Cavity Shell

Sequential Cast-in-Place Method to Create Compression-Only Structures with Ultra-Thin Additively Manufactured Formwork Assemblies

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1 Cavity shell showcasing the load-bearing capabilities of the compression-only system by taking its dead load and external load.

ABSTRACT

A compression-only structure's impressive strength-to-weight ratio allows it to span large spaces using significantly less material. However, prefabricated masonry or concrete components used to construct compression-only structures are prone to damage during handling and transportation, and contribute to CO2 emissions. Additionally, assembling these components requires heavy falsework, which results in material wastage and increased construction costs. This research paper presents an alternative approach to constructing compression-only structures by introducing a new, in-situ construction approach based on coupling 3D-printed, ultra-lightweight plastic formwork and sequential casting of the formwork in compression on site. This is achieved through developing: 1) a new construction method based on the assembly of lightweight, 3D printed plastic formwork in compression-only form, which is then sequentially cast with concrete in place; 2) an integrative formwork system informed by structural and casting logics (i.e., flowability, the height of the casting point in relation to hydrostatic pressure, placement of formwork interface in alignment to internal forces in the structure; and 3) a parametric model for translating force-form diagram to integrative formwork. To verify this research method, Cavity Shell, a 1:1 scale compression-only table leg structure, measuring 1.4 meters in radius and 0.8 meters in height, was designed and built (Figure 1). This ultra-lightweight formwork took less than 48 hours to assemble, and was sequentially cast by two people. This research demonstrates the potential to rethink the construction of compression-only structures by minimizing the material used, and improving economic and environmental efficiency in their construction life cycle.

COMPRESSION-ONLY STRUCTURES

Compression-only structures (Fernández-Ruiz et al. 2019), also called "pure compression structures," are engineering structures that rely solely on the compressive forces acting on their components for stability. In other words, these structures are specifically designed to withstand external loads through compression, eliminating the need for tensile or bending forces. Examples of compression-only structures include arches, domes, vaults, and shells, showcasing the efficient use of materials through well-designed geometries (Block et al. 2018). These structures are typically constructed using unreinforced masonry, such as stone and brick, which possess high compressive strength but lack significant bending properties (Rippmann and Block 2013; Block et al. 2015). One notable advantage of these structures is their impressive strength-to-weight ratio. Due to their unique design, they require less material to span large spaces, resulting in reduced material consumption and increased design flexibility.

In the past, physical design techniques such as cable nets (Antoni Gaudi, Frei Otto) or cloths (Heinz Isler) in the 19th and 20th centuries, respectively, were employed to help design compression shells (Block and Lachauer 2011). However, these methods were often time-consuming and expensive. In the 21st century, advancements in computational form finding, structural analysis tools, and digital fabrication have revolutionized the understanding and analysis of complex compression-only structures. Consequently, designers can now explore the design solutions for these kinds of structures without relying on physical modeling, accelerating the development of structures that minimize material usage (Block et al. 2018).

Various computational design and digital fabrication approaches have been introduced to facilitate the design of three-dimensional funicular networks, enabling precise discretization of each bespoke component and its fabrication (Kilian and Ochsendorf 2005; Andreu et al. 2007). These tools are based on concepts such as Thrust Network Analysis (Block and Ochsendorf 2007) and 3D Graphic Statics (Akbarzadeh et al. 2015). One of these approaches, 'Thrust Network Analysis,' is utilized by the Block Research Group in the construction of 'The Armadillo Vault' at the Architecture Biennale in Venice (Block et al. 2017). This compression-only structure, spanning over 15m, was realized by implementing advanced digital tools. The computational tools aided in the form-finding process of the vault's funicular geometry, the discretization of the thrust surface, computational modeling, and optimization of component geometry. And the Computer Numerical Control (CNC) milling enabled the production of 399 discrete components, known as voussoirs, with thicknesses ranging from 5 to 12 cm. Due to the vault's geometry, the voussoirs were assembled without using mortar or additional structural components. This showcased the potential of digital tools in enabling the design and fabrication of highly precise components that can come together, with a tolerance of less than a millimeter, to form a compression-only structure.

Compression-only structures continue to push the boundaries of architectural possibilities by leveraging computational design and form-finding tools. This enables architects to explore innovative construction methods, and create sustainable and efficient solutions for constructing expansive structures with intricate geometries.

