ARCC 2018 Research Incentive Award – Final Report: September 30, 2019

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Project title:

Polycasting: multi-material 3D printed formwork for reinforced concrete

Project aims and objectives

The goal of this project is to design, construct, and test prototypes for a new generation of non-standard concrete formworks that are structurally efficient, reduce material and labor costs, and expand the expressive design potential of concrete. The project explores dual-extrusion 3D printed formworks for casting concrete: simultaneously printing a combination of containment and integrated reinforcement.

Our research focuses on the following questions: 1. Can water-soluble formworks provide an alternative to, or augmentation of, traditional concrete fabrication by allowing for variable density forms with greater geometric flexibility (e.g. undercuts and non-planar openings)? and 2. Can dual-extrusion additive manufacturing improve the performance and economy of these non-standard geometries through 3D printed embedded tensile reinforcement?

Research summary

Based upon our prototypes, research question #1 appears to have a positive answer: it is possible to create forms which would be difficult to cast in concrete using existing subtractive methods of standard or flexible formwork. We successfully cast a series of scale columns with complex geometry containing undercuts and other attributes that would not be possible to remove without the dissolving properties of the biodegradable formwork. (see Methods 1 and 2) However, the potential of multi-material 3D printed formworks is indeterminate at present. One reason for this is that the 3D printing process is currently slow and unreliable, especially with steel PLA filament. It has been challenging to generate enough physical prints for testing. This may be addressed with reliable and better performing filament materials. (see Method 4)

The answer to research question #2 – performance and economy of multi-material formworks – is not yet determined and will be the focus of our work, moving forward. We recently collected data on the labor and time costs for site-cast concrete. We are still collecting data from our printing experiments so we can make a fair comparison of the economy of 3D printed formworks at-scale. (see Methods 3 and 5) The scalar limitations of PVA are cause for reconsidering material in larger prints. An alternative material may need to be found or developed. Additionally, the complete elimination of formwork (Leach, Carlson, Khoshnevis, & Thangavelu, 2012) may continue to be more preferable than the introduction of biodegradable or water-soluble formworks. The most promising application for these methods might be the augmentation of or compositing with traditional formwork. This would allow for the development of custom liners or the design of sections of formwork which could be dissolved to reveal unique moments of complex geometry within typical concrete construction methods.

Research methodologies

Method 1: Dual-extrusion printing with PVA and steel PLA

The first phase of our research explored the creation of formwork mock-ups using selected materials that work within the scale of available fabrication technology. Our methodology used materials that serve as scaled proxies for construction technologies: steel PLA filament (reinforcement), hydraulic expansion cement (concrete), and polyvinyl alcohol (PVA) (formwork).

Fabrication Equipment
Fabrication for this project relied upon a desktop LulzBot TAZ 6 3D printer which bounded the scale of formwork to the constraints of the print area: 280 mm x 280 mm x 250 mm (11 in x 11 in x 9.8 in). Despite limiting the size of the prints early iterations took approximately 9 hours to print and the final iteration took approximately 20 hours to print. Additionally, the project required a LulzBot TAZ Dual Extruder v3 Tool Head which was used to print two filament types simultaneously at temperatures range of 120- 300° Celsius. Proto-pasta Steel PLA and eSUN PVA were printed at 220° Celsius. As research moves into the architectural scale the project will need to move beyond the desktop scale of fabrication and into the use of robotic arms with custom end effectors.

Reinforcement: Steel PLA Filament
This project used 2.85 mm (0.11 inches) Proto-pasta Steel PLA as a scaled version of variable profile steel reinforcement. PLA filament is a biodegradable and bioactive thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, cassava roots, chips, starch, or sugarcane. Steel PLA is a compound of polylactic acid and finely ground steel held together with a polylactide resin. At 2.4 g/cm3 (2400 kg/m3) Steel PLA is 93% more dense than common 3D printing. It prints at a hot end temperature: 195– 220° C (MSDS Sheet, 2015) As the filament is, at best, a simulation of structural reinforcement, it is at present difficult to accurately calculate the modulus of elasticity or its relationship to that of structural steel E (29,000 ksi).

