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Polycasting: Multi-material 3D Printing for Reinforced Concrete

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INTRODUCTION

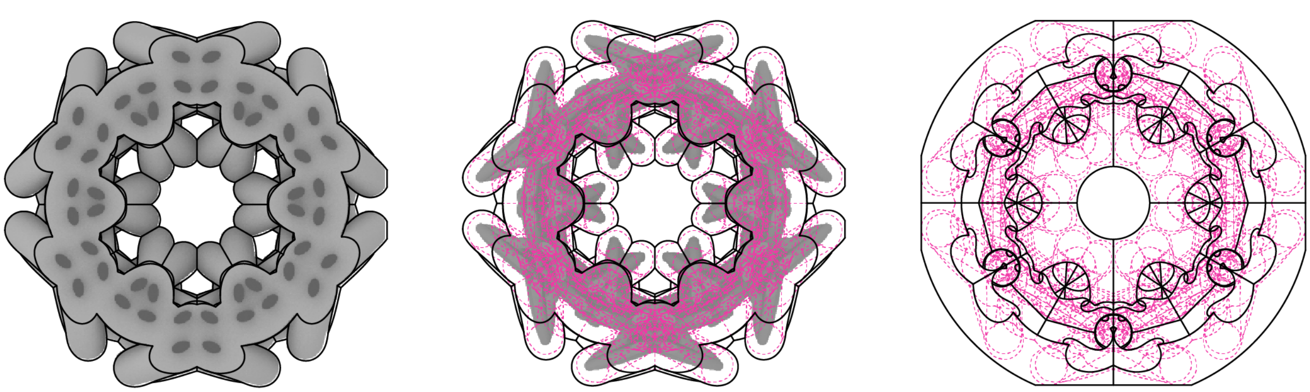
In 2016 the grant authors co-founded the ISU Computation + Construction Lab (CCL), a physical and intellectual space, to enact new ideas about teaching and researching computation, digital fabrication, and design-build. Computational design applies both the science and art of computing to design questions by abstracting information into relationships that encode values and actions. The CCL has catalyzed multiple creative achievements and scholarship through the integration of these methods in research, teaching, and outreach. The central hypothesis of the CCL is that computation in architecture is a material, pedagogical, and social project; computation is both informed by and productive of architectural cultures. This hypothesis is explored, through the fabrication of built projects, writing, exhibition, and material investigation. *Polycasting: Multi-material 3D Printing for Reinforced Concrete* is one such investigation.

PROPOSAL ABSTRACT

Multi-material 3D printing promises to innovate construction and manufacturing practices for reinforced concrete. The potential impact of this research is substantial, as concrete is the most widely-used construction material in the world. While other additive manufacturing (3D printing) research has examined directly 3D printing concrete structures, this project explores dual-extrusion 3D printed formworks for casting concrete: simultaneously printing a combination of water-soluble PVA (polyvinyl alcohol) containment as well as printing integrated steel reinforcement. This is significant because formwork material and labor costs are among the greatest expenses in the construction of reinforced concrete structures. Therefore, the focus 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.

This research focuses on the following questions: 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)? Can dual-extrusion additive manufacturing improve the performance and economy of these non-standard geometries through 3D printed embedded tensile reinforcement?

The research team includes construction engineers, architects, and computational designers and will use simulations and desktop-scale fabrication tests to refine workflows for designing multi-material formworks. Following these experiments, a full-scale mock-up will combine multi-material 3D printing construction methods with traditional formwork to evaluate feasibility for construction scale use.



Resulting Cast *Reinforcement* *PVA Mold*

Plan diagrams demonstrating the relationships between final form, formwork, and reinforcement in an early fabrication study for Polycasting: Multi-material 3D Printing for Reinforced Concrete

EXECUTIVE SUMMARY

A series of desktop-scale material studies determined that PVA filament is a suitable material for 3D printing biodegradable concrete molds. Prototype columns verified that the process could be scaled-up for architectural applications, so long as adjustments were made to account for the additional weight and pressures of the concrete upon the PVA shell. The formworks successfully produced voids and other non-standard geometric features in the concrete.