INTERSECTION OF 3D PRINTING AND COMPRESSION-ONLY STRUCTURES

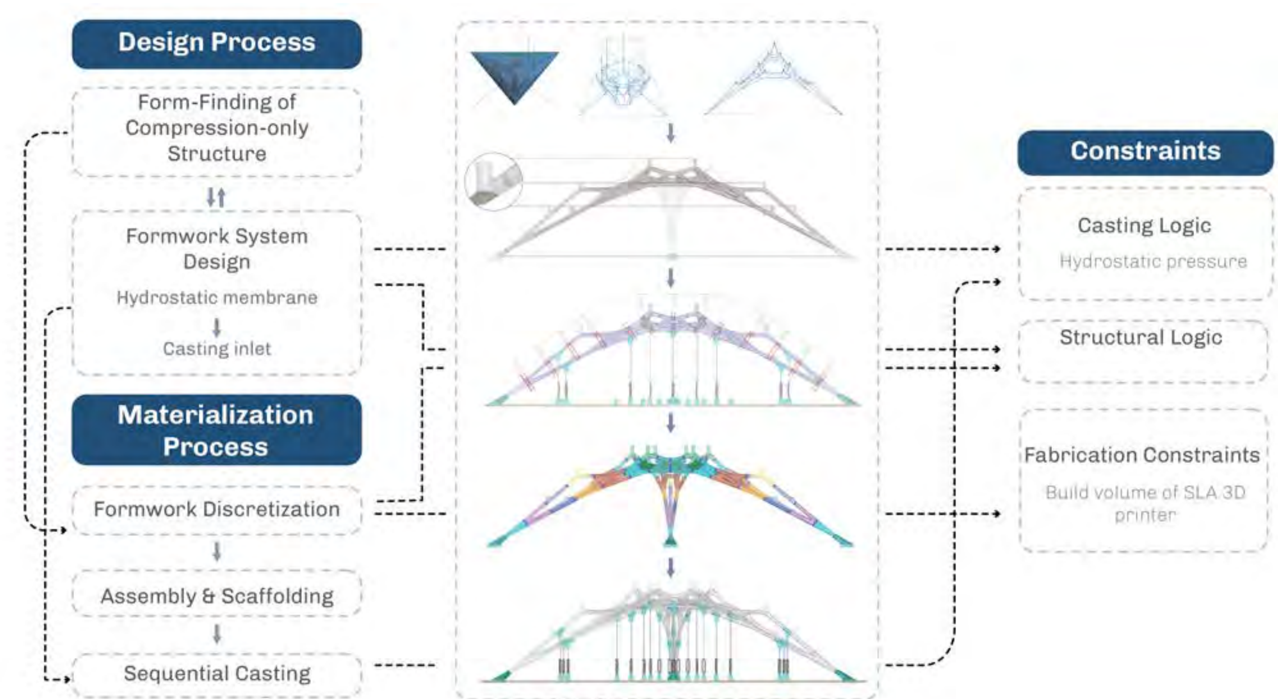
Concrete is one of the most used materials on the planet (Crow 2008); it can be cast into nearly any shape and displays high compressive strength. However, because of its extensive use, it has been responsible for 11% of the world's CO_2 emissions resulting in negative environmental impact. Hence, it has been essential to minimize its consumption in a structure. Emerging studies leverage the 3D Concrete Printing (3DCP) approach to reduce material requirements in concrete slabs and structural elements by taking advantage of compression-only geometries. This approach reduces the volume of concrete consumed in slab construction, eliminates the need for structural rebar, and makes it possible to build a compression-only structure by 3D printing the bespoke components or formwork for casting concrete. Compared to conventional CNC milling and hot wire cutting of components (which lead to excessive material waste), 3D printing reduces the waste, increases the precision, and expands the possible geometric complexity of constructing a compression-only structure.

Emerging research in this area has investigated the 3D printing techniques for both components and formwork, illustrating the technology's capacity to advance the construction methodologies of compression-only structures: (1) 3D Sand-Printed Floors (Rippmann et al. 2018) investigated the binder jetting technology to fabricate bespoke 3D-printed silica sand components assembled in the compression-only form to produce an unreinforced structural floor system made of sand. By strategically placing material in structurally critical areas, this approach facilitated a weight reduction in the volume of sand of up to 70% compared to the volume of concrete used in a traditional solid concrete floor slab; (2) Striatus (Bhooshan et al. 2022) project investigates 3DCP of large components essential for the construction of the compression-only structure. Fifty-three concrete components were 3D printed, collectively weighing 24.5 tons. These components were then transported to the construction site and dry-assembled—without the need for additional mortar—forming a bifurcating arched masonry footbridge that spans 16 meters. This intersection of compression-only design and 3DCP enabled sustainable usage of concrete and precise fabrication of the bespoke concrete components; (3) Saltatur, Node-Based Assembly of Funicular Spatial Concrete (Akbarzadeh et al. 2021) focuses on the prefabrication of concrete elements through 3D printing thermoplastic formwork, then assembling and post-tensioning these discrete prefabricated concrete components into a compression-only structure using steel rods to form a long-span, compression only furniture; (4) 3D Printed Plastic Formwork for Integrated Funicular Concrete Slabs (Jipa et al. 2019) illustrates the use of fused-deposition 3D printing in fabricating bespoke plastic formwork to produce a concrete slab. Using a bio-based, compostable, and recyclable polymer, polylactic acid (PLA), 3D-printed formwork components were produced with commercial 3D printers. With only 14.6 Kg of plastic used for the formwork of the entire prototype, it serves as an efficient solution for crafting bespoke formwork components for stay-in-place casting.

