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# 3D Printing ICONs Cosmic Pavilion: A Case Study in Cementitious Extrusion of Unsupported Cantilevers

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## Abstract

In March 2023, construction technologies company ICON partnered with The Long Center for the Performing Arts to design and construct the first 3D-printed performance pavilion in downtown Austin, called the Cosmic Pavilion. The pavilion demonstrates new design possibilities in large-scale cementitious additive manufacturing of structures using ICON's Vulcan system. Designed by the Bjarke Ingels Group (BIG), the pavilion is an abstract shell geometry that merges two curvatures in concave and convex configurations to loft a wall in 3D-space. While small-scale polymer additive manufacturing demonstrates sufficient tension capacity across extruded filament bonds to resist cantilevering while printing— cementitious extrusion has little to no such tension capacity, which drives the classic limitation of lofted designs. However in the case of the Cosmic Pavilion, these limitations were mitigated through manipulating rheological properties of the cementitious material and executing a highly specific reinforcement strategy. The pavilion is an example of ICON's continued work to advance shell geometries and realize greater cantilevered angles without using shoring or scaffolding. The final result is an undulating structure that pushes the bounds of unsupported cementitious 3D-printed cantilever limitations.

**Keywords**: 3D printing, cementitious extrusion, printed cantilevers, concrete shell structure, construction technology

## 1. Introduction

Frequently in the construction industry, speed, affordability, and scalability come at the cost of beauty and functionality. In March of 2023, construction technology company ICON partnered with the Long Center for the Performing Arts, BIG (Bjarke Ingels Group), and Liz Lambert to construct the Cosmic Pavilion in Austin Texas, the first ever 3D-printed performance stage as shown in Fig.1 . In this paper, we discuss how the case study of this pavilion pushes the bounds of large scale construction 3D printing and detail the unique structural system that blends shell and wall design, culminating in the pavilion's final form.

One of the major benefits of 3D-printing technology is increased construction speed. Traditional construction methods often involve time-consuming design and sourcing, but with 3D-printing technology, the construction process can be accelerated. This not only saves time but also can control costs associated with labor and materials. Additionally, the reduction in material waste is a significant advantage in an industry that is increasingly focused on sustainability [1].

Figure 1: Performances taking place at the 3D-printed pavilion in Austin, TX

Customizability is another major benefit of 3D-printing technology [2]. The ability to create complex and intricate designs opens up worlds of possibilities for architects and designers. Structures can be tailored to meet specific requirements and aesthetic preferences, allowing for greater creativity and flexibility in the construction process without altering the cost. ICON utilizes a vertically integrated approach to implement large scale 3D printing and combines robotics (both design and manufacturing), software, material science, and architecture to provide a seamless workflow and precise structural execution.

ICONs material deposition robot, called The Vulcan shown in Fig.2, was utilized to print the Cosmic Pavilion. This 15’ x 46’ x 130’ robot operates in the cartesian plane and travels on Vulcan Y-rails, allowing for precise material deposition. The proprietary material used in the printing process is called Lavacrete. Lavacrete is a 2-3.5ksi cementitious grout material that is a specific combination of fine aggregate, cement, and admixtures that is entirely designed by ICON. This material is delivered from Magma, which is the Lavacrete handling and batching system, equipped with a mixer and pump delivery mechanism.

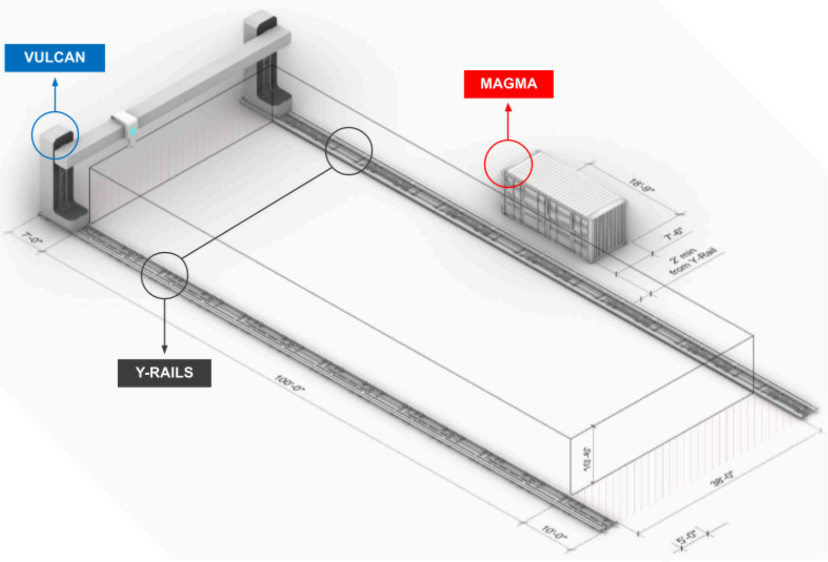

Figure 2: The Vulcan construction system used to print the pavilion

## 2. Cosmic Pavilion Design

Designed in partnership with BIG, the Cosmic Pavilion draws inspiration from the architectural design themes planned within an upcoming expansion of the El Cosmico development in Marfa, Texas. The Pavilion is an undulating curved surface that acts as a landmark, performance stage, and gathering space for culture and community in Austin.