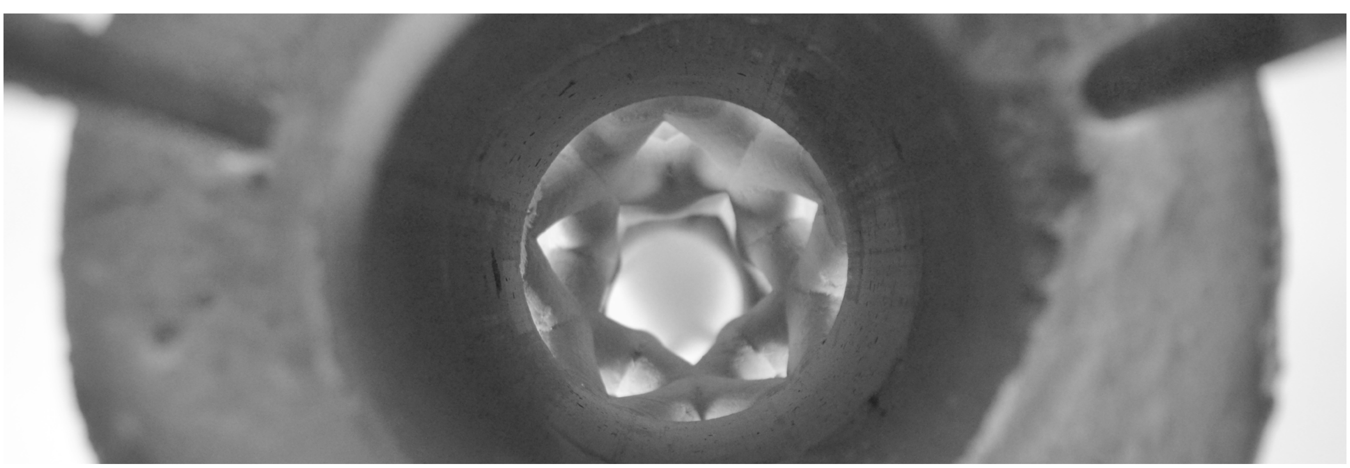
While it appears possible to 3D print embedded reinforcement simultaneously with PVA molds, this aspect of the research remains incomplete. Material testing found that Nylon filament with glass or carbon fibers exhibited the highest tensile strength among commercially available types. With this information, the researchers created a parametric script that generates variable profile 3D printed reinforcement for optimized concrete beams. As a test case, a section of an optimized beam was successfully cast with PVA molds and standard #3 reinforcement. A specialized hardware / software workflow was created and tested to fabricate 3D prints using a six-axis robot arm. However, the researchers have not yet attempted to print two materials simultaneously using two synchronized arms. This will occur during 2021-22.

ACKNOWLEDGMENTS

Our sincere thanks to the American Institute of Architects and the AIA Upjohn Research Initiative for their support of this work.

This research also received support from the ISU Department of Architecture, ISU College of Design, ISU Committee on the Advancement of Student Technology for Learning Enhancement (CASTLE), and the Architectural Research Centers Consortium (ARCC) Research Incentive Award.

The work would not have been possible without a multi-year collaboration with Erin Hunt, former ISU Computation & Construction Lab research associate.



Fabrication test combining PVA and standard formwork with off-the-shelf steel reinforcement.

CONTEXT

Polycasting: Multi-material 3D Printing for Reinforced Concrete draws upon a parallel body of research exploring the viability of PVA for casting water-soluble formwork for column and block typologies. See the following publications and grants as well as Erin Linsey Hunt's *Nublock* and Master in Design Studies in Technology at the Harvard Graduate School of Design Thesis 2021 erinlhunt.com.

RELATED PUBLICATIONS & GRANTS

2020 Melting 2.0

Shelby Doyle and Erin Hunt (Forthcoming) Proceedings of Distributed Proximities the 40th Annual Conference of the Association for Computer Aided Design in Architecture ACADIA, October 24-30, 2020, Online

2019 Dissolvable 3D Printed Formwork: exploring additive manufacturing for reinforced concrete

Shelby Doyle and Erin Hunt in Bieg, K., Briscoe, D., and Odom, C. (Eds.) Ubiquity and Autonomy: Paper Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture ACADIA, October 24-26, 2019, Austin, Texas (pp. 178-188)

2019 Autodesk ACADIA Emerging Research Award for Melting

Project Category Co-PI with Erin Hunt ($6,000)