The advantages of 3D printed (3DP) components for compression-only structures are evident in the above-mentioned projects. In most cases, such as the 3D Sand-Printed Floors, Striatus, and Saltatur, transporting these heavy and fragile, particularly sand or 3DCP components, to the construction site poses substantial challenges. These components are prone to damage during transportation and handling, potentially leading to unplanned costs and project delays. Transporting these heavy prefabricated components is challenging and expensive, and contributes to CO2 emissions, posing an environmental concern.

Additionally, the construction of compression-only structures entails prefabricating components that are often heavy, such as bricks, pre-cut stones, tiles, or 3D-printed concrete blocks. Assembly of these prefabricated components at a construction site will require extensive scaffolding that increases the construction cost, environmental impact, time of construction, and labor. The assembly of these elements necessitates extensive falsework, typically crafted through CNC milling of materials like timber, plywood, or cardboard, to support their weight transfer during construction. This results in a time-consuming process generating large amounts of waste and increased construction costs.

In this context, 3D printed formwork, particularly those crafted from lighter materials such as plastic, presents a



2 Flowchart illustrating the different phases of the proposed method.

compelling solution. Its lower weight makes it less costly to transport and easier to manage during assembly, thereby reducing the risk and cost of potential damage.

METHOD

This research advances the field of 3D printing for the construction of compression-only concrete structures by introducing a new in-situ construction approach using 3D printed plastic formwork and sequential casting. Instead of using 3D printing technology to prefabricate final components, this research focuses on 3D printing lightweight plastic formwork that will be assembled on-site purely in compression, creating a continuous cavity. The cavities would subsequently be filled through the sequential casting of concrete, resulting in a compression-only structure made of concrete. The flowchart in Figure 2 illustrates the different phases of this method, from the computational design of the form to the materialization of a structure, as well as constraints and interdependencies that inform these phases. These steps are categorized into two main phases: the design process and the materialization process.

Design Process

The design process consists of two major steps a) the design of the compression-only structure through the computational form-finding method and b) the formwork system design informed by structural and casting logic.

Form-Finding of Compression-Only Structure

This research utilizes 3D Graphic Statics (3DGS) as a form-finding method to generate a compression-only structure as the first step of the design process. This method is a three-dimensional extension of Graphic Statics (GS) principles in 3D Space. Graphic Statics is a graphical methodology of solving the forces acting in equilibrium on a rigid structure by representing forces as vectors or polygons. 3D Graphic Statics is utilized to derive 3D funicular structural lines by subdividing force polyhedrons (Akbarzadeh et al. 2015) based on reciprocal polyhedral diagrams (comprising edges and vertices). With geometrically linked force and form diagrams, this approach permits alterations in support positions, magnitude, and angle of applied forces, and their overall distribution.

While 3DGS facilitates the exploration of various spatial funicular geometries, it does not incorporate material properties into the form-finding process (Bolhassani et al. 2018). Usually, the form diagram, made of edges and vertices, is translated into a compression-only form based on the material's geometric properties. For example, the form diagram in projects Hedracrete (Bolhassani et al. 2018), MycoTree (Heisel et al. 2017), and Saltatur (Akbarzadeh et al. 2021) was translated into components made of concrete with a hexagonal profile, mycelium with a triangular profile, and concrete with a hexagonal profile, respectively. In this research, we developed a computational algorithm that would translate the form diagram (edges and vertex diagram) to a representation of concrete structure through the parametric choice of the "profile cross-section."

Formwork System Design Informed by Structural and Casting Logics

In recent years, there has been a growing interest in leveraging additive manufacturing (AM) methods like Binder Jetting (Aghaei Meibodi et al. 2017; Dillenburger 2016; Jipa et al. 2019) and Fused Deposition Modeling (FDM) (Peters 2014; Jipa et al. 2019; Jipa et al. 2017) for producing formwork for non-standard geometry showcasing enhanced geometrical complexity and intricate surface detail. The most common constraint with 3D printed formwork for casting fluid concrete is hydrostatic pressure, especially on a large scale (Peters 2014; Jipa et al. 2017; Burger et al. 2020). Hydrostatic pressure is a lateral pressure exerted by fluid concrete to the formwork. It is determined by the fluid concrete's height and density.