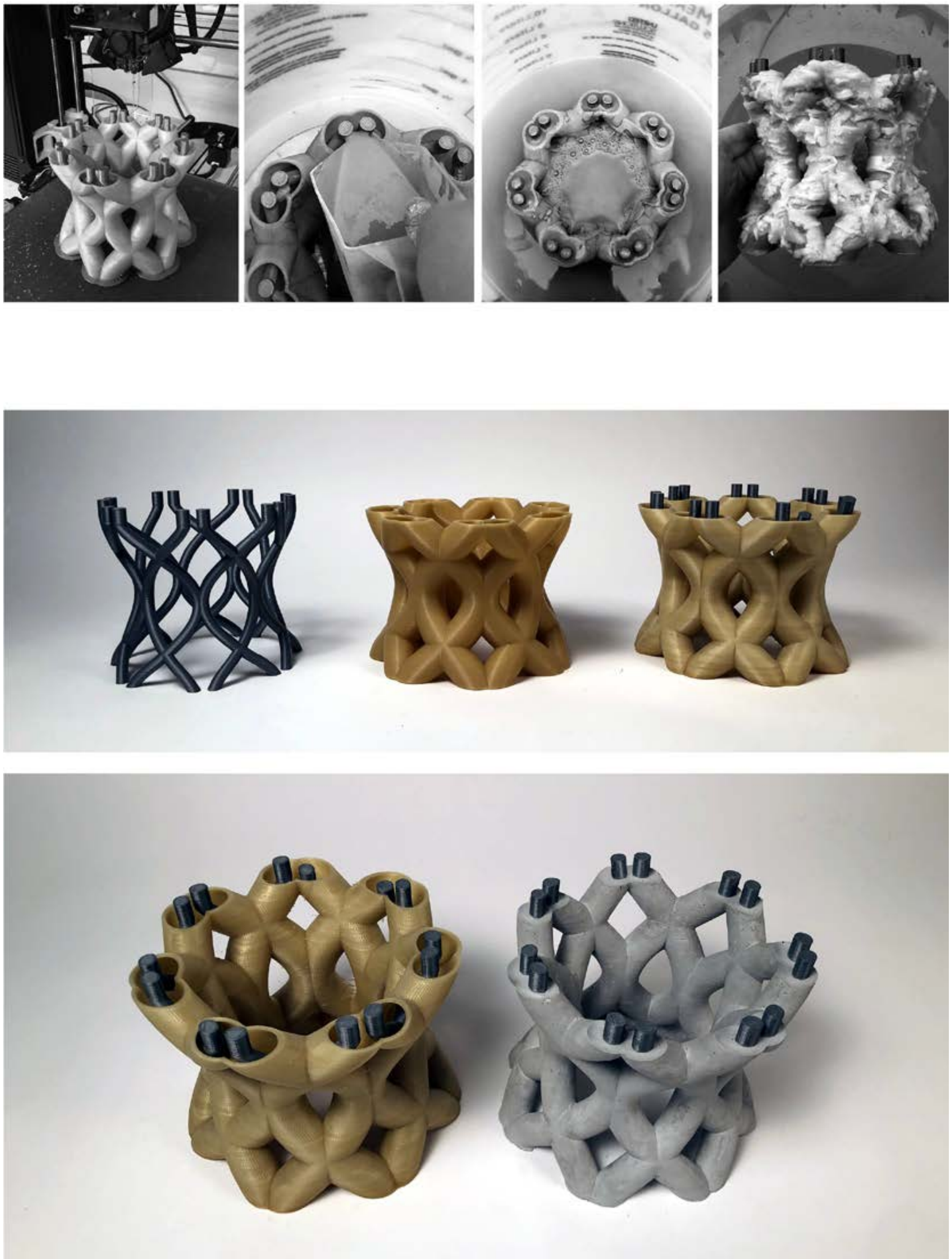
Formwork: Polyvinyl Alcohol Filament
This project used 2.85 mm (0.11 inches) eSUN PVA or Polyvinyl alcohol, a water-soluble synthetic polymer which is biodegradable and nontoxic. This filament has a low melting point of 190° Celsius and begins to undergo an irreversible degradation of the material known as pyrolysis at temperatures higher than 220° Celsius. (MSDS Sheet, 2014) It prints on a 60° Celsius heated bed at a slow printing speed of 30 mm/s. PVA objects will start to dissolve in room-temperature water within approximately twenty minutes of submersion and will completely dissolve within twenty-four hours. Warmer water and changing the water once it becomes saturated with PVA will speed dissolving rates.

Hydraulic Expansion Cements (HEC)
Given the small scale of these experiments, concrete mixtures (sand, gravel, cement, and water) were not possible or appropriate. Instead, Hydraulic Expansion Cements (HEC) were used. HEC are a combination of sand, cement, and water. They are fast setting with more than twice the strength of fully cured conventional concrete with an initial set time of 15-20 minutes. Within one hour of pouring they develop compression strengths of 31 Mpa or 4500 psi. Due to outward pressure of hydraulic forces the HEC when set grips metal to concrete permanently. (About Rockite, 2018) As the research evolves into the architectural scale, the addition of aggregates is a material constraint which will need to be addressed.

Parametric Model Design
The parametric model for the project was produced in Grasshopper with the goal of generating a form which would be difficult, if not impossible, to cast using traditional mold making methods or flexible molds. Additionally, the model integrated the fabrication tolerances of the equipment and materials used in this research. The model was developed as a tool to be used throughout the design process, from the first iteration and into future design proposals.

To begin, the model was bounded to the scale of the LulzBot TAZ 6 print area: 280 mm x 280 mm x 250 mm (11 in x 11 in x 9.8 in). It would be difficult to remove support structures when printing with PVA filament therefore our design was limited to a 45-degree overhang, the angle FDM can print to with no loss of quality. This limitation informed the designs. To establish the geometry a series of graph mappers were used to manipulate the rotation and profile of a range to create the elevation of a series of cylindrical points. The points were then interpolated, polar arrayed and radially mirrored around the center of the volume to create an interwoven design. Resulting curves were subsequently piped. To minimize the amount of PVA used to create the formwork, the positive was scaled up to generate the formwork. The scaled formwork was then differenced from the positive HEC form to produce the PVA print. This method allowed for quick testing of the shell thickness. The rebar was inversely scaled to three millimeters. In future iterations Karamba will be introduced to calculate variable diameters of the rebar for efficiency and structural integrity. Upon competition of the design the top face of the rebar was extruded ten millimeters in the z-axis, so it would protrude from the column and offer a potential construction method to connect to standard formwork.

