figure 6 First and second joints prototype; Same joints using bent steel and 3D printed with holes

In the second series, the joints were configured to connect only two neighbouring sides. While these joints successfully connected the components, the need to enhance structural integrity and sturdiness necessitated refinements in the connection system. Additionally, it was identified that the use of 5mm screws significantly increased the weight of the structures during assembly. Consequently, in the third iteration, the joints were further refined to connect three adjacent components using 3mm screws.

The joints were designed in a radial triaxial node configuration and positioned at the nodes of the components and their axes were aligned with the edges of the components. The design incorporated multiple facets to accommodate different orientations and arrangements, with each facet aligning with the tilt of the components on its respective side. Functionally, each joint linked three adjacent components while securing the upper and lower parts together using six screws on each connection. The joints were fabricated using 3D printing technology, specifically employing silver PLA-Silk Filament with a diameter of 1.75mm on the Luzbot PRO S printer (Figure 7). Initially, some parts were printed as solid structures, but they proved to be excessively heavy. To address this, the subsequent series utilized a reduced infill pattern (Grid infill type at 20% density), which resulted in lighter components while still maintaining adequate rigidity.

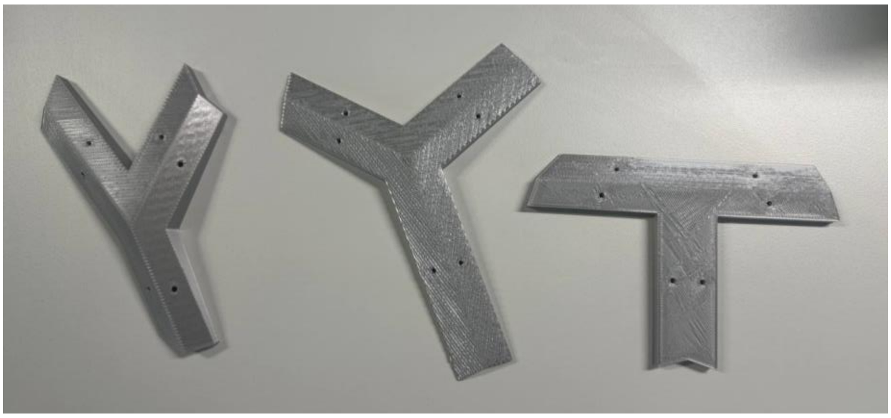

Figure 7 radial triaxial node

The third iteration proved functionally sound, but the joints appeared rigid with sharp corners, contrasting with the organic form of the components. To improve aesthetics and functionality, the joints were made slimmer, and the corners were filleted. They were 3D printed using the Bambu Lab X1 printer with Silver PLA-Silk material and a reduced Grid infill at 15% density (Figure 8).

Figure 8 Filleted radial triaxial node

4. Discussion

This research showcases the potential of integration of computational design and fabrication through prototyping. The combination of digital model and robotic fabrication setup has resulted in the examination of specific physical aspects that cannot be completely replicated in the digital realm. This, in turn, influenced the design process. The seamless transition between design and fabrication, which arises as a solution to limitations encountered during the physical model-making process, represents an opportunity afforded by the iterative hybrid process involving human, computer, and robotic elements. Developing prototypes with a combination of direct modelling and scripting methods, analytical tools and robotic simulation, leads to advanced knowledge generated in the process (Figure 9).

Figure 9 3 images of components connected to each other using joints from below and top

The iterative process of prototyping, evaluating, and updating parameters facilitated comprehensive improvements in detailed design, fabrication, and assembly strategies as a cohesive whole, rather than fragmented developments in each aspect. It also enabled the researcher to investigate issues of assembly and fabrication and resulting in design and fabrication of innovative and material efficient structures with aesthetic qualities. As proof of concept, Diatoma Pavilion were fabricated in ½ scale covering span of 1.5 meters with the developed joint system, demonstrating sound design and fabrication of the parts (Figure 10). Further research needs to be conducted with robots that have higher payload capacity to enable the fabrication of thicker sheet metals. The use of computational design tools and robots in structural design and material deployment presents an opportunity to push the boundaries of construction and address environmental challenges. Fabricating cladding structures are not only innovative in form but also efficient in their use of materials.

Figure 10 Diatoma Pavilion

Acknowledgements

This research is supported by Queensland University of Technology and Building 4.0 CRC. The support of the Commonwealth of Australia through the Cooperative Research Centre Program is acknowledged.

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