2019 Melting: Augmenting Concrete Columns with Water Soluble 3D Printed Formwork

Shelby Doyle and Erin Hunt in Bieg, K., Briscoe, D., and Odom, C. (Eds.) Ubiquity and Autonomy: Projects Catalog of the 39th Annual Conference of the Association for Computer Aided Design in Architecture ACADIA, October 24-26, 2019, Austin, Texas (pp. 92-97)

2018 Architectural Research Centers Consortium Research Incentive Award

Shelby Doyle and Nick Senske, Polycasting: Multi-material 3D Printed Formwork for Reinforced Concrete ($5,000) Final report: http://www.arcc-arch.org/wp-content/uploads/2019/10/ARCC-Polycasting-final-report.pdf

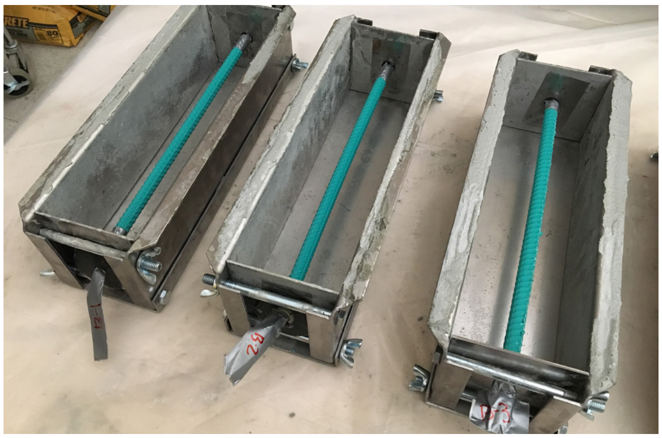
RESEARCH PHASE 1
DESKTOP FABRICATION AND STRUCTURAL ANALYSIS OF 3D PRINTED TENSILE REINFORCEMENT FOR CONCRETE

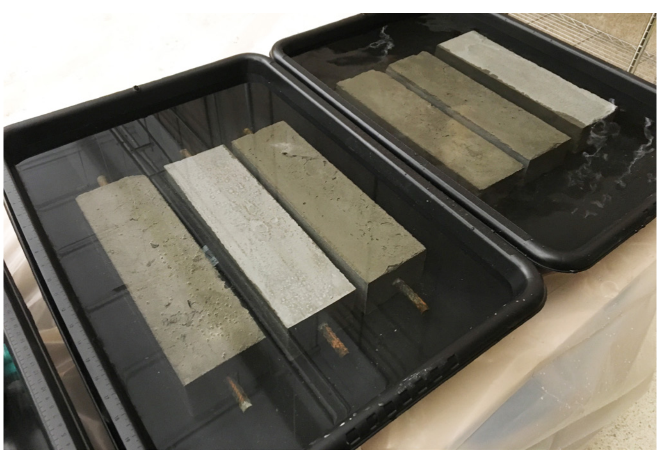
Although there are many examples of 3d printed concrete in architecture (e.g. Zeeshan, 2016), the integration of reinforcement remains a challenge for this construction method. (See literature review in Nerella, Ogura, & Mechtcherine, 2018) Recent examples include extruding reinforcement in layers during concrete printing (Hack, et al., 2017; Kunchinskas, 2019) and printing a concrete formwork with reinforcement simultaneously using dual extruders. However, it is not clear which filament materials are best suited for these applications, how to optimize their placement within the geometry, and how they perform under loading.

This first phase of research presents flexural test results for 3d printed tensile reinforcement in concrete towards the development of structural baselines and design tools for future construction applications. The findings suggest that it is possible to print structurally viable tensile reinforcement with commercially available Nylon / carbon fiber filaments, if the volume of reinforcement is increased and if placement considerations are observed. A further result is that the failure mode of 3d printed reinforcement appears to be different from steel reinforcement. This has potential implications for the design and safety of concrete structures with 3d printed reinforcement.