Printing and finishing
The first series of digital models was printed in PVA on the Lulzbot Taz 6. Printing a typical model (7.5” [190 mm] in diameter and 8.2” [210 mm] in height at a standard resolution or 0.25 mm layer height) takes approximately 120 hours to complete. On average, printing requires 1660 grams or 208 meters of PVA filament and 243 grams or 36 meters of steel filament to print (approximately five rolls of PVA and half of a roll of SS PLA filament for a total material cost of one hundred eighty-five dollars). Once printed, the molds are filled with hydraulic expansion cement (Rockite) and left to set for one hour. Then, the molds are submerged in room-temperature water for twenty-four hours at which point the majority of the PVA dissolves. Remaining PVA is removed by hand using dental instruments.



Polyvinyl Alcohol (PVA) formwork with Steel PLA reinforcement

The images above demonstrate from left to right: a final PVA mold with embedded variable profile reinforcement, the mold halfway through the process of dissolving (upper-left image), and then final images of the resulting cast on the bottom row. In the printing process of this example, two sections of the reinforcement filament failed during the print and the PVA print offset horizontally slightly at about 7” (177 mm) in height. At the most extreme angles the reinforcement comes very close to the outer edge of the pour. Establishing and maintain proper ‘rebar cover’ minimums and establishing tolerance protocols will be necessary in future research. The standard print settings also result in a striated surface finish which could be reduced or possibly eliminated by higher resolution printing, at the expense of a longer fabrication time. Aside from these issues, printing and casting have proceeded as expected.

While we did manage to successfully print designs that demonstrate the potential of biodegradable formworks, the difficulties of printing metal PLA make it unlikely as a viable material for printing reinforcement. Because have been unable to produce enough formworks to allow us to use concrete testing equipment, we are now exploring alternatives to metal PLA. See Method 4.

Method 2: Clay printing as an alternative to PVA

Summary images of full-scale ceramic formwork prototypes.

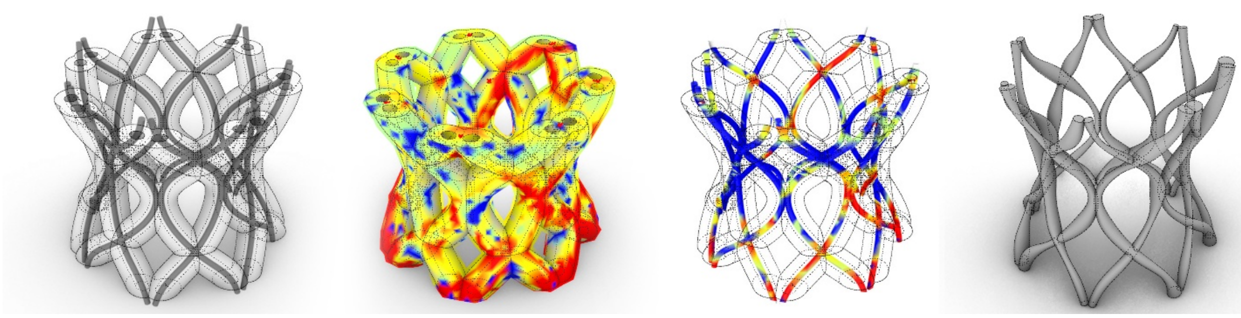
In an attempt to address the issues that we encountered with PVA printing, we began experimenting in parallel with 3D ceramic printed formworks using a Potterbot 7 (3DP7) by Deltabot. The printer has an envelope of X-17" (432 mm), Y-14" (356 mm), and Z-19" (483 mm). Each form used a custom 3D printed ABS nozzle with a start geometry. The forms are each 7.5 inches in diameter to match an off-the shelf tube form (8" nominal / 7.5" actual diameter) and a height of 15".

The ceramic 3D printed form was cast using Rockite and the standard formwork was cast using off-the-shelf Quickrete ProFinish concrete. A ring of 3/8" rebar was used to tie the two forms together and to experiment with locating rebar within a non-standard column form. Even the minimal curve of this design required developing a jig to keep the rebar under cover. Future work will need to be done regarding bending and placing non-standard rebar.

One advantage of this method is that the nozzle is much larger, which reduces the printing time considerably. In addition, the clay does not need to be dissolved in the same manner as the PVA, which makes it easier to remove. However, the time involved remains nontrivial. Each test print took about 3 hours in addition to several hours committed to making and pug milling the clay. Furthermore, the clay cannot be reused for future prints as it now contains bits of concrete.

Another disadvantage of using 3D printed clay is that the medium does not always provide sufficient containment for the concrete. This is a material limitation of casting wet concrete into leather-hard clay. A reusable sand enclosure could be used to provide counter forces to the outward thrust of the concrete. However, this would involve construction a formwork for the sand to surround the clay evenly which leads to a "double formwork." And so, ceramic printing does not appear to be an efficient method, particularly at full-scale.

