Compound Robotic Approaches to Contactless Incremental Thermoforming and FGF Additive Manufacturing

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Abstract. Thermoplastic surface cladding panels are widely used in building construction for exterior envelopes and interior walls and ceilings due to their transparency and ease of forming into diverse shapes only millimetres in thickness. Their ability to span and hold shape is achieved through profiling and internal support structures – possibilities closely tied to manufacturing methods such as die-cast extrusion, injection molding and vacuum forming that use a mold or die that involves time and material costs. Due to this, such methods are typically employed for the mass production of identical parts. Designs that involve geometric variation across multiple assembled thermoplastic panels are challenging to realize within competitive time and cost constraints. While robotic methods like incremental forming can variably shape thermoplastic sheets and Fused Granulate Additive Manufacturing (FGF-AM) supports the fabrication of variable volumetric parts, neither approach can replicate the benefits of traditional methods in rapidly producing thin-shell panels with integrated internal ribbing or lattice structures. This research introduces a custom robotic manufacturing process for thermoplastic surface panels, that combines a Contactless Incremental Thermoforming (CIT) method with FGF-AM to produce variably curved surfaces with integrated ridging and interior support structures. Conformal FGF-AM is investigated as a means to both augment the CIT process, and to create three-dimensional spatial lattices bonded with formed PETG sheets. CIT and its combined use with FGF-AM is demonstrated to produce geometrically variable parts without the use of molds. A series of parts are manufactured to evaluate the formative capabilities of the approach, the capacity to enhance a PETG sheet's structural stiffness, and correlated aesthetic possibilities.

Keywords.
Robotic Fabrication, Additive Manufacturing, Incremental Forming, Thermoplastics, PETG.

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1 Introduction

Over the past century, over a hundred plastics have been utilized in building construction, with recyclable thermoplastics playing a key role. Thermoplastics like polycarbonate are commonly used as surface panels on roofs and facades, and for interior wall and ceiling applications, due to their transparency, impact strength. They can be treated for fire and UV resistance and are easily formed into diverse shapes. Their structural capacity is enhanced through profiling and internal support structures, enabled by various manufacturing methods. For instance, panel stiffness can be improved by corrugating sheets via thermoforming or by creating twin-walled profiles with internal ribs through die-extrusion manufacturing. Increasing a panel's spanning capabilities can lead to larger-sized panels and a reduction in steelwork in subframes required to support panels. Beyond sheets, complex extruded profiles are used in window framing and roof eaves, though these methods typically produce straight extrusions, limiting variability. Vacuum forming and injection molding offer more formal variation, but require costly, one-off molds, making them less viable for large-scale, geometrically diverse projects that might consist of hundreds or thousands of panels.

Several robotic thermoplastic manufacturing approaches offer part variability, but they often fall short in producing complex parts with the material efficiency and speed of industrial methods. Additionally, few studies explore how robotic processes can create surface panels with integrated ribbing or spatial lattice reinforcement to enhance stiffness. This research introduces a custom-developed compound robotic manufacturing process for PETG thermoplastic, capable of producing complex surfaces and internal structures that can be rapidly manufactured without molds. The research investigates the feasibility of variations of the method to form different geometrical conditions that are aesthetically diverse while also capable of increasing the structural stiffness of a thermoplastic part. A custom robotic process for PETG thermoplastic was developed that combines Contactless Incremental Thermoforming (CIT) with Fused Granulate Fabrication (FGF). This study explores 2D conformal FGF-AM before thermoforming to control surface characteristics, and 3D conformal FGF-AM after CIT to create hybridized surface and lattice structures for greater stiffness. Each method is evaluated for manufactured outcomes' material usage, structural performance, manufacturing time, and visual appeal, while demonstrating potential for architectural applications.

2 State-of-the-Art

The research presented in this paper contributes to the growing interest in robotically manufactured plastics within architecture. Over the past decade, there have been limited examples of Thermoplastic Fused Granulate Fabrication Additive Manufacturing (FGF-AM) used for building envelopes and walls in both research[1] and practice.[2,3] FGF-AM offers a zero-waste solution for variably formed 3D panels. However, despite its advantages, manufacturing times are considerably long—with one recent research example requiring 44 hours to manufacture a 1170 x 200 x 2270 mm hollow wall panel that varied in thickness from 8-50mm consisting of 44.5kg of material.[1] Exceptions demonstrating thinner parts exist for non-building applications, such as for precast concrete formwork.[4] While lighter, more intricate FGF-AM lattice structures have been achieved[5,6], they require even slower fabrication speeds to allow the material to cool and become self-supporting. In contrast, traditional thermoplastic sheets for similar building applications are thermoformed or die-extruded in seconds. However, these industrial methods rely on materially and economically costly, time-intensive molds,

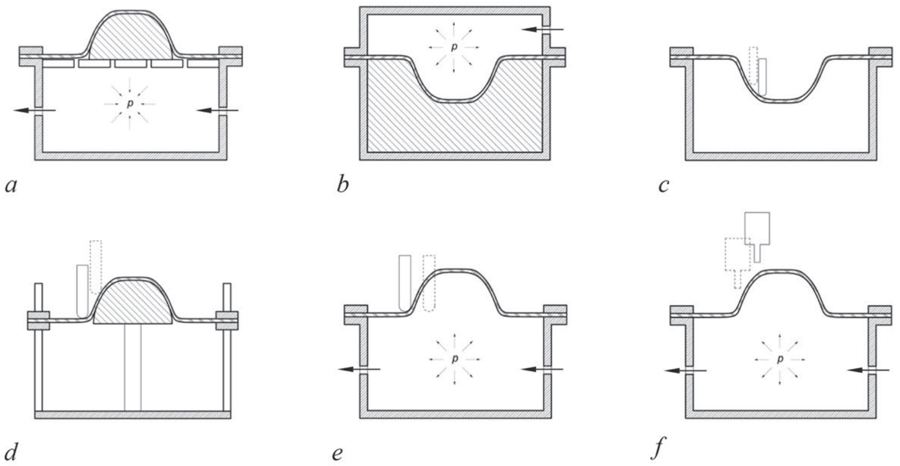


Fig. 1. Industry approaches to thermoplastic sheet forming include: a) vacuum forming, b) pressure forming, c) single point incremental forming, d) two point incremental forming, e)fluid filled active incremental forming, f) proposed approach: contactless incremental thermoforming (CIT).

limiting their suitability for geometrically variable production scenarios. This research aims to bridge these gaps by exploring faster and more versatile robotic methods.