$p = \rho \times g \times h$

where, p = lateral pressure/ hydrostatic pressure in N/m2

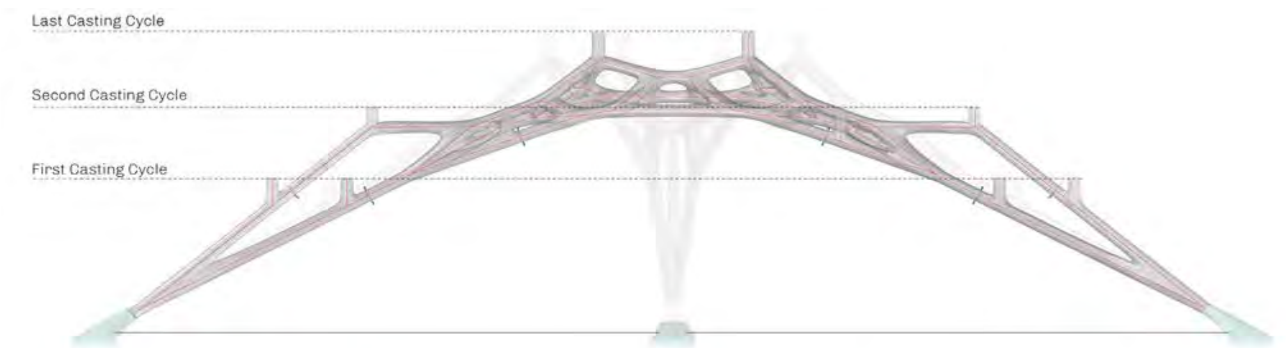
ρ = density of concrete in Kg/m3

g = gravitational acceleration in m/s2

h = height of the fluid or plastic concrete in the cast in m.

As the height of the fluid concrete increases during casting, the hydrostatic pressure exerted on the formwork increases. A few approaches carried out in earlier research to overcome the hydrostatic pressure are (1) submerging the formwork in a bed of sand, water, or any other substance when casting the formwork (Jipa et al. 2017; Leschok and Dillenburger 2019; Aghaei Meibodi et al. 2020), where the sand acts with a counterpressure to the hydrostatic pressure from the concrete; (2) casting fast-setting concrete (with an added accelerator) simultaneously while 3D printing formwork (Burger et al. 2020) to remove hydrostatic pressure; (3) integration of a patterned reinforcement system with the 3D-printed formwork (Aghaei Meibodi et al. 2021) following the curvature of the casting surface, spanning from top to bottom, to transfer the load of the hydrostatic pressure to the ground.

Even though utilizing sand might be a feasible method to counterbalance hydrostatic pressure, it is challenging



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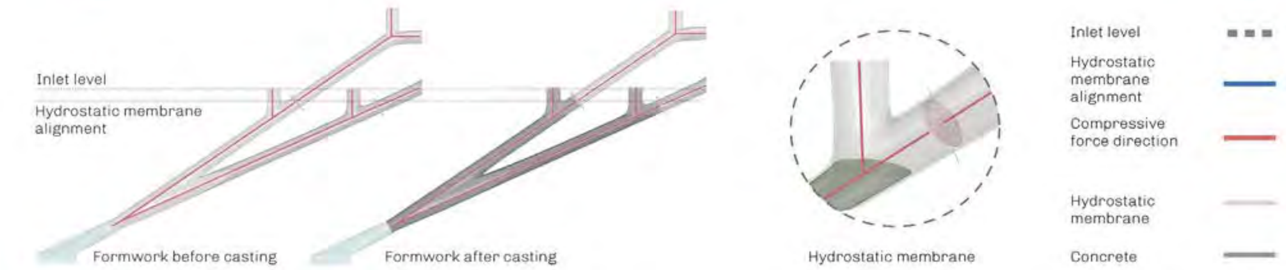

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3 Position of casting inlet openings on the same Z plane.

4 Alignment of hydrostatic membrane perpendicular to the dominant flow of compressive forces to ensure that the cold joints are perpendicular to the dominant flow of compressive forces while casting.

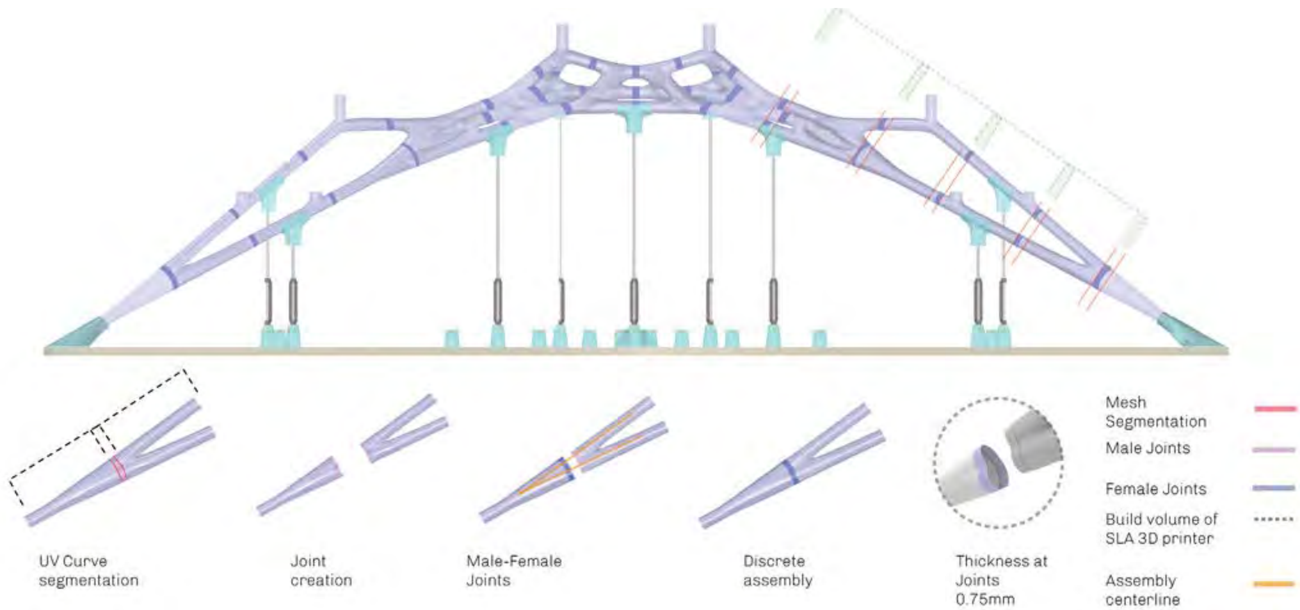
to scale it for on-site, large-scale construction. Even in off-site fabrication, a system must be developed to ensure that the sand is poured almost at the same rate as pouring the concrete mix to avoid the formwork from collapsing inwardly. Similarly, it becomes challenging to print and cast simultaneously for large-scale, on-site construction or it becomes an additional cost to transport heavy pre-cast/fabricated components on-site for assembly.

