DE:Stress Pavilion

Print-Cast Concrete for the Fabrication of Thin Shell Architecture

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1 DE:Stress Pavilion: Concrete 3D Printed Panelized Shell (Hadley Fruits, September 2019).

Intro & Context

Print-Cast Concrete investigates architectural-scale concrete 3D printing in robotically tooled recyclable green sand molds for the fabrication of rapidly constructed, structurally optimized, architectural-scale concrete structures. Utilizing a three-dimensional extrusion path for deposition, this process expedites the production of doubly curved concrete geometries by replacing traditional formwork casting or horizontal corbeling with spatial concrete arching. Creating robust non-zero Gaussian curvature in concrete, this method increases speed for mass customized concrete elements, eliminating two-part mold casting by combining robotic 3D printing and extrusion casting. Through the casting component of this method, concrete 3D prints have greater resolution along the edge condition resulting in tighter assembly tolerances between multiple aggregated components.

Methodology

In exploring the intersection of mass customization, rapid manufacturing techniques, concrete 3D printing, and pre-cast construction, this research developed a process of robotic fabrication combining both CNC robotic milling and concrete material deposition. Looking at low-cost reusable aggregate formwork, a green sand mixture was utilized for the creation of bespoke molds. Used in the casting of molten metal and glass sand molds, green sand can resist materials with high temperatures and retain resolution when making molds of intricate geometries. The green sand is utilized for the fabrication of the Print-Cast molds as it is inexpensive to produce in large quantities, can be CNC tooled at high

PRODUCTION NOTES

Architect:	Battaglia+Miller
Client:	Exhibit Columbus
Status:	Temporary Exhibit
Location:	Columbus, Indiana
Date:	2019

2 Print Cast Concrete Green Sand Tooling (Hadley Fruits, June 2019).

3 Finished Print Cast Panel (Hadley Fruits, June 2019).

4 Robotic Print Casting in Sand Mold (Hadley Fruits, June 2019).

speeds, and can be recycled, remolded, and reshaped with little effort. Utilizing all six robotic axes, the sand mixture was strong enough to perform undercut milling geometries into the side wall of the sand forms, proving the concept of precise interlocking plug to socket edges could be implemented into the design process.

With the sand mold processed, the material deposition of 3D printable mortar can begin. Switching end effectors from the CNC spindle to the concrete extrusion end effector, 3D printable mortar is weighed and mixed in relation to the toolpath generated for the Print-Cast Panel. Partnering with LATICRETE International, Inc, 3D printing mortar was developed that exhibited an open extrusion time between 45 minutes to one hour, could deposit and stack 9 mm layers consistently, and had a load bearing capacity of 29.2 MPa after a curing period of 28 days. Over-extrusion was utilized along the sand mold edges to press the material against the mold and cast into the undercut edge geometry necessary for the panel-to-panel connections.

The process of Print-Cast Concrete was developed in conjunction with the necessity to produce a full-scale architectural installation commissioned for Exhibit Columbus 2019. The proposal was to design and fabricate a concrete 3D printed compression shell, spanning 12 meters in length, 5 meters in width, and 3 meters in height, with four parabolic arches allowing entry into the proposed project, consisting of 110 bespoke panels ranging in weight of 45 kg to 160 kg per panel. Using this production method, the project had the ability to be assembled and disassembled within the timeframe of the temporary outdoor exhibit, produce <1% of waste mortar material in fabrication, and utilize 60% less material to construct than cast-in-place construction.

Looking at pure compression structures, the application of Print-Cast Concrete centered around shell design and typology. The design of the concrete shell was tasked to respond both to material, form, site, and context within the scope of the overall exhibition. Using evolutionary solvers, one parameter of the shell was to touch down to