Robotic single-point incremental forming (SPIF) allows for the variable shaping of thermoplastic and metal sheets by incrementally stretching the material through continuous pressure applied along concentric toolpath contours. This method has been widely explored in architectural research for applications such as architectural skins.[7,8] However, SPIF has limitations: parts with draft angles steeper than 60° risk tearing, and the incremental stretching process can reduce the sheet's clarity and transparency unless the stepover between toolpath contours is minimized. Reducing the stepover, however, significantly increases manufacturing time, making SPIF a slow alternative to rapid industrial methods like vacuum forming, especially for plastics.[9]

While SPIF offers geometric flexibility, it is generally considered too time-intensive to replace established thermoforming techniques. Enhancements such as two-point incremental forming (TPIF) have been developed, where a second point is added to the opposite side of the sheet, either through a passive mold or a robotically positioned forming tool, allowing for greater formal variation. A more adaptable approach for metal SPIF involves using periodically activated fluid pressure beneath the sheet, which helps control the process by providing additional support.[10] These variations aim to address SPIF's limitations while maintaining its geometric flexibility (Figure 1).

Mueller et al. introduced a contactless forming method that uses periodically activated pressurized air beneath ABS and PETG sheets, heating them to their glass transition temperature (Tg) with a heat gun positioned above the sheet. Once malleable, the sheets are shaped by bursts of pressurized air, allowing the creation of spherical forms that surpass the draft angle limitations of mold-based or SPIF processes.[11] This non-continuous technique involves robotically assisted, human-directed thermoforming, iteratively sculpting the sheet into three-dimensional geometries. While effective for small-scale applications like sculptures, the substantial stretching involved reduces the material's stiffness, making the method unsuitable for architectural use. Additionally, heating entire regions before applying pressure poses scalability challenges for larger sheets, such as 8' x 4', where early-heated areas would cool before the entire sheet is uniformly heated. In contrast, an incremental thermoforming process offers scalability by shaping the sheet immediately as each section reaches its Tg, making it more viable for large-scale architectural applications.

For architectural panels, established methods like SPIF, TPIF and active forming of thermoplastic sheets offer limited sheet stiffness in their thin surface outcomes compared with die-cast extruded or pultruded processes that produce ribbed internal structures, or FGF-AM that can produce a filagree three-dimensional lattice structure. While extrusion methods are rapid, they are unable to support variable part production, and though FGF-AM offers flexibility, it is comparatively slow and material-intensive. This research explores a hybrid solution that combines the strengths of both sheet forming and FGF-AM for a more efficient and expedient manufacturing process. A continuous, contactless incremental thermoforming process (CIT) is investigated as a formative means to produce sheet-based geometries with sufficient thickness to achieve increased stiffness and resistance to deflection. Additionally, a conformal approach to FGF-AM is explored to further improve the forming process and structural performance. Rather than employing simulation modeling, this research focuses on gathering data from fabricated outcomes to inform the future development of design and simulation software capable of modeling the complex material dynamics inherent in CIT.

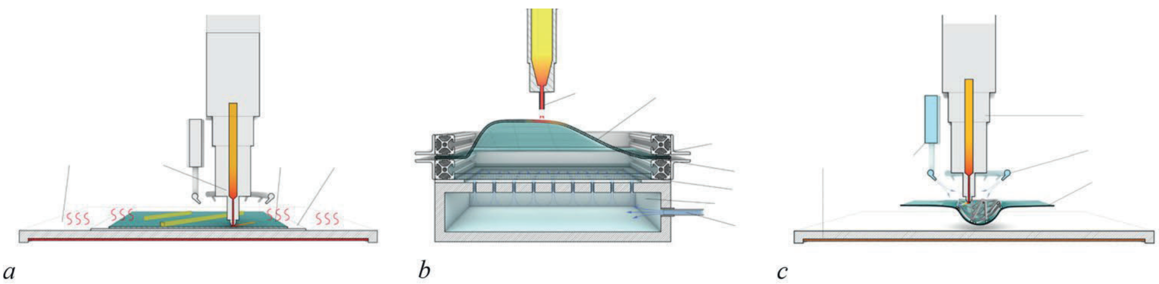


Fig. 2. The compound robotic thermoplastic manufacturing method involves (b) contactless single-point incremental thermoforming (CIT), and variations that include either: a) horizontal conformal FGF-AM prior to CIT, or c) conformal FGF-AM of spatial lattices following CIT.

3 Methods

A compound robotic thermoplastic manufacturing method was developed that combines a custom approach to contactless single-point incremental sheet thermoforming together with conformal fused granulate fabrication additive manufacturing (FGF-AM) prior to, or after forming (Figure 2). A series of parts were incrementally thermoformed with different geometrical conditions including symmetrical domes, an asymmetrical dome, bubbles, ridges, hybrid bubbles and ridges.

Additionally, a subset of these parts incorporated one of the following two experiments:

a) Horizontal conformal FGF-AM patterns were manufactured on top of a sheet prior to its thermoforming to partially constrain and influence sheet formation. Alternatively,
b) A sheet was flipped post-thermoforming and used as a substrate for three-dimensional conformal spatial-lattice printing in order to investigate the possibility of fabricating a complex monolithic surface-lattice hybrid part (Figure 3).

Manufactured parts explored variations of the robotic fabrication methods described above. Post fabrication, parts were 3D scanned, geometrically analyzed to evaluate manufacturing outcomes relative to robotic fabrication input instructions, and structurally analyzed to evaluate fabricated parts' structural resistance to deflection relative to an unformed sheet. The research was conducted using PETG due to the material's recyclability and cost advantages over several other thermoplastics and its availability in both sheet and pellet forms which would enable monolithic parts to be fabricated using combinations of the two mediums.