Hence, to mitigate formwork failure due to excess hydrostatic pressure, this research proposes Sequential Casting (SC) of concrete and develops a system that would facilitate the SC. The SC method involves staggered pouring cycles with timed intervals to allow the cast material to set. This approach involves filling the assembled formwork with concrete, allowing sufficient setting time, and proceeding with the next section's pour, consequently forming cold joints between each casting cycle. Therefore, the number of casting cycles depends on the height value from the above equation. In this method, the casting height was determined by performing a series of mechanical tests on the designed formwork samples to determine the lateral pressure (representing the hydrostatic pressure) that it could withstand. Subsequently, this empirically measured hydrostatic pressure is used to calculate the appropriate SC height that the formwork requires. These tests further informed the refinement of the formwork design and iterations.

The following formwork features are introduced and developed to facilitate sequential casting. These features are designed taking into the consideration the concrete casting constraints (i.e., flowability, the height of the casting point in relation to hydrostatic pressure) and structural parameters.

Casting Inlets are introduced to enable SC into the cavity of the assembled compression-only formwork. The placement and height of these inlets within the formwork depend on the achievable casting height, with respect to hydrostatic pressure for each casting cycle. The formwork has numerous casting inlets for each pouring cycle. The inlet openings are strategically located on the same Z plane, which enables the concrete to flow through the interconnected channels, filling each segment adequately until complete saturation is achieved during the designated casting cycle (Figure 3).

Hydrostatic membranes are introduced to ensure each segment of cast concrete supports the weight above it and transfers the load to the next one, distributing the forces throughout the structure. The interlocking nature of adjacent cast sections provides stability and allows the structure to withstand compression forces without collapsing. Similar to masonry principles in arched Roman bridges, where the faces of components in compression are perpendicular to the dominant flow of compressive forces, the cold joints between the sequentially casted



5 Formwork discretization workflow based on build volume of the SLA 3D printer for assembly of the formwork in compression.

segments should be perpendicular to the dominant flow of compressive forces. This is achieved by integrating hydrostatic membranes, which are aligned perpendicular to the dominant flow of compressive forces and are positioned at the maximum casting height per cycle. These membranes feature small openings that permit venting during the casting process (Figure 4).

To attain a strong formwork structure, different formwork thicknesses are assessed in relation to formwork material and hydrostatic pressure using physical tests and prototyping. An algorithm is developed that would allow parametric adjustment of formwork thickness.

Materialization Process

The materialization process represents the second phase of the computational workflow, focusing on formwork discretization, assembly, and scaffolding based on the fabrication constraints.

Formwork Discretization

The size of the formwork segments directly correlates with the build volume of the 3D printer. To meet these fabrication constraints, the overall design of the formwork is discretized into segments. The cutting plane of these segments is perpendicular to the direction of the dominant compressive forces. This is done to preserve the structural integrity of the formwork and ensure these formwork segments are in compression, once assembled (Figure 5). An algorithm is developed to automatically discretize the formwork based on the bed volume of 3D printer input. Stereolithography (SLA) 3D printing of a highly complex, detailed, and ultra-thin formwork is done using Acrylonitrile-Butadiene-Styrene (ABS)-like resin. This fabrication method enables the 3D printing of sophisticated interlocking joints for the formwork segments at a minimu layer height of 25 microns, reducing the risk of any leakage during the casting process and optimizing material consumption in formwork production. The formwork features (a) hydrostatic membrane, (b) casting inlet. The joinery connections are integrated and 3D printed as a part of the formwork segments, making it a uniform geometry for casting (Figure 5).