Study #1: Methods

The first study examined the material performance of 3d printed filament in comparison to standard steel rebar. Seven commercially available filaments were tested: ABS (acrylonitrile butadiene styrene), PLA (polylactide), PET G (polyethylene terephthalate glycol), and plastic composites with carbon fiber, glass fiber, and nylon. These filaments were printed on a LulzBot Taz 6 with a 100% line infill from a 1.2mm hardened nozzle as 3/8" (10 mm) diameter rods at a length of 15 inches (380 mm) and then tested in comparison with a North American standard #3 steel reinforcement. For each filament type, sets of three 4" x 4" x 14" (100 mm x 100 mm x 355 mm) standard concrete testing beams were cast using a mixture of 1:2:1 (cement: sand: water). The

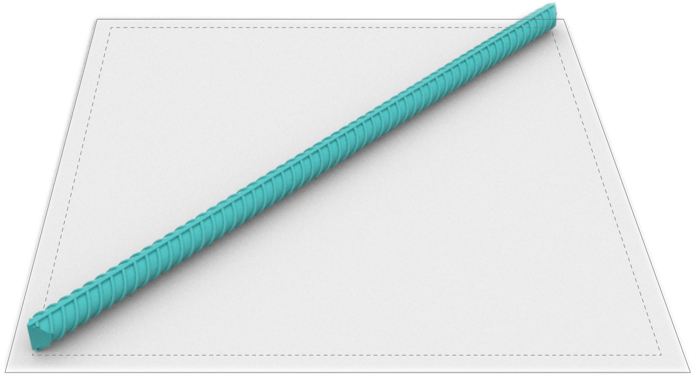




Images from top to bottom: Completed printed reinforcement, printed reinforcement in molds, concrete poured into molds, concrete curing in water for 28 days.

Parametric model developed in Grasshopper to replicate standard #3 Rebar.

Positioned on the hypotenuse of the print bed and raised 5 mm above the bed to force support material to be printed and avoid a flattening of the bottom of the print.



Angled at each end to maximize print length a 14.5" for the 14" concrete molds

Lulzbot TAZ 6 Printer Bed 280 mm x 280 mm x 250 mm (11.02" x 11.02" x 9.80").

Offset 3/8" to accommodate Hardened Steel 1.2mm Nozzle

Constants (All prints)

Printer	Lulzbot Taz 6
Nozzle	HS+ Hardened Steel 1.2 mm
STL File	Rebar Solid
Filament Diameter	2.85 mm
Slicer	Cura
Infill	100%
Infill Type	Lines
Shell Thickness	3 mm
Generated Supports	Yes
Layer Height	0.6 mm

Note: The following filaments were tested but replicable results were not achieved and these results are not included here: Protopasta Stainless Steel PLA, Protopasta Magnetic Iron PLA, and Taubman Alloy 910

** (Name) indicates abbreviated name used in results table*

Type of Filament	Print Speed (mm/sec)	Nozzle Temp (OC)	Bed Temp (OC)
Push Plastic ABS *(ABS)	50	265	100
PRO Series ABS (ABS Pro)	50	265	100
3DX Tech Carbon Fiber ABS (CF ABS)	35	250	110
Nylon X Carbon Fiber (Nylon X)	25	270	85
Nylon G Glass Fiber (Nylon G)	25	280	85
PRO Series Nylon (Nylon)	25	280	75
PRO Series PET G High Strength (PET G)	35	250	70
3DX Carbon Fiber Reinforced Nylon (CF Nylon)	25	270	85

Top image: Diagram of the printing set up on the Lulzbot Taz 6 with 1.2 mm HS+ nozzle. Bottom chart: constants and variables tested.

beams were then cured in room temperature water (23C / 73F) for twenty-eight days and then mechanically flexure-tested to determine their average loading at failure.

Study #1: Results

The steel reinforcement reached an average of 4,593 lbf before failure, compared to 1,157 lbf in the unreinforced controls. The MatterHackers Nylon X filament performed the best of the first round 3d printed reinforcements, with an average failure at 1,928 lbf. While this load is 40% of the steel samples, the Nylon reinforcement only weighs one-quarter as much as the steel.