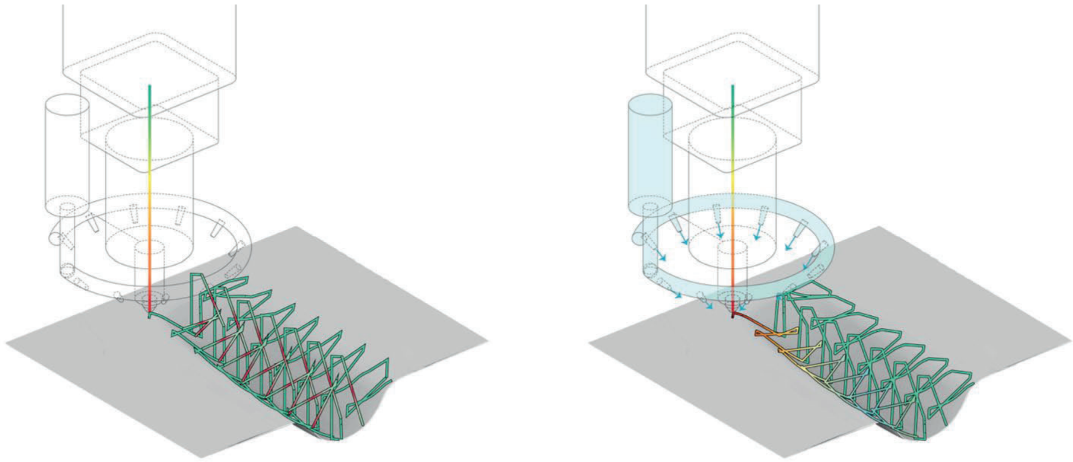
3.1 Contactless Incremental Thermoforming (CIT)

In contrast to most single-point incremental forming approaches that apply force directly to a sheet material, this research provides a constant air pressure beneath a sheet while locally heating it from above. A robotic toolpath guides a heat gun over the sheet, controlling both trajectory and velocity to locally soften regions of the material to its glass transition temperature (Tg). This contactless approach allows the sheet to be formed by the underlying air pressure. The width and depth of the affected region depend on several factors, including the nozzle size of the heat source, its vertical distance from the sheet, the temperature, and the velocity of the robotic toolpath.

Experiments were conducted on 1'x1' PETG sheets of 1/16" thickness, clamped in an airtight aluminium frame with a 40mm high air pocket below the sheet pressurized to 80 psi using a compressed airline. Mounted on an ABB IRB4600-60 articulated robot arm, a robot end-effector tool incorporated an electric heat gun with a 8mm diameter nozzle (set to a constant temperature setting of "7", measured to be 300°C exiting the nozzle tip). Initial tests indicated that variations in airflow rendered outcomes difficult to control. To ameliorate this, a perforated MDF board with 6mm diameter holes was first installed above the airline inlet location. To further dissipate airflow, a 10mm thick sheet of high-density foam was later placed above the perforated board to block direct flow from any individual hole affecting formation outcomes. Initial tests established a constant robot velocity of 90mm/s and tool path vertical offset of 10-20mm above the PETG sheet. A series of geometries were developed through different tool path configurations, including various forms of dome, bubble, ridge, and combinations of these. A selection of formed sheets also incorporated one of the following two methods described below.

3.2 Subset 1: 2D Conformal FGF-AM Prior to Thermoforming (FGF-CIT)

An additional set of experiments involved FGF-AM in horizontal layers conformally onto PETG sheets in specific patterns prior to CIT. Outcomes were evaluated for the ability of the FGF material to locally stiffen and partially offer resistance to displacement during the thermoforming process. FGF-AM was undertaken at 12 mm/s using a Massive Dimension MP10 extruder with a 1.5mm nozzle and Eastman 6763 PETG pellets. The extruder was set to an auger voltage of 1.0V, and nozzle temperature of 240°C with a front heat zone 190°C , with a heat bed temperature of 80°C. A EX-AIR 8cfm 550 BtuH cooling capacity air vortex tube was added to the extruder to facilitate rapid cooling of extruded material at point of deposition. To manufacture on the 2D sheet, an ABB "work object" local coordinate space aligned to the sheet had to be established using ABB's 4-point calibration process. During CIT, robot toolpaths were explored that either crossed over or steered clear of these FGF regions, ensuring the FGF pattern received less heat than the sheet.



a *b*

Fig. 3. CIT-FGF. a) spatial lattices are 3D modelled to conform to a 3D scanned model of a CIT formed panel with live extruder collision detection feedback highlighted on the tool path. b) the lattice is fabricated as a continuous spatial print trajectory with active cooling from an air vortex appendage.

3.3 Subset 2: 3D Conformal Spatial FGF-AM Post-Thermoforming (CIT-FGF)

Robotic spatial printing on the surface of a formed sheet requires accurate knowledge of the sheet's form and position. Sheets were 3D scanned using a Revopoint Miraco 3D Scanner with an error tolerance of +- 0.05mm. Scans were imported into Rhino3D, where conformal tool paths were projected onto the scanned surfaces. Conformal tool paths were manufactured to bond FGF-AM material to the sheet before more three-dimensional spatial printing aspects of the tool path were executed. Similar to CIT-FGF, an ABB 4-point calibration process was performed prior to manufacturing. To manufacture a spatial lattice the extruder auger voltage was reduced to 0.17v and robot velocity had to be reduced to 1.5mm/s to provide sufficient time for material to cool and stiffen (in conjunction with the use of the air vortex tube that helped expedite cooling). Executing the robot trajectory faster results in slumping or collapse.

Lattice designs were explicitly modeled with feedback from a custom C# software developed in Rhino3D Grasshopper, which integrated a 3D collision detection method for pre-manufacture simulations. This allowed real-time evaluation of potential collisions between the extruder, the sheet, or the already-manufactured FGF-AM lattice during 3D modelling. By visualizing collision points, the software provided critical feedback, enabling collision mitigation strategies to be implemented prior to manufacture (Figure 3).

3.4 Geometrical Analysis

To establish a set of heuristics for controlling the research method's formative effects, 3D scans of a selection of manufactured outcomes were compared to their respective robot tool paths. A subset of scanned results was also analysed in Rhino3D to evaluate their depth, inclination (draft angle), and mean curvature. Several spot measurements of initial dome tests were also obtained using a iGaging 8" digital outside caliper to determine formed sheets' modified thickness.