Method 3: Structural simulation and variable reinforcement

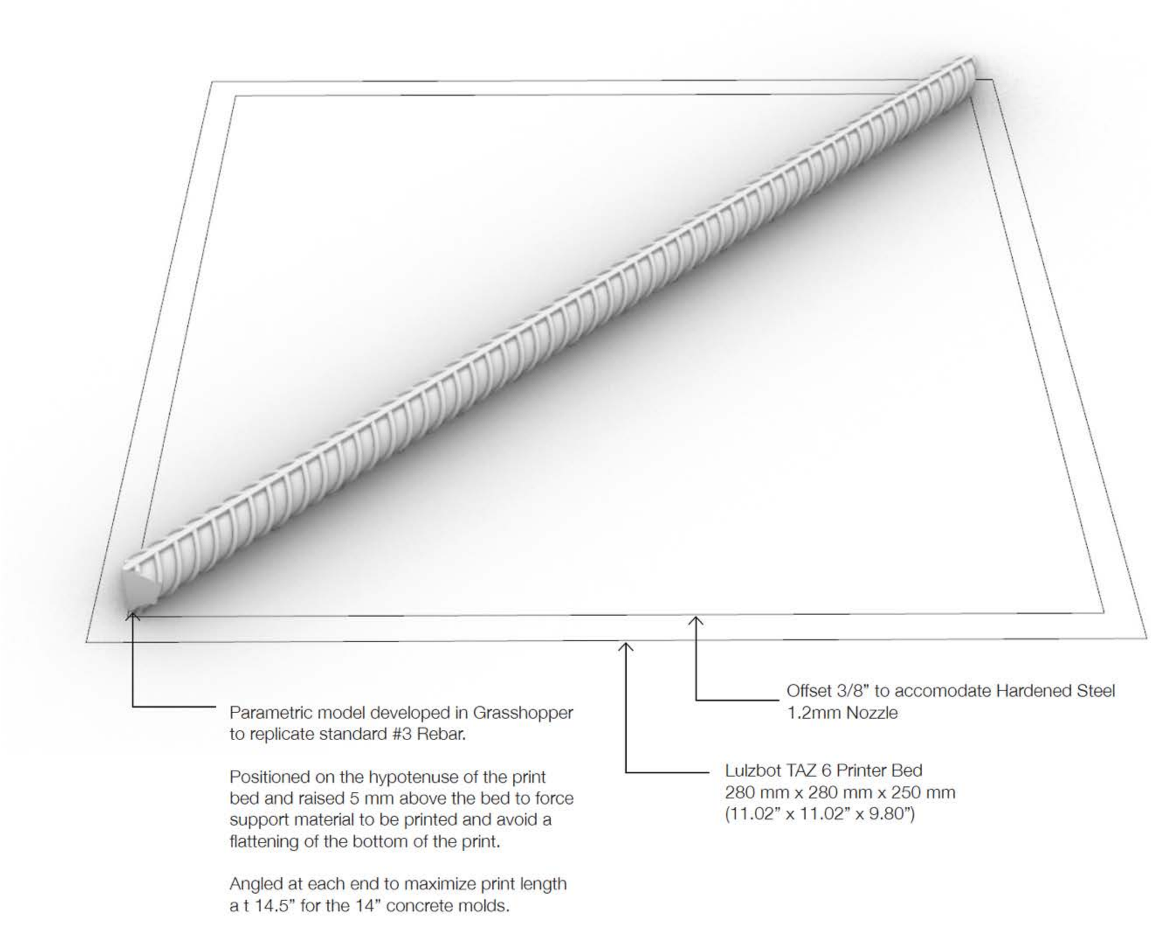


Karamba analysis of concrete column, illustrating transfer of forces to variable-profile reinforcement model

Traditional rebar has a consistent cross-section and limited ability to conform to its containment. We propose that 3D printing can be used to generate reinforcement with variable cross-section and reinforcement to optimize performance within a non-standard 3D printed formwork. We used Karamba simulations to calculate stress points in our concrete geometry. Using these points, we moved the profile center and increased the radius of the rebar cross-section to optimize the geometry of the reinforcement. However, we still need to determine a simulation method to re-analyze the column with our updated reinforcement process, as Karamba presently assumes uniform reinforcement. ANSYS may be more suitable for a non-standard configuration of this type. Because of the failures with the metal PLA filament, this part of the research is suspended for now, pending our testing of other material performance.

Method 4: 3D printed reinforcement materials testing

The latest phase of Polycasting is an effort to determine a faster printing and more reliable filament material to use for the reinforcement. There have been previous experiments with mixing fibers into 3D printed concrete (Hambach & Volkmer, 2017), extruding cables (TU Eindhoven, 2019), and printed meshes (Hack, et al., 2017). Printed solid reinforcement appears to be an uncommon method of introducing it into concrete. The manufacturers list tensile strength information for each filament, but to best of our knowledge, there is no data available regarding the performance of commercially available filaments used as concrete reinforcement.



3D printed rebar, modeled and oriented for TAZ 6 printer bed.