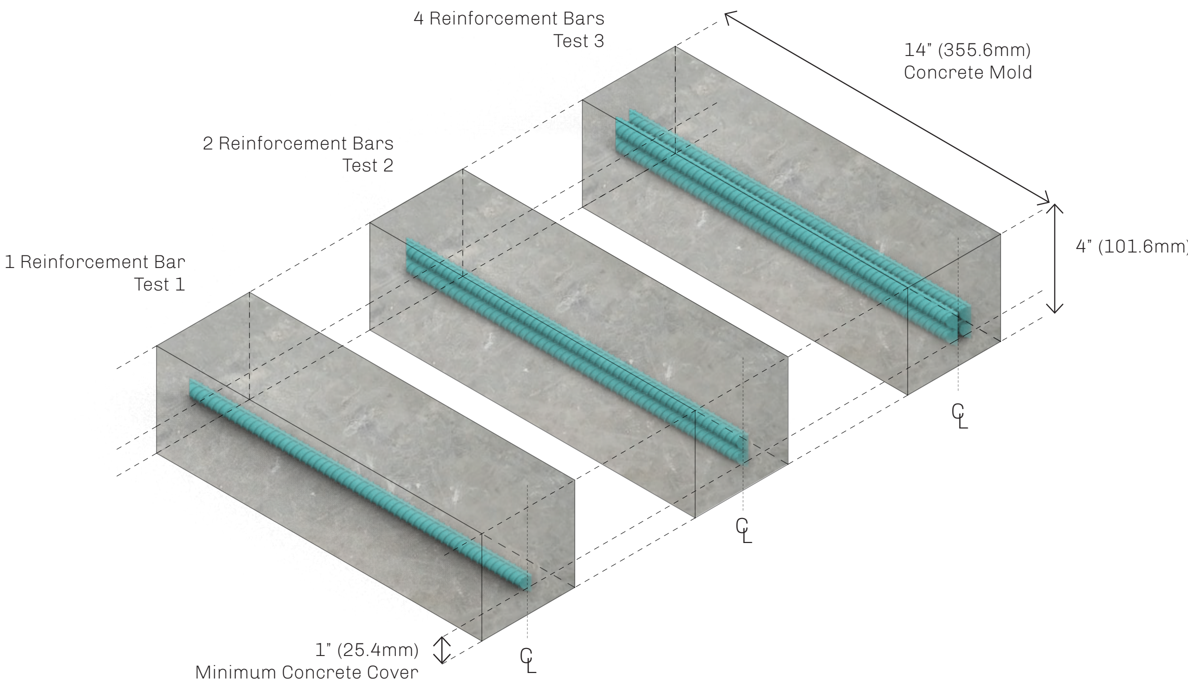
Study #2: Methods

In an attempt to improve tensile performance, the next phase tested more types of Nylon filament and reinforcement configurations within the test beams. A second round of material experiments, using the same methodology as in Study #1, focused on MatterHackers Nylon G (glass fiber reinforced) and MatterHackers Nylon X (carbon fiber reinforced) filaments. These filaments performed the best in the previous experiment and are widely available. The configuration was adjusted for the test beams to include double the 3d printed rebar from earlier experiments (two bars), with the hypothesis that the final tensile performance would be closer to the steel control.

Study #2: Results

Nylon X performed the best of all the filaments tested, although Nylon G was close – within 5-10% the maximum load. However, not all Nylon filament with carbon fiber