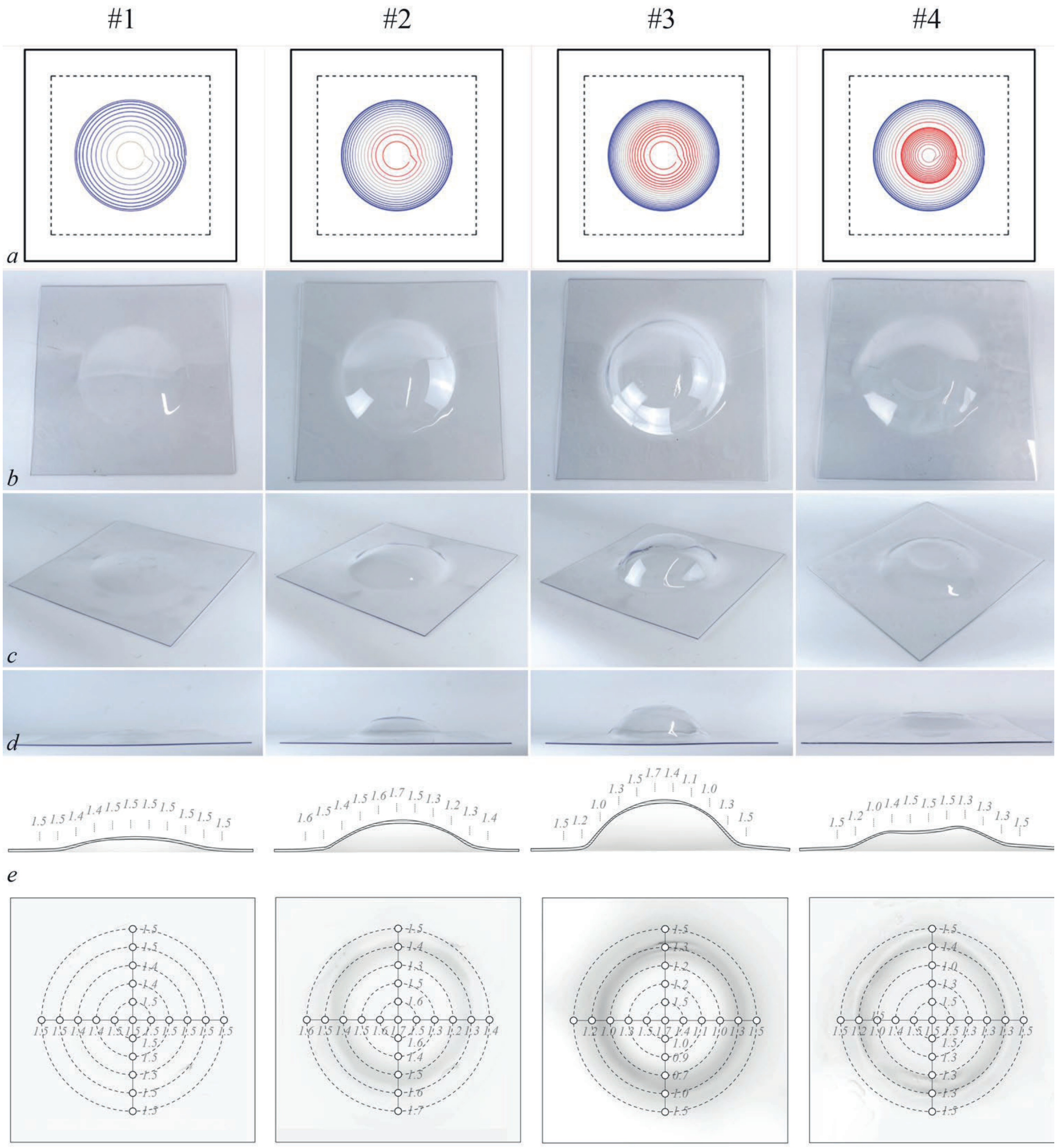


Fig. 4. CIT dome experiments with columns 1-4 results illustrating rows: a) robot heating tool path, b) top photo, c) perspective photo, d) side photo, e) formed panel thickness variation (illustrated at 2xenlarged scale), f) top view of calliper data points for (e).

3.5 Structural Analysis

As an initial foray into the manufacturing method, structural analysis of formed outcomes was undertaken digitally, using 3D scans as input into a Karamba3D structural shell analysis in Rhino3D, tuned to PETG material settings. In this experiment, end-use structurally feasibility and part orientation is not considered. Parts are comparatively analyzed to ascertain strengths relative to each respective forming process and outcome. For the sake of the experiment, three vertical loads were applied to the part: self-weight, snow loading of 1KN/m² and a 1.1 KN/m² live loading, while the four-sided boundary frame of each sheet was defined as structural support.