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Assembly and Scaffolding

The discrete segments of the formwork are assembled without any mechanical connections. Instead, the compression-dominant structural shape of the formwork enables a simple interface design, utilizing a male-female interlocking mechanism (Figure 5). These interlocking features ensure precise alignment of the formwork segments during assembly, and prevent any concrete leakage during the casting process. A minimal scaffolding system was designed. This system provides support during the formwork assembly and prevents any deflection in the formwork during the casting process. It consists of 3D-printed upper and lower holders, threaded rods, and turnbuckles, allowing the scaffolding system to facilitate the structure's leveling in cases of variations in the ground level.

CASE STUDY: CAVITY SHELL

To verify this research method, a 1:1 scale table leg structure, Cavity Shell, measuring 1.4 meters in radius and 0.8 meters in height, was designed and built. This compression-only structure with three supports entails intricate and interconnected, branched tubular geometries, which would have been almost impossible to fabricate using another fabrication method than 3D printing formwork and casting concrete.

Form-Force Diagram

The form-finding process involves generating the form diagram based on the 3DGS approach. This approach was employed using the PolyFrame plug-in for Grasshopper (Nejur and Akbarzadeh 2021). Using this parametric plug-in, an algorithm was developed to iteratively subdivide and transform a tetrahedron, which served as the initial force polyhedral diagram. These transformations were controlled and modified by various design constraints such as table dimensions, the number of branching edges, maximum and minimum edge lengths, and angles between them until the desired form diagram was achieved—the form-finding stage resulted in a multi-branched network of lines representing a compression-only structure (Figure 6).

Form Realization

The form diagram was translated into a volumetric model using a circular cross-section representing the geometry of the intended concrete structure. The circular cross-section ensured uniform stress distribution and smooth concrete flowability during the casting process (Figure 7). The resulting tubular branches range from 30mm to 90mm in diameter, emphasizing a thicker node where multiple branches converge. To ensure optimal concrete flowability during casting, the confluence between the branches was smoothed and rounded, facilitating easy movement of fluid as per the structural and casting logic. In Cavity Shell, the SC was divided into three casting cycles based on the height value achieved from the hydrostatic equation. This division determined the placement of the 1-mm-thick hydrostatic membranes, resulting in 15 cold joints in the formwork. The position and alignment of these membranes informed the integration of casting inlet parameters, such as their position, height, and diameter, into the parametric model. Additionally, this computational model also analyzed the integration of casting inlets parallel to horizontal branches in the form to utilize pressure differences and assist in directing the concrete flow horizontally. Based on the formwork prototyping, a constant thickness of 1.5 mm was maintained throughout the formwork, making it ultra-lightweight to transport to the site.

3D Printing

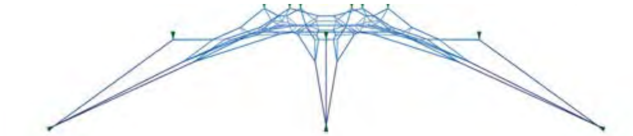
This research uses a setup of three SLA 3D printers, each having a build volume of 219x123x250 mm, to 3D print the formwork of Cavity Shell using ABS-like resin. Stereolithography uses a low-powered laser to harden a liquid resin contained in a reservoir to create the desired 3D geometry. Stereolithography printing was chosen based on its ability to generate high-quality surface finishing and intricate details, while upholding strict tolerances necessary for the formwork joinery system and scaffolding. The entire formwork was segmented into 54 discrete 3D printed segments based on the build volume of the SLA 3D printers, and was distributed over 27 prints (Figure 8). These 54 discrete segments were printed at a layer height of 50 microns culminating in a total printing time of approximately 400 hours. In addition to these formwork segments, 21 custom scaffolding structures, accounting for a total of 42 parts, i.e., 21 lower and 21 upper parts with a 25% infill, were also printed on the SLA 3D printer using ABS-like resin. This process took around 60 hours of print time to complete.

Assembly and Casting

The formwork assembly relied on scaffolding holders comprising 3D printed holders, 5/16" threaded rods and turnbuckles, and 54 discrete 3D SLA printed segments. These scaffolding holders were instrumental in securing the structure's position and mitigating any deflection during the casting process (Figure 9). Cavity Shell's formwork was assembled on an medium-density fiberboard (MDF) base, supported by 21 vertical scaffolding and three 3D SLA-printed foundations for optimal load transfer to the ground. Commercial Portland fast-setting concrete was used for sequential casting in three cycles. Each cycle took approximately 40 minutes to cast, and two and a half hours of setting time between each pouring cycle. The formwork assembly took less than 24 hours, and the casting process was successfully conducted within a day, demonstrating the success of 3D-printed plastic formwork, and sequentially casting it for constructing a compression-only concrete structure.