Diagram of Testing Set Up



Testing Results Round 1

Control - Steel Reinforcement	4,933
Sample 1	4,932
Sample 2	3,987
Sample 3	4,861

Control - No Reinforcement	1,157
Sample 1	1,270
Sample 2	1,032
Sample 3	1,168

ABS - 1 Bar	1,382
Sample 1	1,469
Sample 2	1.462
Sample 3	1,214

CF ABS - 1 Bar	1,495
Sample 1	1,199
Sample 2	1,635
Sample 3	1,651

Nylon G - 1 Bar	1,928
Sample 1	1,818
Sample 2	2,097
Sample 3	1,928

ABS Pro - 1 Bar	1,895
Sample 1	1,815
Sample 2	1,762
Sample 3	2,109

CF Nylon - 1 Bar	1,550
Sample 1	1,190
Sample 2	1,180
Sample 3	2,281

PET G - 1 Bar	1,309
Sample 1	1,331
Sample 2	1,002
Sample 3	1,593

Testing Results Round 2

Nylon X - 1 Bar	1,866
Sample 1	1,802
Sample 2	1,873
Sample 3	1,923

Nylon X - 2 Bars	3,110
Sample 1	3,032
Sample 2	2,716
Sample 3	3,583

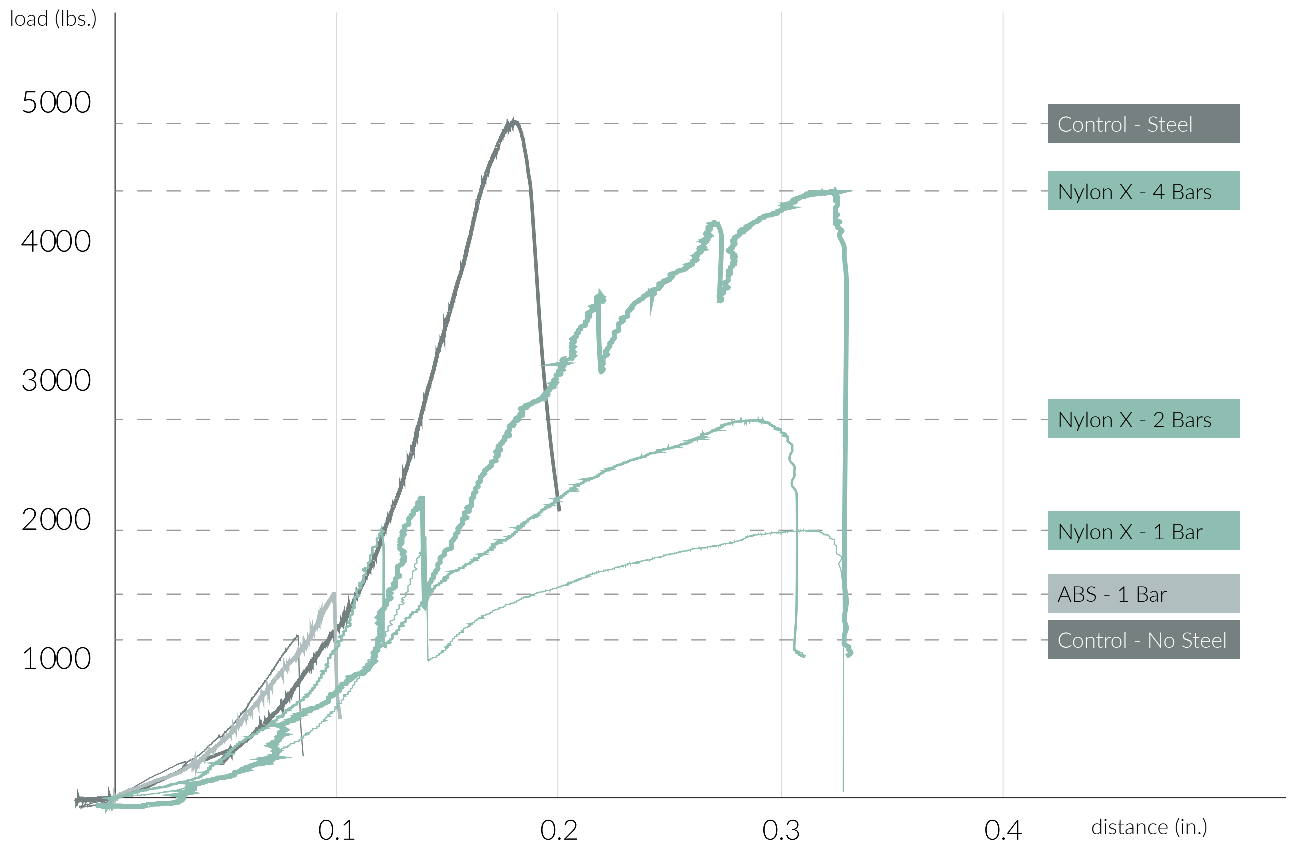
Nylon G - 2 Bars	2,904
Sample 1	2,840
Sample 2	2,431
Sample 3	3,442