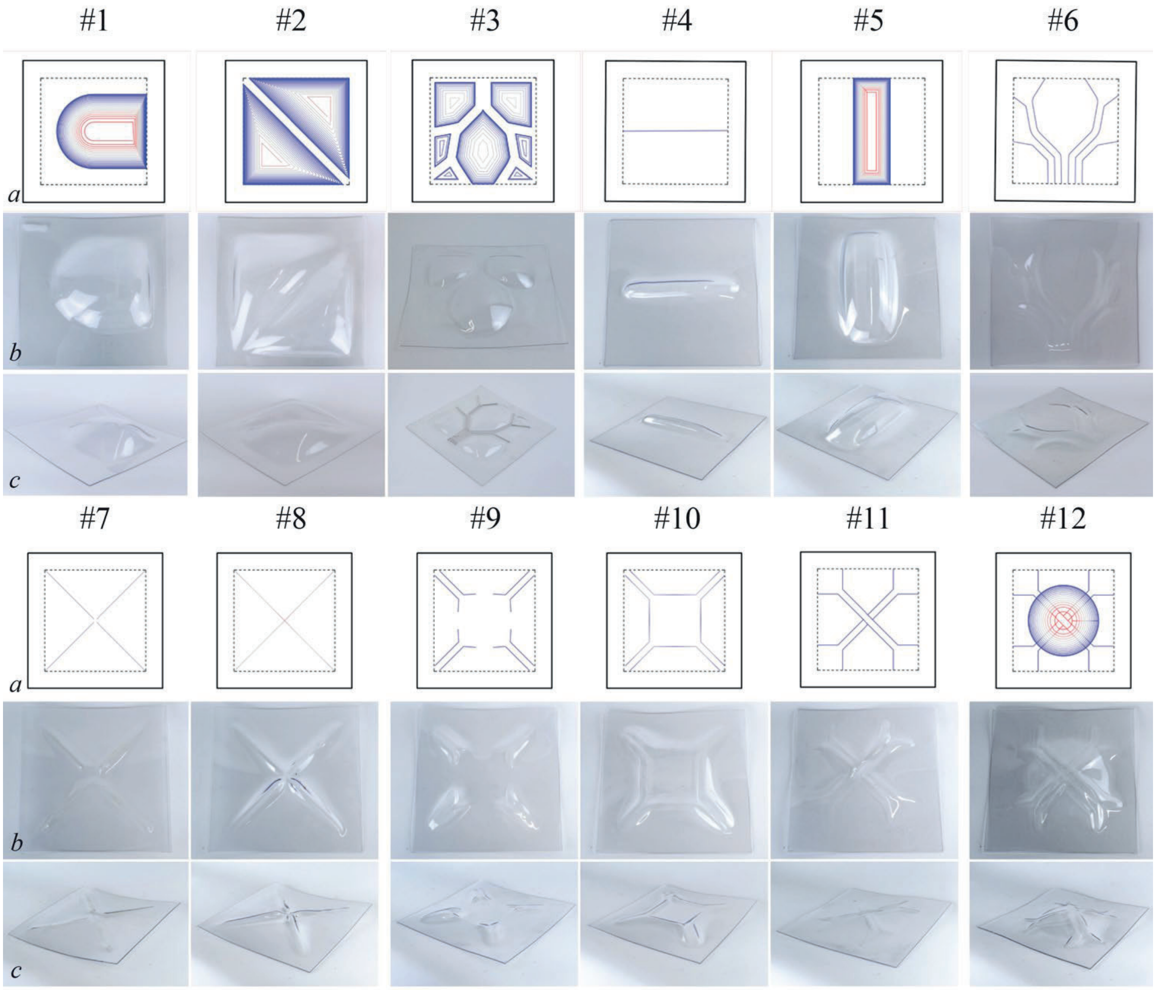


Fig. 5. CIT formation studies shown in columns 1-12 illustrating: a) robot heating tool path, b) top photo and, c) perspective photo

4 Results: Manufacturing Approach

4.1 CIT Method

The CIT process proved successful at supporting a programmable variation in sheet formation without the need for a mold. Three variations of a 160mm diameter circular dome were successfully manufactured with varying depth and curvature (Figure 3). Calliper measurements of sheet thickness expectedly indicated thinner areas in regions with greater vertical displacements in form, with smooth transitions for these areas to adjacent thickness levels (Figure 3). A cratered dome was also successfully manufactured by switching from positively pressurized air to a negative vacuum condition during the last central heating tool paths. Following the dome experiments, additional formation tests were undertaken to produce a variety of formal typologies (Figure 4). Hybrid bubble and ridge experiments were also successfully demonstrated (Figure 5). These involved two stages of formation, first a continuous formation of a bubble form, then after cooling back to room temperature, a second formation process for the ridges required a tool path to rise up over the bubble to avoid collisions or overheating of the sheet. Manufacturing times ranged from 1-2 minutes to manufacture a dome up to 10 minutes for multiple branched ridge tool paths which required pauses to enable the sheet to return to room temperature before each successive ridge was formed. Different formal possibilities thus had different manufacturing time requirements.

4.2 FGF-CIT

Bonding of FGF additively manufactured layers onto flat PETG sheets was obtained through an offset of 2mm for the toolpath. Incremental forming of the 2D conformal AM toolpaths was initially tested with the AM contours on the top side of the sheet. Results improved considerably when the sheet was flipped prior to CIT so that the AM layers were further from the heat source, allowing them to remain marginally cooler and stiffer than the PETG sheet. Incremental forming toolpaths were tested that crossed the entire PETG surface indiscriminately or aligned and avoided regions with FGF AM material, ensuring those regions remained cooler. Outcomes range from being completely unconstrained by the FGF parts, partially or fully constrained in surface formation outcomes. Results with most formal interest were partially constrained by the FGF parts, which were also partially formed – acting as a soft constraint that resulted in more variation in curvature and depth