To begin our experiment, we created a 3D model that duplicates the geometry of standard #3 rebar (~3/8” in section) and printed copies in ABS, ABS Pro, PET-G, nylon, nylon with glass fibers, nylon with carbon fiber, and ABS with carbon fiber. Then 14” lengths of rebar were printed by a TAZ 6 fitted with a recently released high strength, larger nozzle (1.2mm rather than the 0.5mm nozzle from earlier tests) to improve material flow and reduce printing time. The printer settings varied depending upon the material, but all copies used a 100% linear infill for strength. Average printing time was 56 minutes, compared to 2 hours 46 minutes with the smaller nozzle.

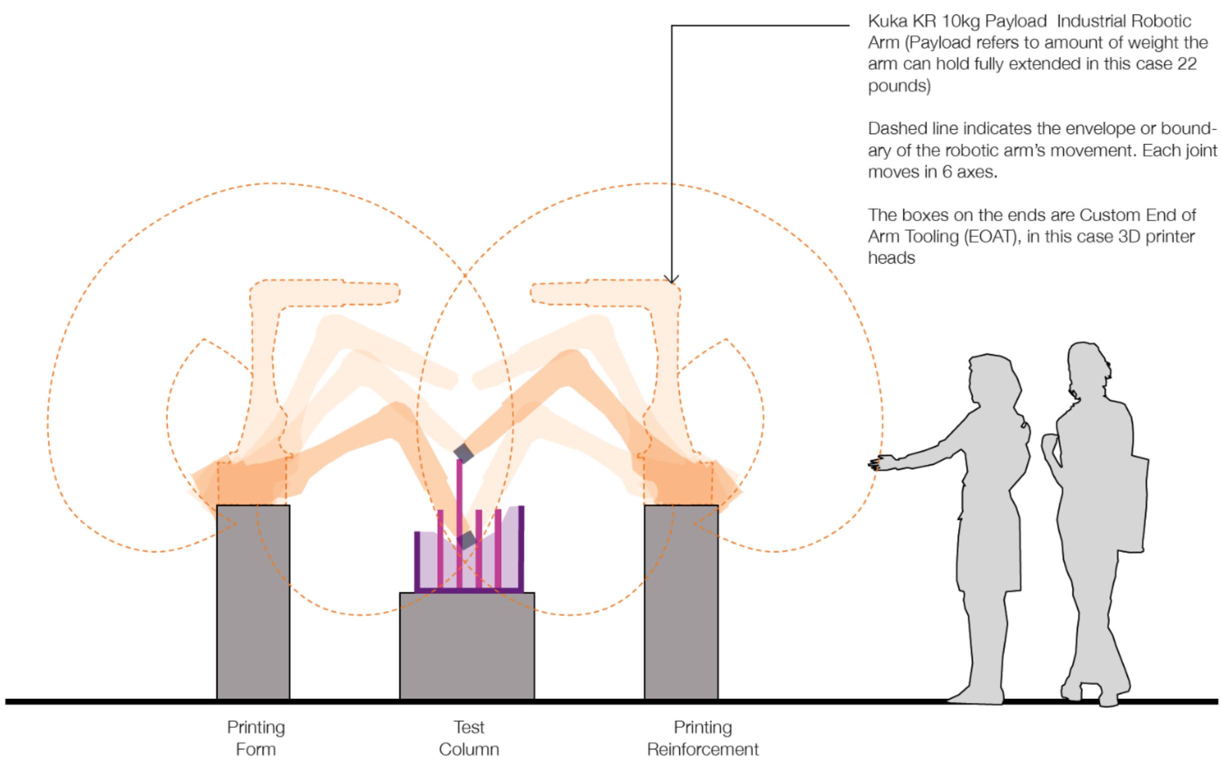
Concrete molds with carbon fiber PLA (left) and ABS (right) rebar.

The printed rebar was inserted into 4”x4”x14” concrete testing molds and cast with 3800 PSI concrete with no aggregate (1:2:1 ratio of cement, sand, and water; in our testing the ratio of water was closer to 0.8). Each filament material was cast three times, in order to generate an average performance profile. We also cast one set of three molds with #3 steel rebar and another three molds without rebar, as controls. The molds are currently curing in water to ensure equal humidity for testing. 28 days after casting (early October) we will use a hydraulic testing machine to determine their performance. See Appendix A for more about the concrete testing methodology.

We do not expect any of the filaments to perform as well as steel reinforcement, but we do hope to determine the best performing filament that can be printed within a 3D printed mold at this time. Our testing should provide data on tensile strength and failure modes as it compares to other filament variables such as cost, weight, temperature, printing time, etc. Once these criteria are understood, it may be possible to achieve more strength and/or efficiency by adjusting the printed rebar profile, geometry, and placement within the formwork. As we move forward, the data we collect would allow for more specialized formwork designs with different types of filaments selected for their reinforcement properties.

See Appendix B for a list of the filament types, printer settings, and other materials data.

Method 5: Multi-material printing beyond desktop scale



Proposed workcell configuration for multi-material formwork printing.

Following the conclusion of the filament experiments, our plan is to modify two industrial robotic arms to serve as a multi-material extrusion workcell. We received the robots in late May and have spent the summer installing, integrating, and training with them. Many of the end-effectors have not yet arrived and others require custom tooling to install that we are still designing. This has prevented us from developing any workflows. We are in the process of installing grippers to experiment with the placement and bending of steel rebar within a 3D printed formwork. However, because there are no off-the-shelf 3D printer end effectors, we will have to create those in our lab. We expect to complete this work during Spring / Summer 2020.