CF Nylon - 2 Bars	2,389
Sample 1	2,510
Sample 2	2,557
Sample 3	2,100

Testing Results Round 3

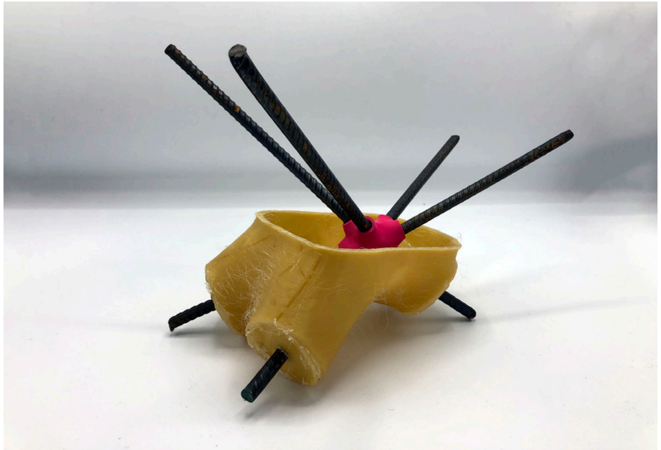
Nylon X - 4 Bars	3,291
Sample 1	4,387
Sample 2	1,967
Sample 3	3,519

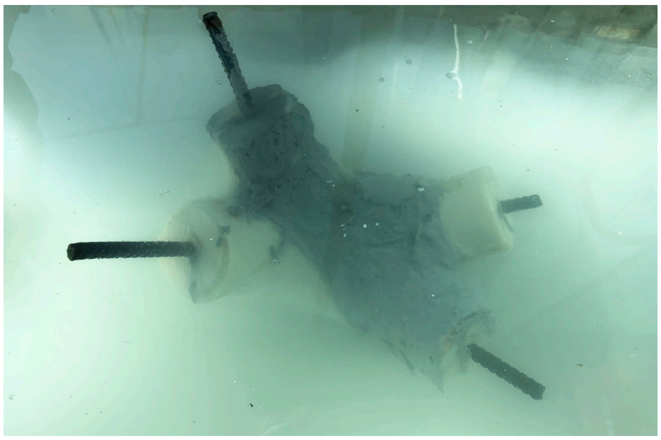
Concrete Flexure Graphs



appears to perform equally well. The MatterHackers Nylon X demonstrated ~25% better tensile strength over the 3DX carbon fiber reinforced Nylon (CF Nylon) in both the one-bar and two-bar tests. The experiments with two printed rebars found that increasing the amount of reinforcement improved tensile performance but it did not do so linearly (from 40% of control to 63%). To further test with four rebars and found it came closest to steel in terms of overall strength (88% of control). While the amount of material used weighed almost as much as the steel it replaced, the printed Nylon filament is much easier to shape and place than steel and so it could still offer some benefits over conventional rebar.

The flexural graphs of the testing from both studies indicate that 3d printed reinforcement presents a different failure mode than the steel reinforcement. Whereas the steel data illustrates that peak loading occurs with little deformation, the Nylon curves are flatter with deformation continuing to increase with loading until failure. This suggests that the Nylon reinforcement may not fail as suddenly in concrete. An implication of this finding is that 3d printed formworks might not be suitable for critical structural applications but are acceptable for creating concrete geometries that are ornamental or otherwise sculptural. Another potential benefit of 3d printed reinforcement is that greater precision of geometry and placement could allow for smaller concrete depths while also reducing the steel corrosion problems that are present in many concrete failures. Further experiments will be needed to determine minimum cover for filament reinforcement within concrete. Once this information is available, optimizing concrete structures with printed reinforcement may lead to non-standard designs which are structurally safe, lighter, use less material, and can be fabricated with less labor (compared to assembling and placing standard reinforcement).





Fabrication Tests

Beginning with these results, two structural nodes were fabricated using PVA molds and 1) #3 reinforcement 2) Nylon X reinforcement. Based upon the findings of Phase 1 volume of Nylon X reinforcement was four times that of steel, the concrete coverage half of the radius, and necessary concrete volume 60% less.

Next Steps

3d printed formworks offer many possibilities for concrete geometries with textures, voids, and undercuts that are difficult or impossible with conventional formworks. However, the potential of printed formworks may be limited if no suitable methods are available for integrating tensile reinforcement. This research indicates that 3d printed reinforcement is achievable, with a few caveats.