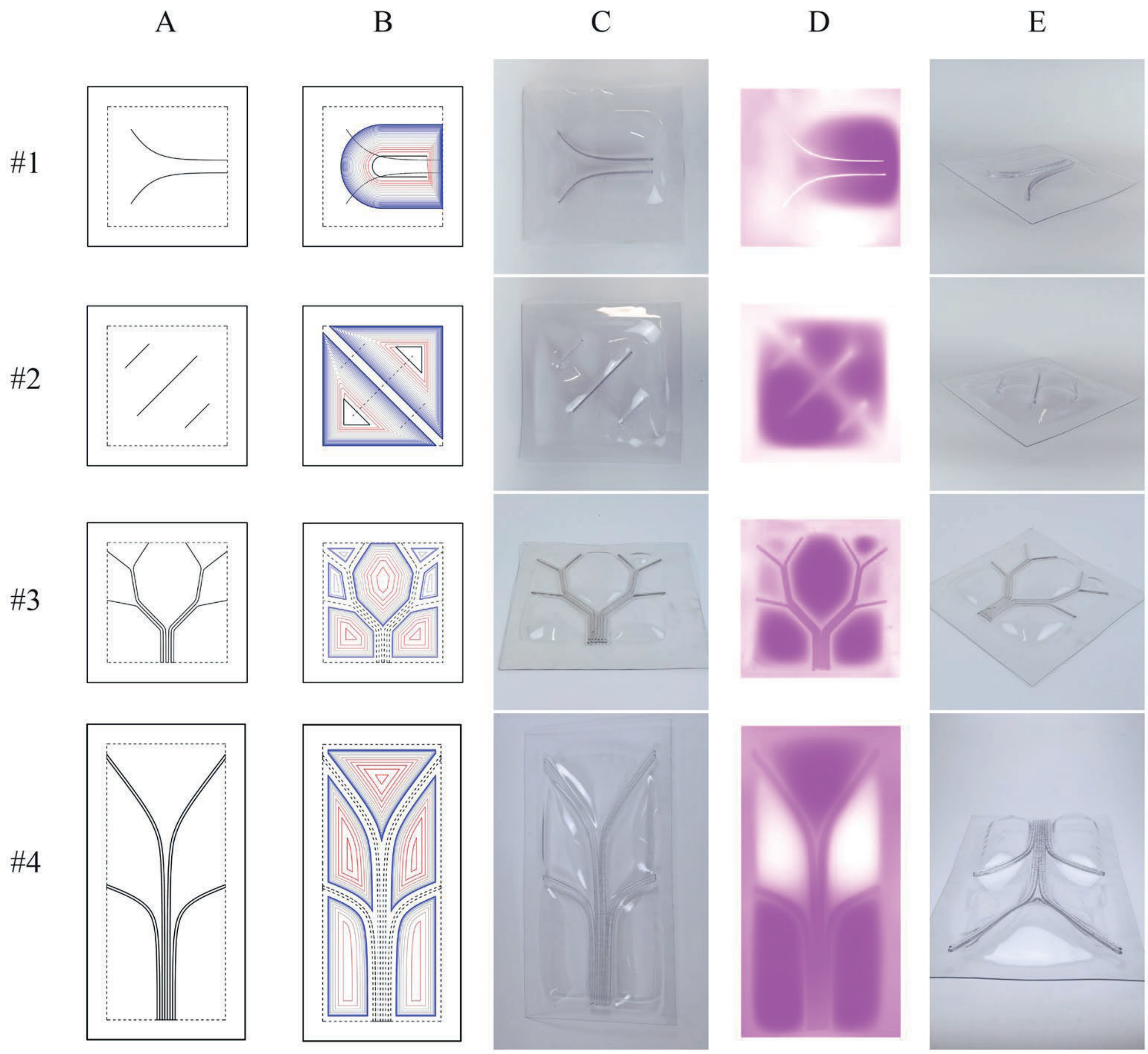


Fig. 6. A selection of FGF-CIT experiments 1-4, each showing: a) 2D conformal FGF pattern, b) CIT robot toolpath, c) top view photo, d) depth map from 3D scan, e) perspective photo. FGF patterns are deformed during CIT in tests 1-2 and remain in their original position in tests 3-4.

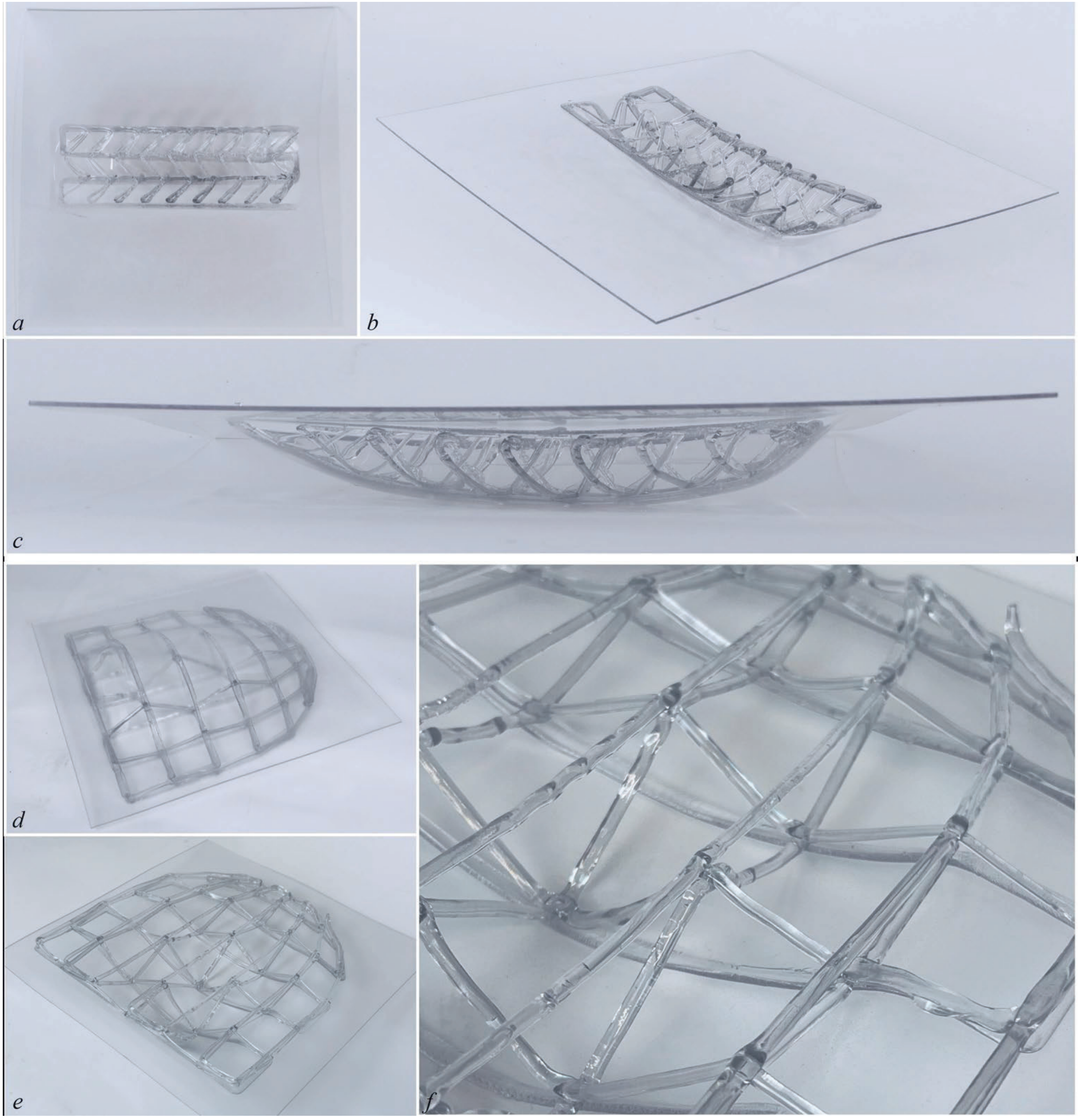


Fig. 7. CIT-FGF hybrid surface-lattices. a-c) conformal freeform curve spatial lattice, d-e) grid-based spaceframe conformal spatial lattice.

than fully constrained or unconstrained CIT-formed parts. This qualitative observation corresponds to metrics highlighting an increased range in curvature and depth variation (Figure X). Initial tests deposited a single layer of material 2mm above the sheet. This proved insufficient to affect formation in CIT, and was increased to several layers ranging from 2 to 6. The most successful results had 6 numbers of printed layers. Manufacturing times ranged from 3 to 5 minutes.

4.3 CIT-FGF

Two approaches to 3D conformal spatial printing were explored; a grid-based truss and an approach that utilized an array of free-form spatial curves. Both methods were successfully manufactured without the need for temporary support structures. Inconsistencies in extruded thickness are visible in both outcomes, suggesting more investigation is needed into extruder auger speeds in relation to the robot's velocity to ensure constant relative throughput. Manufacturing time for the spatial curve lattice was 1 hour and 25 minutes.