The most interesting aspect of the Cosmic Pavilion is its freeform geometry. This can be seen in Fig.3. The structure features multiple layers of circles and leaning out of plane walls, creating a design that would be challenging and expensive to achieve using traditional construction methods. Laminar deposition of material naturally creates striations in the print, which gives the structure a unique rammed earth aesthetic.

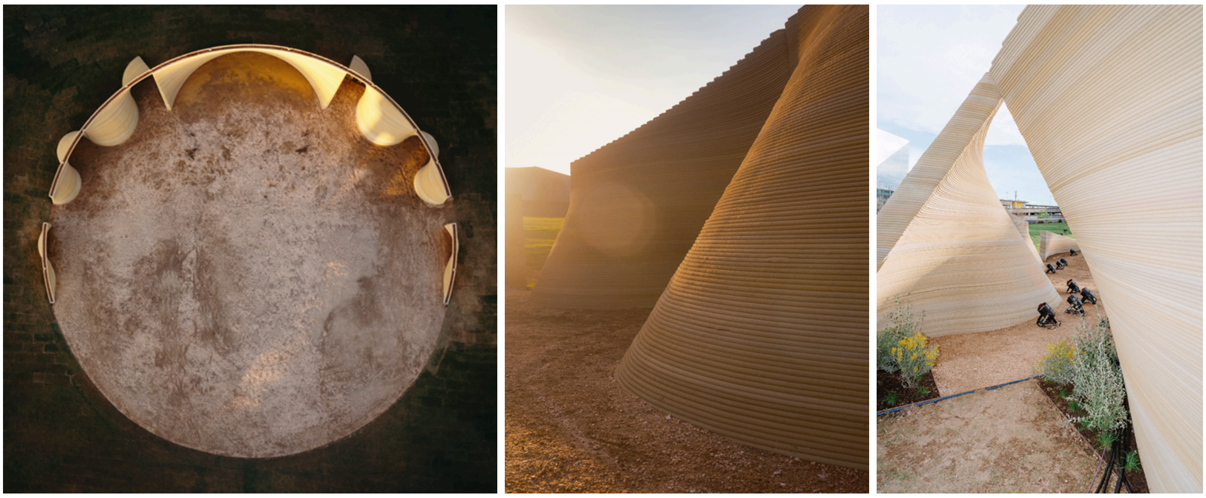

Figure 3: Photos of the Cosmic Pavilion

Printing was the primary function that enabled the architectural expression of The Cosmic Pavilion. From first to the last layer, the print only took two weeks, while the design and engineering for permitting required three months to prepare. In addition, reliance on digital and automated construction methods guided creative engineering solutions. The digital twin, or print path, used to direct Vulcan where to deposit material enabled geometrically precise rebar fabrication. It also enabled easy transition to other analytical tools that further assisted the structural design. The printing method took advantage of the ability to cantilever bead-to-bead in real time, which bypassed the use of formwork, thus reducing costs, time, and eliminating waste.

## 3. Cantilever Printing

A major classic limitation to architectural design of 3D printed structures is the permissible cantilever angle. This is due to the lack of tension capacity across extruded bonds in cementitious extrusion. This limitation becomes a significant hurdle when attempting to realize lofted designs without formwork, especially when depositing beads in a horizontal or corbelling configuration [3]. Overcoming this challenge required a collection of approaches (Fig.4).

To understand the solution space for the pavilion, existing literature on classic masonry solutions was reviewed. The internal angle of friction and cohesion of the material is what primarily determines the maximum cantilevering angle in any 3D printed cementitious object [4]. Typically, a common angle limitation is about 25 degrees from vertical. Exceeding this angle can lead to elastic buckling, plastic collapse, and structural instability[4]. In order to achieve the pavilion design without expensive and time consuming formwork, a highly specific solution was formulated to mitigate common cantilevering failure modes.