Once the 3D printer end effectors are working, the goal will be to demonstrate a successful printed piece at a larger scale than is possible with conventional, enclosed 3D printers, on the way toward construction-scale prints. One robot will print the PVA enclosure, while the other will print the reinforcement. This should allow us to use significantly different extrusion temperatures without issue. It may be possible print both materials in the same layer, coordinating their paths to avoid collision. Otherwise, the process could alternate active robots for each pass. We will need to experiment with methods for printing with two robots simultaneously – the synchronization and coordination challenges are nontrivial.

Key findings

- We created prototype concrete column sections of geometric and formal complexity which would have been difficult to create using other subtractive casting methods. This suggests that, under the right conditions, multi-material 3D printing is a potentially viable alternative to traditional concrete formworks. However, several technical and design challenges remain in order to make the method more reliable and extend it to construction scale. These include: filament selection, formwork and reinforcement geometry optimization, and the design of multi-material extrusion hardware for printing at construction scale.

- Our initial material studies identified PVA as the best-performing biodegradable filament -- albeit one with its own unique challenges. In a comparison to HIPS and HIGH T-LAY, eSUN PVA was less expensive with easier removal and higher-quality casting outcomes. However, PVA can be a challenging material in its own right. When exposed to ultraviolet light, it begins to biodegrade. Furthermore, it is aggressively hygroscopic, which can make it prone to breaking, especially during long prints. For these reasons, biodegradable molds for construction may have to be fabricated in a controlled shop or factory setting, rather than on-site.

- Due to the significant temperature differences between the PVA and high tensile strength filaments, multi-material printing with a standard dual-extruder may not be possible. Printing with two separate extruders, using synchronized robotic arms, could overcome this limitation.

- Printing time remains a significant challenge. It took approximately 120 hours to complete a mold 7.5” (190 mm) in diameter and 8.2” (210 mm) in height at a standard resolution or 0.25 mm layer height. One of our priorities is to experiment with new methods and workflows to make this process more efficient. A larger nozzle does seem to help improve printing speed, but it is unclear if there are structural consequences arising from larger layer sizes.

- The performance of metal PLA reinforcement in the multi-material print appears to be poor. In many of our tests, it did not print in a reliable fashion compared to the other filament types. Because it is so brittle, it often stops printing or prints incorrectly, resulting in unacceptably exposed reinforcement. Tests following our interim report resulted in damage to our 3D printers. Less brittle filaments with high tensile strength, such as nylon and carbon fiber, may be a better substitute for 3D printed reinforcement.

- Ceramic printing may also be a viable multi-material method for printed biodegradable formworks, but more research is needed to overcome the limitations of this method.

- Following our estimations of the cost of multi-material 3D printed formworks, a biodegradable custom formwork seems most economical for complex geometries and conditions where constructing or installing wooden formworks would be prohibitive. It does not compare favorably to traditional formworks in standard applications, where economies of scale and labor tend to optimize costs.

Future work

This research was recently awarded an AIA Upjohn Research Initiative Grant, which we are in the process of applying towards the next stages of the work.

We are continuing to study the structural characteristics of printed reinforcement compared to traditional rebar. Once we determine a suitable replacement material, we will continue to refine our process and understanding of multi-material printing of molds at the desktop scale.

We are currently completing the installation of two 10kg robotic arms. When they are ready, we will begin transitioning toward the full-scale mockup to examine how best to reduce the amount of variable-profile reinforcement materials needed and to improve their placement within the model to avoid printing errors, such as exposed reinforcement.

Our plan is to submit our current research to the upcoming ARCC / EAAE conference, as well as next year’s TexFab and ACADIA conferences. The robotics work will be submitted to the next RobArch conference. At the conclusion of the study, we will seek to publish an article in Technology + Design (TAD) and, pending the outcome of the materials research, potentially articles in concrete construction and/or additive manufacturing journals. We will also seek additional funding to scale up the process with a different additive manufacturing technology using robots with larger payloads.

Acknowledgements

Erin Hunt, our CCL Research Associate, provided valuable support and additional research for this work.

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Appendix A. - Concrete flexure tests

Flexure tests are generally used to determine the flexural modulus or flexural strength of a material. A flexure test is more affordable than a tensile test and test results are slightly different. The material is laid horizontally over two points of contact (lower support span) and then a force is applied to the top of the material through either one or two points of contact (upper loading span) until the sample fails. The maximum recorded force is the flexural strength of that particular sample.

Why perform a flexure test?
Unlike a compression test or tensile test, a flexure test does not measure fundamental material properties. When a specimen is placed under flexural loading all three fundamental stresses are present: tensile, compressive and shear and so the flexural properties of a specimen are the result of the combined effect of all three stresses as well as (though to a lesser extent) the geometry of the specimen and the rate the load is applied.

The most common purpose of a flexure test is to measure flexural strength and flexural modulus. Flexural strength is defined as the maximum stress at the outermost fiber on either the compression or tension side of the specimen. Flexural modulus is calculated from the slope of the stress vs. strain deflection curve. These two values can be used to evaluate the sample materials ability to withstand flexure or bending forces.