5 On Site Construction and Assembly (Hadley Fruits, August 2019).

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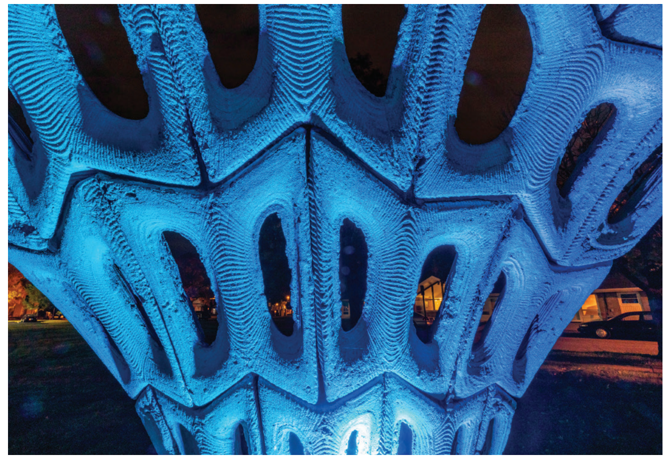


7 DE:Stress Pavilion: Interior Shell (Hadley Fruits, September 2019).

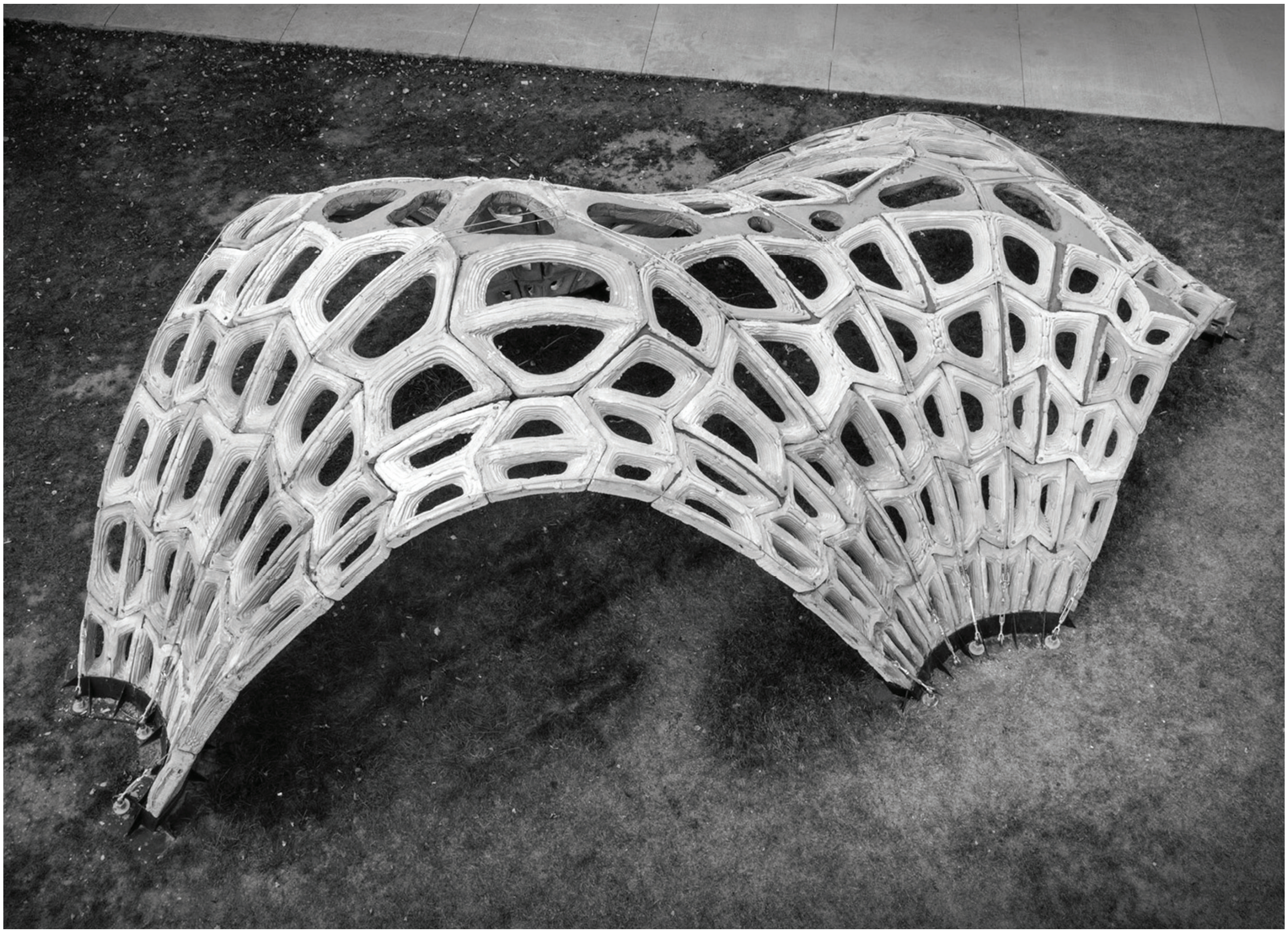
8 DE:Stress Pavilion: Interior Shell (Hadley Fruits, September 2019.