RESULTS AND DISCUSSIONS

The 'Cavity Shell' successfully demonstrated an in-situ construction of a compression-only concrete structure using 1.5-mm-thick, 3D printed, ultra-lightweight plastic formwork for the sequential casting method. The entire formwork was only 5.2 kgs, and took less than 48 hours to assemble and sequentially cast by two people. The cavity shell structure, measuring 1.4 meters in radius and 0.8 meters in height, utilized a total of 36 kgs of concrete. As compared to the heavy falsework required to construct a



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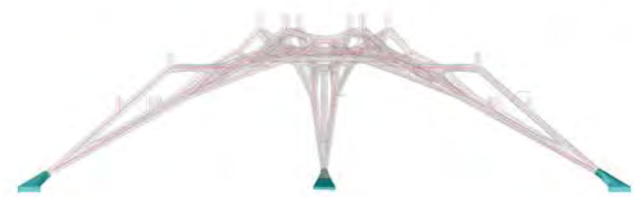

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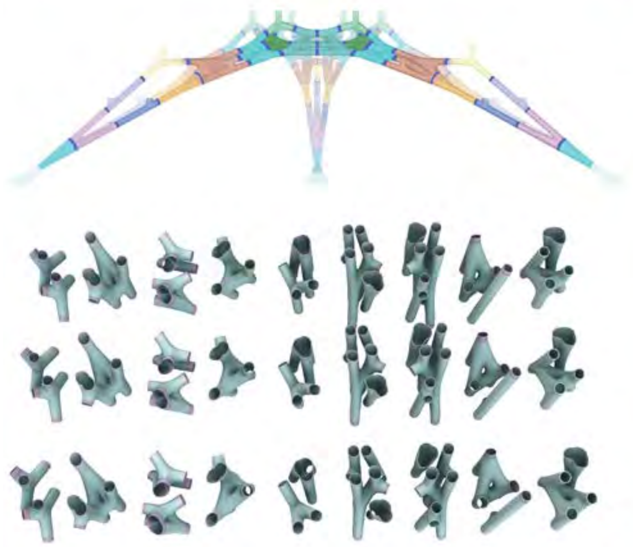

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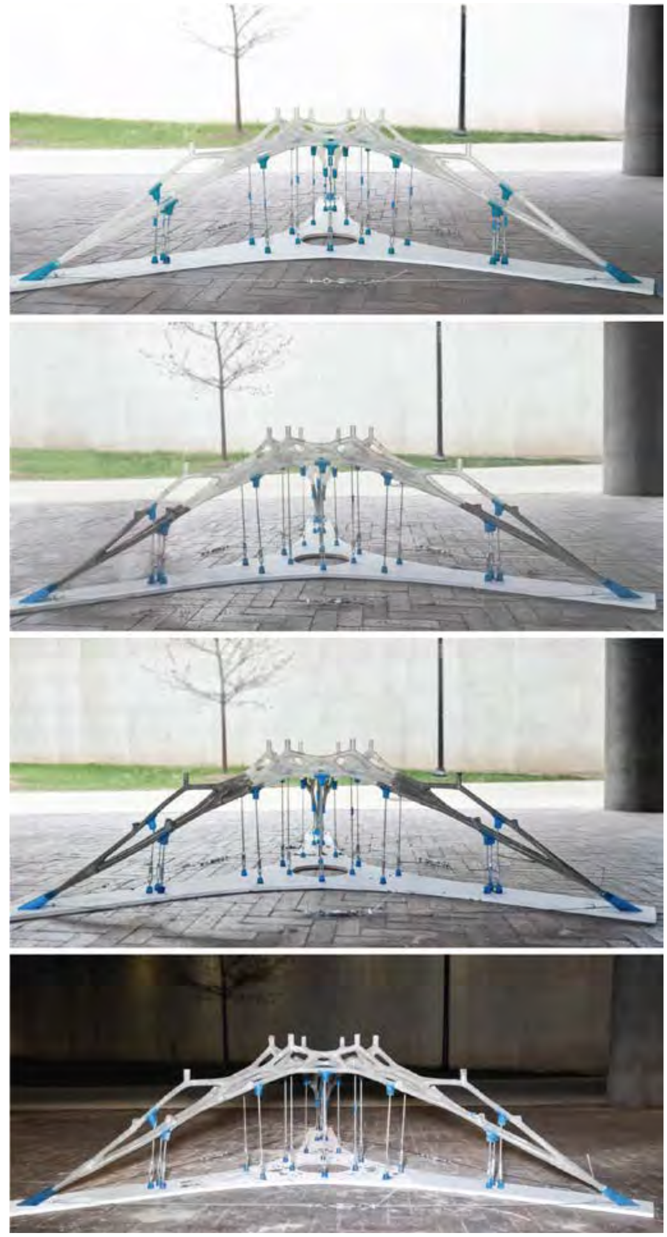

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6 Form diagram representiong a compression-only structure.