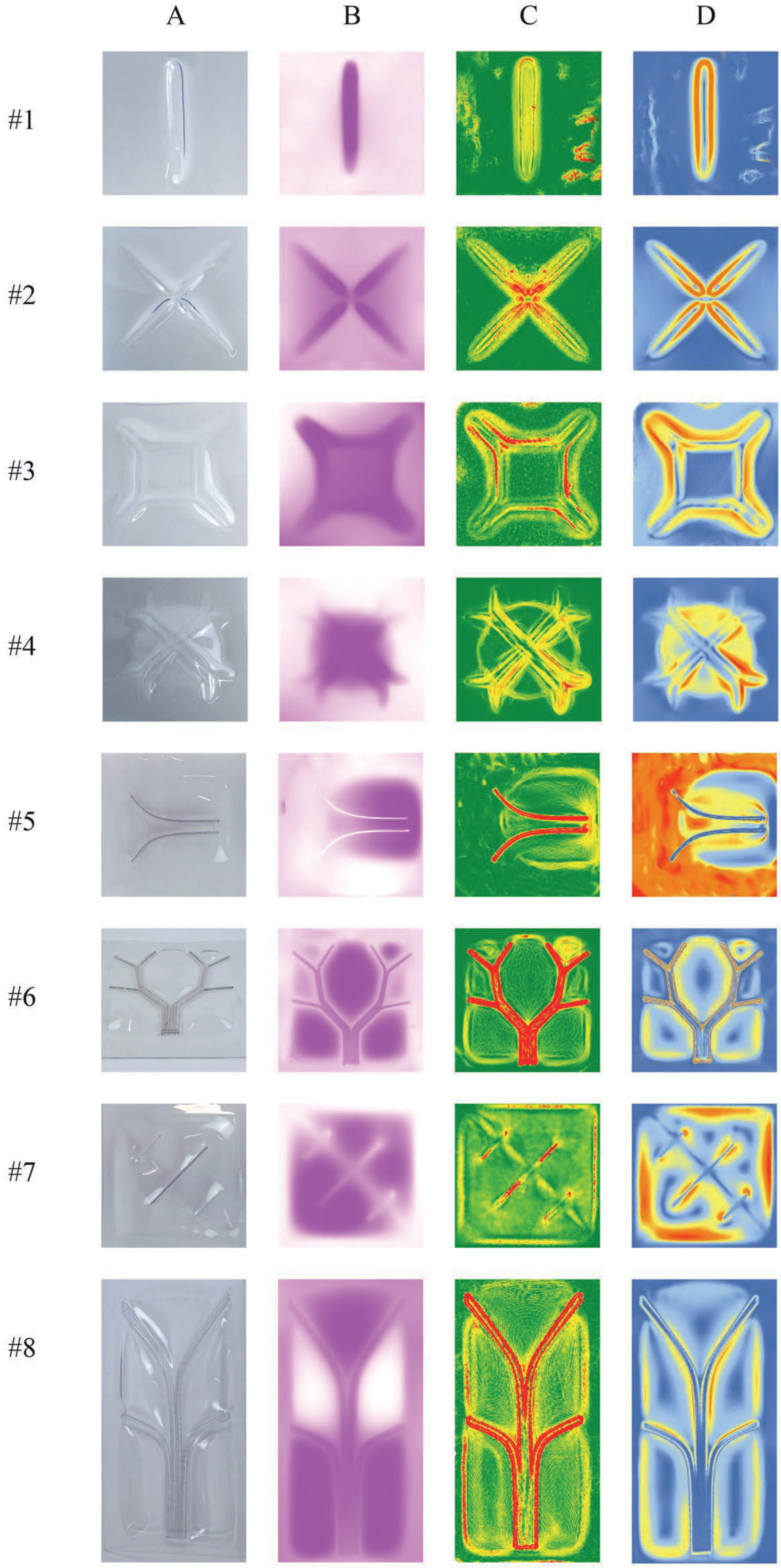


Fig. 8. Formal analysis of CIT outcomes (rows 1-4) and FGF-CIT results (rows 5-8), indicating: a) top photo and 3D scan analysis of: b) depth, c) mean curvature, d) inclination angles. Results highlight diversity in organization and surface character.

5 Results: Comparative Analysis of Fabricated Outcomes

A series of 1x1’ PETG sheets were formed using the three described methods (CIT, FGF-CIT, CIT-FGF) in various configurations of dome, bubble, ridge, and hybrid bubble-ridge combinations. Results demonstrate that each method successfully formed a 3D surface without the need for a mold. Two CIT methods were also successfully combined to produce a ridged bubble, demonstrating that CIT can deploy multiple formation methods in successive iterations of forming without overly thinning out a sheet and causing a rupture.

Geometrical analysis of 3D scans from a selection of formed results reveals productive formal variation in outcomes (Figure 8). FGF-CIT results were notably different in formal configuration and character from CIT-only results when FGF regions were partially displaced during the CIT process – this occurred when heating tool paths crossed over and partially heated FGF patterns. Naturally, FGF patterns were unaltered due to no crossover with a heating tool path, with results appearing like sheets only manufactured by CIT without FGF.

Two CIT-FGF methods were also successfully manufactured. In considering variable geometric applications, of the two — the linear spatial curve option embodied a more directional capacity and may, therefore, be better suited to designs that require variations in alignment and density relative to both formal and structural possibilities. Structurally it could be improved with more nodal interconnectivity between its curve profiles, as the spaceframe alternative had better nodal interconnectivity.

The visibility of FGF regions in both FGF-CIT and CIT-FGF results also noticeably impacted the transparency, refraction, and visual character of a part. FGF regions that aligned to CIT formations produced a more coherent aesthetic outcome, such as branching FGF regions between multiple bubbles in a FGF-CIT result (Figure 6) or the directional spatial curve of FGF material in one of the CIT-FGF results (Figure 7).

Structural analysis of outcomes (Figure 9) showed result #4 x-ridge had the least structural deflection that was 50 x stiffer than a flat sheet. Results #3, #5, #6 are performed well, with 20 x the stiffness of a flat sheet. Result #7 dome-ridge was expected to fair well as it hybridized features existing in both #4, and #6, however #6 dome featured a much deeper profile that provided structural depth, trumping the formal complexity of #7. From these outcomes, #6 dome took only 2 minutes to manufacture whilst #4 x-ridge took 10 minutes. The hybrid #7 dome ridge took the time of both processes – 12 minutes. Although eight to ten minutes difference is not huge, scaling these methods up to larger sheet sizes would have a sizeable multiplying effect on production times and energy use.