the ground plane at four locations with curvilinear radii. The resulting parabolic arches of various heights created the openings into the structure that responded to both compression forces and site conditions. Structural analysis integrated into compression form-finding algorithms produced the curvature of the overall geometry placing the project in a state of pure compression. Since the installation was temporary, 6.35 mm steel cabling and tension rods spanned over the exterior of the shell placing additional compression forces on the arches and spans. The addition of this force load was to ensure that an acting force of an unexpected live load would not shift the structural integrity of the structure.

The shell geometry was subdivided into 110 bespoke panels, with constraints determined by the bounding box geometries of the compressed sand mold blanks and reach of the Kuka kr60 robotic platform. Form generation for these panels looked at interlocking geometries that when placed into compression would interlock within one another. Formally resembling a bow tie, the edge seams between panels would not span across multiple rows of individual geometry. Panel sub-divisions and openings within each of the panel geometries corresponded to the optimized force loads moving through the structure, resulting in the reduction of weight and material usage. Due to the fabrication process, the material texture on the panel's interior inherits the ornamentation of tooling and casting while the exterior layering expresses the extrusion process.

Results

Using the sand mold to contain the edge conditions of each panel geometry, the Print-Cast technique allows for precise geometry along the edges. To increase the pavilion's resistance to shear forces, interlocking nesting geometries are integrated into each edge condition of the panels. Not exceeding 0.785 rad of undercut, the CNC spindle end effector on the robotic platform tooled out the plug and socket sand geometry. Utilizing the precision of casting during the printing process insures accuracy and tight tolerances within concrete 3D printing. When nested together, the edge condition informs the construction



9 DE:Stress Pavilion Completed Shell Structure (Hadley Fruits, 2019).

logic of both the panel's placement and orientation for the temporary concrete panelized shell. This project was fabricated by 2-4 team members over the course of three months utilizing one robotic arm, simulating a larger manufacturing cycle. For on site assembly, a temporary waffle form was utilized for panel placement and then disassembled upon shell completion.

ACKNOWLEDGMENTS

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IMAGE CREDITS

Figures 1-10: © Hadley Fruits, 2019

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Christopher A. Battaglia was formerly the Design and Innovation Fellow and Associate Research Professor at Ball State University College of Architecture and Planning, researching concrete 3D printing robotics, heavy timber construction, and structural optimization techniques. Battaglia's work looks to the intersection of material handcraft through the lens of digital tools and experimental processes. Battaglia teaches studios and seminars focused on architectural design-build projects in collaboration with industrial partners.

Martin Miller is primarily concerned with how the digital onslaught will define our future realities, both physical and virtual. He is the co-founder of the design office AntiStatics Architecture based in Beijing and New York City. Defining a mantra which is ever adaptive to emerging technologies, AntiStatics' work seeks to find a balance between our convergent existences. Miller is currently a Professor of Practice at Cornell University's AAP, where he teaches graduate studios as well as seminars focused on the implementation of computational design techniques including artificial intelligence, simulation, and robotic fabrication.

Dr. Kho Verian is a scientist at LATICRETE International, Inc. He graduated with a bachelor's degree from the Civil Engineering Department of Universitas Katolik Parahyangan, Indonesia in 2008. He earned his MSCE (2012) and PhD (2015) from the Department of Civil Engineering at Purdue University, USA. His current research focuses on the innovation and development of sustainable construction materials. One of his works in innovation is in developing LATICRETE® 3D Printing Mortars, which have been used in several 3D construction printing projects worldwide.