Figure 4: Construction printing an unsupported cantilever

Lavacrete is a proprietary mortar that uses fine aggregates, cement, and admixtures to make up the printed material. While in classic construction, mortars' fresh yield stress is commonly regarded as negligible, mortars' yield stress is actually nonzero even in fresh and green states. Lavacrete in the fresh state has enough yield strength to support itself and resist plastic collapse in the vertical condition. However, any cantilever condition inherently induces more stress on the material than a standard vertical condition. Given the Pavilion exceeds the classic angle limitation, plastic collapse in local areas (~10 layers) that exceed this limitation was the major construction and structural consideration. To overcome this local loading challenge, rheological properties were dynamically adjusted at magma using several admixtures, and an operations strategy that relied on coordinated timing of the specific layer length, hydration rate of the previous layers, and batch timing was executed [5]. This timing allowed the material to gain more yield strength in its green phase, and thus decreased the Lavacrete's internal angle of friction immediately prior to deposition. This allowed the local shear forces to be resisted when the structure was in shell form (during printing, before the cores were poured).

In addition to the standard in-bead reinforcement depicted in the 'Structural Approach' section of this paper, steel wire was employed to improve the tensile capacity of the structure while the lavacrete was in its green phase. The tension on the bead-to-bead interface and the global out of plane shear induced by cantilevering created a higher risk of elastic buckling during the green phase of hydration. Wire reinforcement was placed between beads in the longitudinal direction every other layer in areas where the structure exceeded the 25-degree from vertical failure limit. This reinforced against the shear loads during printing and supported the structure during the curing process. By increasing the individual beads' shear strength, and the tensile capacity of the individual wythes locally, ICON was able to achieve a cantilever angle of 35 degrees from vertical, without altering the bead shape.

Another aspect that played a crucial role in overcoming the instability challenge was the build rate. Build rate is a significant factor in any 3D - printing project, especially when dealing with cantilevered designs. The length of the print path on a construction scale can be long, and this fact makes it easier to outrun the relationship between the additional layers' self-weight and the material's yield strength development.

## 4. Structural Approach

The structural design of the Cosmic Pavilion combines elements of shell, wall, and beam design principles. Key elements of the structural design include tilted cores, a stepped bond beam, and a robust reinforcement design. The three phases of structural considerations for the pavilion are the material deposition/green phase, the shell phase, and the final fully grouted form. The material deposition/green phase was discussed in the previous section relative to the material properties and how the local plastic collapse and elastic buckling failure modes were mitigated on the local scale. This section will primarily focus on the shell and final wall phases.

Once the material hydrates past its green phase, structural action can begin to engage the newer layers in tandem with the older layers. This is where we can begin to consider the shell phase. This is governed by only the beads and the printed wythes of the cores providing structure. Because the geometry is only briefly in this shell phase, and is primarily in compression globally once the lavacrete begins to engage, the laminar bond strength can be considered negligible. This would not be the case if the geometry induced major areas of tensile forces across extruded bonded layers. The Pavilion was designed with this primarily compression shell phase in mind and it guided placement of additional core wythes where necessary.

The primary final structural form is composed of cores connected to an upper stepped bond beam, and a lower planar bond beam. These vertical cores were created by voids included with the print path inside the hollow wall. After printing, vertical rebar was placed in these cores and was quality control checked by the structural engineer. Finally they were grouted with Lavacrete using the Vulcan printer. These cores follow the profile of the pavilion, because it undulates between -35 and 35 degrees from vertical; this requires the cores to be tilted in some areas as shown in Fig.5.