Flexure Test Types
The two most common types of flexure test are three point and four point flexure bending tests. A three point bend test consists of the sample placed horizontally upon two points and the force applied to the top of the sample through a single point so that the sample is bent in the shape of a "V". A four point bend test is roughly the same except that instead of the force applied through a single point on top it is applied through two points so that the sample experiences contact at four different points and is bent more in the shape of a "U". The three point flexure test is ideal for the testing of a specific location of the sample, whereas, the four point flexure test is more suited towards the testing of a large section of the sample, which highlights the defects of the sample better than a 3-point bending test.

A bend test is similar to a flexure test in the type of hardware and test procedure involved. Bend tests are used with ductile materials whereas flexural tests are used with brittle materials.

Source: www.testresources.net

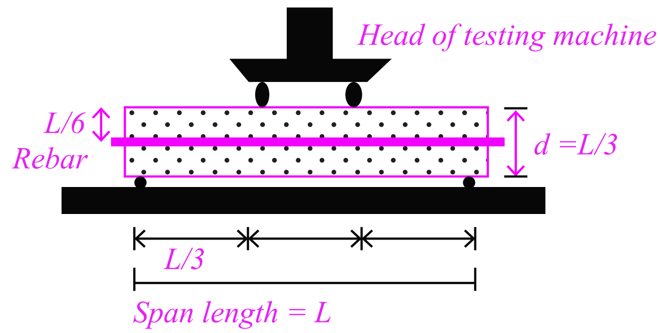
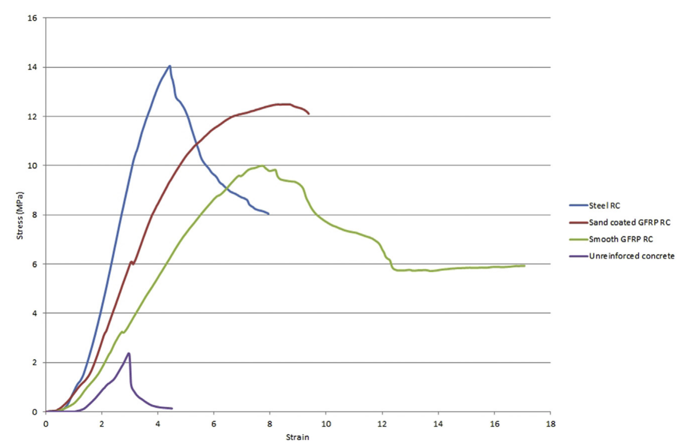


Diagram of testing set up.
Source: Redrawn and edited from diagram on theconstructor.org



Example testing results.
Source: Shahad AbdulAdheem Jabbar*, Saad B.H. Farid "Replacement of steel rebars by GFRP rebars in the concrete structures"

Example testing equipment.
Source: www.testresources.net

Appendix B. - Filament data and printer settings

Type of Filament	Label	Color	Density (g/cm3)	Generated Supports (y/n)	Layer Height (mm)	Print Speed (mm/s)	Nozzle Temperature (C)	Bed Temperature (C)	Part Removal (C)	Est Length of Filament (m)	Est Weight of Filament (g)	Est Print Time (min)	Actual Print Time (min)	Actual Printed Weight (g)
		Filament Properties		Print Settings						Printed Rebar				
				***Cura Settings*	*0.6*	*50*	*265*	*102*	*50*					
Standard ABS	A-1	Black	1.04	Yes	0.6	50	265	100	50	8.72	59	63	72	52
	A-2			Yes	0.6	50	265	100	50	8.72	59	63	73	50
	A-3			Yes	0.6	50	265	100	50	8.72	59	63	72	51
				****Seller Settings*		*50*	*230 - 240*	*80 - 110*						
ABS Pro	B-1	Teal	Unknown	Yes	0.6	50	265	100	50	8.72	59	67	68	52
	B-2			Yes	0.6	50	265	100	50	8.72	59	67	72	53
	B-3			Yes	0.6	50	265	100	50	8.72	59	67	73	52
				****Seller Settings*			*195-220*		*50 (not required)*					
				***Cura Settings*			*230*	*60*	*50*					
Stainless Steel PLA	C-1	Gray	2.4				All prints failed							
	C-2													
	C-3													
				****Seller Settings*			*185-205*		*60-70*					
				***Cura Settings*			*230*	*60*	*50*					
Magnetic Iron PLA	D-1	Brown	2.00				All prints failed							
	D-2													
	D-3													
				****Seller Settings*		*50*	*220- 240*		*100 - 110*					
Carbon Fiber ABS	E-1	Black	1.34	Yes	0.6	35	250	110	80	8.95	63	74	83	55
	E-2			Yes	0.6	35	250	110	80	8.95	63	74	84	54
	E-3			Yes	0.6	35	250	110	80	8.95	63	74	85	50
				****Seller Settings*		*25- 35*	*250-265*	*60-65*						
Nylon Carbon Fiber Filament	F-1	Black	1.00	Yes	0.6	25	270	85	70	8.95	65	99	105	49
Nylon X	F-2			Yes	0.6	25	270	85	70	8.95	65	99	104	49
	F-3			Yes	0.6	25	270	85	70	8.95	65	99	104	49
				****Seller Settings*			*255 +/- 10*	*65*						
Nylon Glass Fiber Filament	G-1	Blue	1.00	Yes	0.6	25	280	85	50	8.95	65	100	104	53
	G-2			Yes	0.6	25	280	85	50	8.95	65	100	109	54
	G-3			Yes	0.6	25	280	85	50	8.95	65	100	110	55
				****Seller Settings*		*30*	*240 - 260*	*65*						
Pro Series Nylon Filament	H-1	Orange	1.14	Yes	0.6	25	280	75		8.95	65	100	105	56
	H-2			Yes	0.6	25	280	85		8.95	65	100	112	57
	H-3			Yes	0.6	25	280	85		8.95	65	100	117	57
				***Cura Settings*	*0.9*	*35*	*260*		*70*					
				****Seller Settings*			*240-260*	*X*						
PET G High Strength	J-1	**Red**	**1.27**	Yes	0.6	35	250	70	50	8.83	67	63	75	63
	J-2			Yes	0.6	35	250	70	50	8.83	67	63	72	63
	J-3			Yes	0.6	35	250	70	50	8.83	67	63	73	63