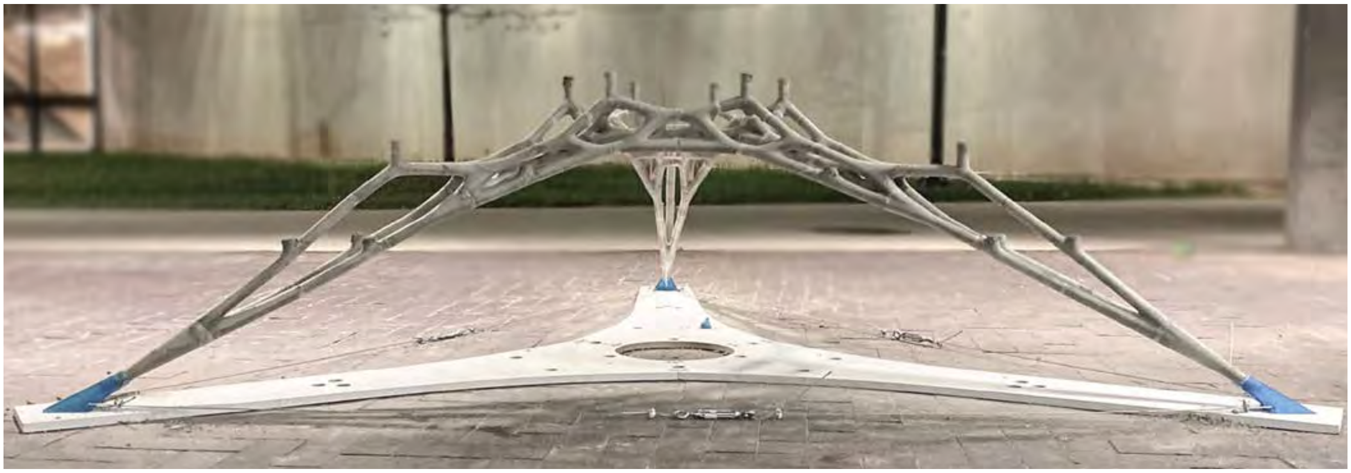
7 Tubular geometry ranging from 30mm to 90 mm in diameter generated from the lines achieved from the form diagram.

8 Formwork discretization into 54 discrete segments, 54 segments distributed over 27 prints for 3D SLA printing.

9 Step-by-step assembly of 3D SLA printed formwork in the compression-only followed by sequentially cast-in-place concrete in three casting cycles.

traditional compression-only structure made up of either heavy 3DCP components or small bricks/stones, the cavity shell only used 12 pieces of scaffolding to assemble the formwork. It successfully avoided any deflection during the casting process (Figure 9). The formwork easily withstood the hydrostatic pressure during the sequential casting process, demonstrating the potential of 3D plastic formwork printing for this method. Even if the structure is upscaled 5 to 10 times, the total weight of the formwork and concrete used for casting would still be comparatively less than the weight of components used in compression-only structures like Striatus or Armadillo, which are made on an architectural scale. Factors like weight reduction of formwork and decreased amount of scaffolding contribute to easy transportation to the construction site and reduced construction costs.

The 3D Graphic Statics method allowed for the development of an intricate tubular compression-only form with the minimized volume of concrete and carbon footprint, while maintaining the necessary mass for structural performance and specific architectural detailing. This intertwined tubular topology, ranging from 30mm to 90mm in diameter, highlights the optimized load-bearing capabilities of this compression-only system by not only taking its dead load but also maintaining its structural integrity after external load.



10 Cavity Shell, after removal of formwork, successfully demonstrated an in-situ construction of a compression-only concrete structure using 1.5-mm-thick 3D printed ultra-lightweight plastic formwork for the sequential casting method.

Using SLA 3D printing for formwork joints, with a thickness of 0.75mm, enabled precise fitting that successfully eliminated any leakage during the casting process. To ensure symmetrical load distribution on the formwork, and to control the atmospheric pressure which impacts the concrete flowability inside the formwork, it was observed that the sequential casting process needed to be carried out concurrently from all the inlets in the same Z plane of the structure. While the tubular formwork geometry allowed easy flowability of concrete and successfully resisted the hydrostatic pressure, the formwork was vibrated locally to remove the air gaps while casting in the form's horizontal branches. Future work will explore methods to remove the air gaps in horizontal branches.

CONCLUSION

In conclusion, this research highlights the digital design to materialization workflow of 3D printing ultralightweight formwork and sequential casting to construct compression-only structures. This integration of in-situ sequential casting of 3D printed formwork with compression-only structures provides the potential to rethink the construction of compression-only structures by minimizing the material used, and improving economic and environmental efficiency in their construction life cycle.

Sequentially casting this ultra-lightweight formwork in compression-only structures/architectural components like slabs, floor systems, columns, furniture, or any pavilion/habitable space will expand the possibilities of cast-in-place concrete structures, reducing the risk of cracking the ultra-thin formwork due to hydrostatic pressure. This research opens up the possibility of using materials like clay, biomaterial, and earth-based materials for casting and creating structural components, contributing to a more sustainable construction industry.

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IMAGE CREDITS

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