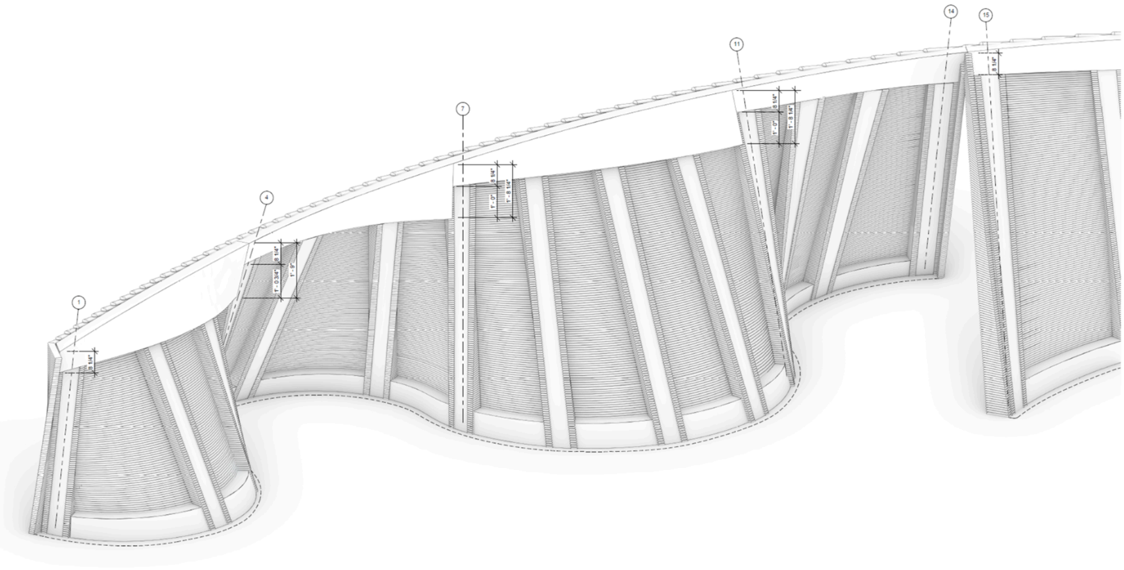

Figure 5: X-Ray View of the Cosmic Pavilion structural system

Because the topline of the geometry comes down at the wing tips to embrace the earth, the upper bond beam is stepped in sections to brace this topline. The reinforcement consists of large rebars in the cores and placed in the void that forms the upper and lower bond beams, with smaller rebars placed longitudinally between the beads during the printing process. The aforementioned digital twin enabled exact rebar shapes to be prefabricated and bent to match the printed geometry. In addition to the repeated rebar reinforcement, there is a reinforcement tie point at the connection of the stage backdrop and the wing walls. As shown in Fig.6 this rebar tie ensured stability and structural continuity between the three walls. The pavilion also includes a halo ring around the top of the geometry to light and shade the stage for performances. The load path for the halo was initially a challenge, which the structural engineer resolved by dropping its load path at the inflection point of the back wall. This eliminated inducing any additional tensile forces in the wall.

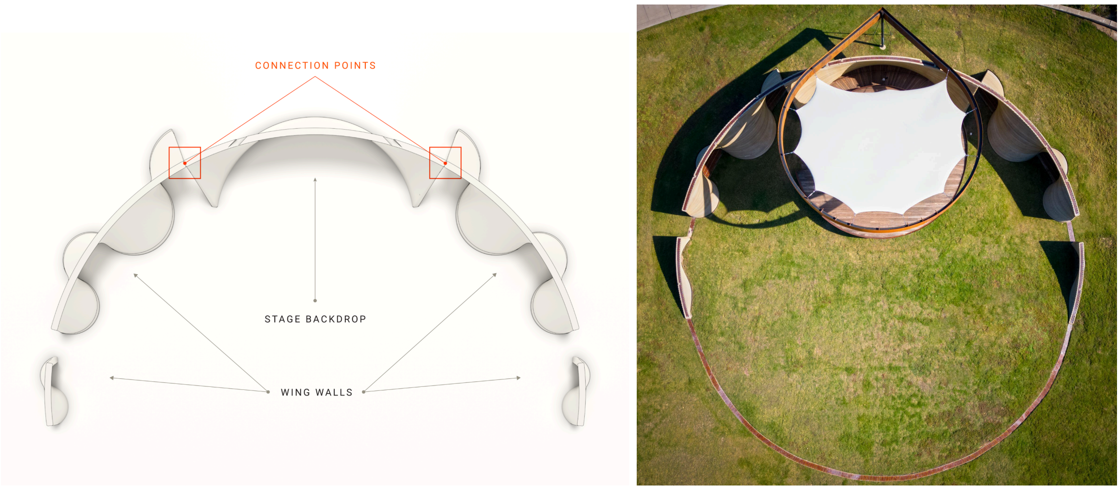

Figure 6: Diagram of the stage backdrop vs. wing walls, and Stage halo

To validate the integrity of the pavilion, as with most primarily concrete based structures, a quality control and engineering validation plan was executed throughout the print. Material cylinders were taken and tested periodically to ensure that the structure reached the required compressive strength. A Finite Element Analysis (FEA) was also conducted on the pavilion. This computational technique served multiple purposes, including:

- Validation of Structural Mechanics: FEA was used to ensure that the structure met necessary safety standards.
- Connection Point Investigation: A specific focus of the FEA model was an investigation of the connection point. This critical juncture required careful analysis to ensure it could withstand loads effectively.
- Construction Sequencing Analysis: FEA played a crucial role in analyzing the construction sequencing of the pavilion. This ensured that stability was maintained during the construction process, minimizing the risk of structural issues during assembly.
- The FEA was conducted using both shell and solid elements, allowing for a comprehensive evaluation of the pavilion's structural system. By comparing various approaches, a resilient structural design that could withstand the dynamic forces at play was created.

## 5. Conclusion

In conclusion, the Cosmic Pavilion pushes the boundaries of construction as a permitted structure printed at 35 degrees from vertical without using any formwork. The methods developed to improve the cantilever angle address the three major concerns with 3D printing: elastic buckling, plastic collapse, and structural instability. These methods provide innovative construction examples of real time cantilevering to enable more innovative architecture and showcase the immense potential of advanced robotic construction practices. The Cosmic Pavilion challenges the structural industry to push boundaries, embrace advanced methodologies, and reimagine what's possible.

## Acknowledgements

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