Constants	
Printer	*Lulzbot Taz 6*
Nozzle	*HS+ Hardened Steel 1.2 mm*
Repaired STL File	*Rebar Solid 14pt5 Off Bed*
Rebar Design Specs	*See grasshopper definition*
Model Volume	
Filament Diameter	*2.85 mm*
Slicer	*Cura*
Infill	*100%*
Infill Type	*Lines*
Shell Thickness	*3 mm*

** Hydroscopic filaments were stored in X with*

*** Existing Cura Profiles -available for download or within the Cura Software - not calibrated specifically for 1.2 mm nozzle - https://www.lulzbot.com/taz-6-cura*

*** From purchasing website

Type of Filament	Label	Cost / KG			
		Cost		Links	
Standard ABS	A-1	$	26.50	Puchase Link	https://www.pushplastic.com/collections/3-kg-bulk-reel/products/abs-10kg-22-lbs
	A-2			Technical Data	https://cdn.shopify.com/s/files/1/0260/7421/files/Push_Plastic_ABS_Technical_Data_sheet.pdf?1811896236209650042
	A-3			MSDS	https://cdn.shopify.com/s/files/1/0260/7421/files/PA-747_MSDS.pdf?788
ABS Pro	B-1	$	42.00	Purchase Link	https://www.matterhackers.com/store/l/teal-pro-series-abs-filament-3.00mm/sk/M7M0N3J1
	B-2			Technical Data	https://www.matterhackers.com/r/8ufmBp
	B-3			MSDS	
Stainless Steel PLA	C-1	$	99.98	Puchase Link	https://www.matterhackers.com/store/l/proto-pasta-stainless-steel-pla-3.00mm/sk/MN0RZYZ2
	C-2			Technical Data	
	C-3			MSDS	https://www.lulzbot.com/sites/default/files/MSDS_Proto-pasta_Stainless_Steel_PLA.pdf
Magnetic Iron PLA	D-1	$	69.98	Purchase Link	https://www.matterhackers.com/store/3d-printer-filament/proto-pasta-magnetic-iron-pla-3.00mm
	D-2			Technical Data	
	D-3			MSDS	https://www.lulzbot.com/sites/default/files/MSDS_Proto-pasta_Iron_PLA.pdf
Carbon Fiber ABS	E-1	$	77.33	Puchase Link	https://www.matterhackers.com/store/l/3dxtech-carbonx-abs-3mm/sk/M2MLE9K0
	E-2			Technical Data	
	E-3			MSDS	https://www.3dxtech.com/content/CF_ABS_SDS_v1.0.pdf
Nylon Carbon Fiber Filament	F-1	$	116.00	Purchase Link	https://www.matterhackers.com/store/l/nylonx-carbon-fiber-filament-3mm/sk/MNP2JAEC
Nylon X	F-2			Technical Data	https://www.matterhackers.com/r/xCSnpt
	F-3			MSDS	https://www.3dxtech.com/content/CF_Nylon_SDS_v1.0.pdf
Nylon Glass Fiber Filament	G-1	$	128.00	Puchase Link	https://www.matterhackers.com/store/l/blue-nylong-300-05/sk/MCWMHHFZ
	G-2			Technical Data	https://www.matterhackers.com/r/eZ4iY1
	G-3			MSDS	
Pro Series Nylon Filament	H-1	$	73.33	Purchase Link	https://www.matterhackers.com/store/l/orange-pro-series-nylon-285-3D-printer-filament/sk/M4WCWXDG
	H-2			Technical Data	https://www.matterhackers.com/r/RczMCr
	H-3			MSDS	
PET G High Strength	J-1	$	55.00	Puchase Link	https://www.matterhackers.com/store/l/red-pro-series-petg-high-strength-filament-1.75mm-1.0lb/sk/MCK0PGQQ
	J-2			Technical Data	https://www.matterhackers.com/r/4b8JqK
	J-3			MSDS	