Results presented in Figure 8 demonstrate a variation of results that exhibit notable formal character. Some of these results fair well in the structural analysis while others do not. As with any architectural project, a balance of aesthetic interest, structural efficiency and manufacturing costs will heavily influence a designer’s decisions. While results demonstrated up to a 50-fold improvement in structural stiffness compared to a flat sheet, these results suggest there is room for further improvement and a need for further

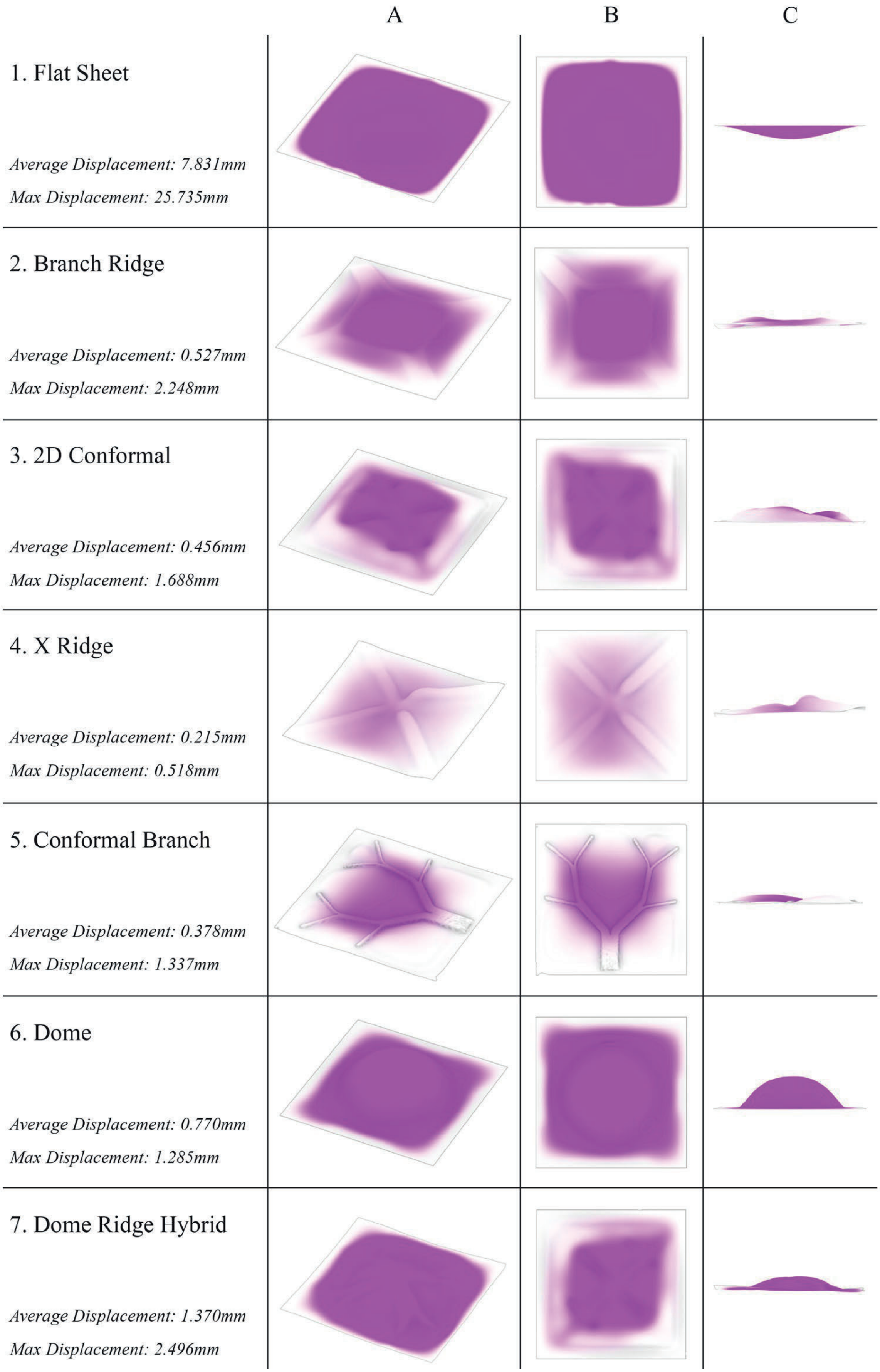


Fig. 9. CIT and FGF-CIT 3D scanned outcomes 2-7 are structurally analysed for deflection and compared to row #1's flat unformed sheet. Deflection: A) perspectives, B) top views, c) elevations.s

investigation to ascertain the full structural and time impact of the most exciting aesthetic possibilities the CIT methods enable. Given that most formative experiments did not form a sheet all the way to its boundary, much flat surface remained. Substantially improved structural performance results could be achieved by forming to the edge of a panel and trimming off the region clamped by the frame.

6 Conclusion

The CIT methods successfully produced a range of formal configurations in outcomes without requiring the material and time cost of molds during the production process. Without molds, the combined CIT methods offer substantial possibilities for a variably formed aesthetic outcome with improved sheet stiffness that could offer benefits for applications where thermoplastic sheets and panels are currently utilized in buildings.

The research demonstrates an alternative approach to moldless robotic forming of PETG sheets capable of producing smooth, transparent and diversely formed parts that have varying aesthetic and structural capacities, expanding the formal possibilities of rapid, robotically produced thermoplastic panels and sheets.

The research lends itself well to architectural expression, and potentially at larger spans than the thermoplastics are customarily tasked with. Given such applications, research should be conducted to establish whether the method can be repeated in other thermoplastics also used for architectural applications such as polycarbonate. Further research is also required to establish structural performance metrics for parts manufactured by the method, most likely through physical load testing. To support further research and application scenarios, a simulation model must also be developed to enable the design and visualization of parts prior to manufacture with the ability to capture variations in formation and material wall thickness.

Compound Robotic Approaches to Contactless Incremental Thermoforming and FGF Additive Manufacturing offers a flexible and relatively rapid variable manufacturing process for the production of stiffened or curve-formed sheets, and complex 3D hybrid surface-lattice parts. With further research and development, the approach offers exciting potential for variably formed stiffened sheet and panel applications.

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