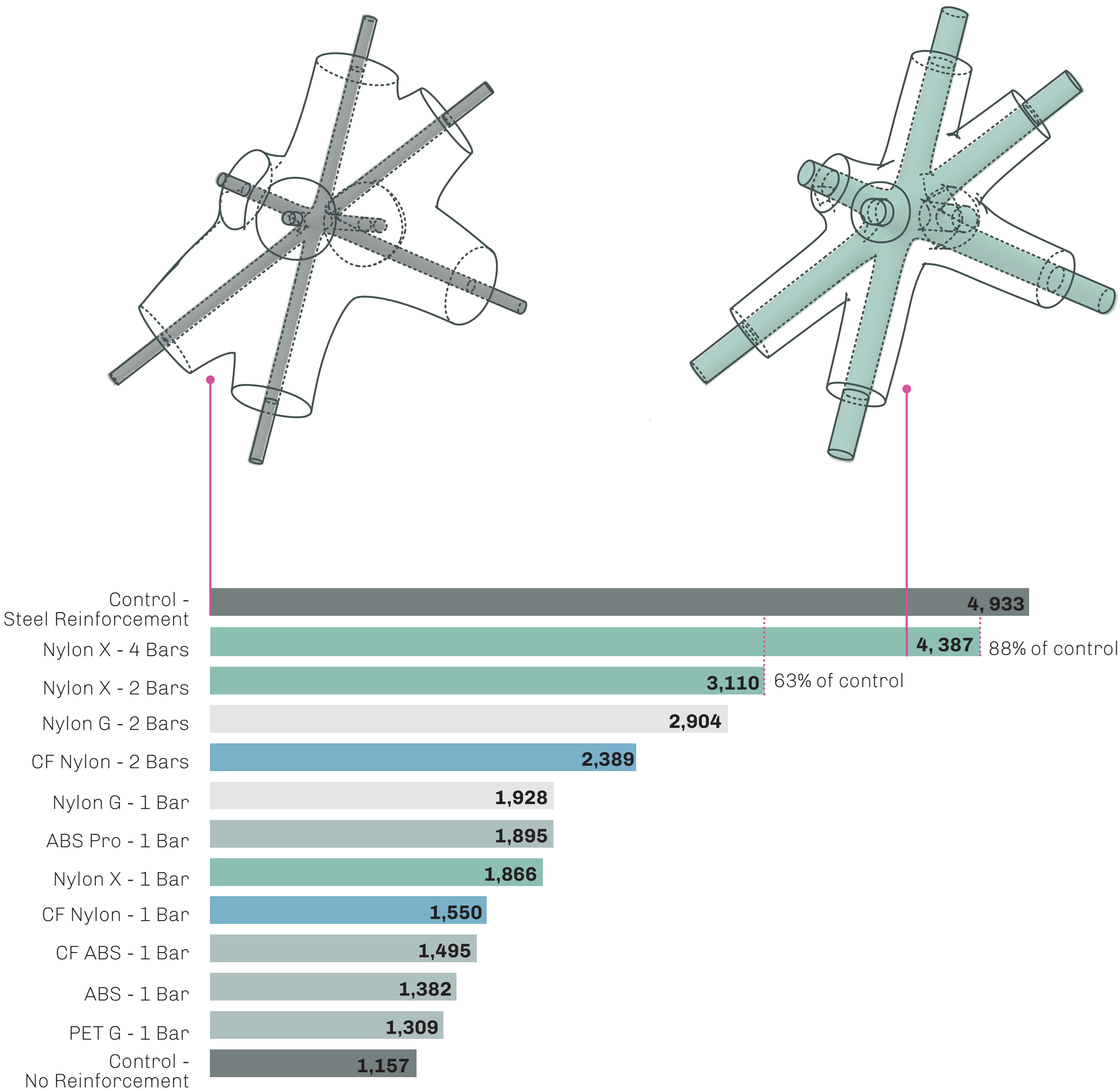
Nylon with carbon fiber had the highest listed tensile performance of any of the materials selected, and this was confirmed by beam testing. Achieving the nearly same maximum flexural load as steel required four times the volume of Nylon filament. However, this does not mean that further improvements are impossible. The experiments in this phase used off-the-shelf filament and standard geometries of both rebar and concrete, but 3d printing allows for the production of non-standard formworks. Structural simulations can be used to optimize placement of 3d printed reinforcement.

Images from top to bottom: Half completed PVA mold with #3 reinforcement, mold dissolving in water, complete cast with #3 reinforcement, half cast of Nylon X reinforcement

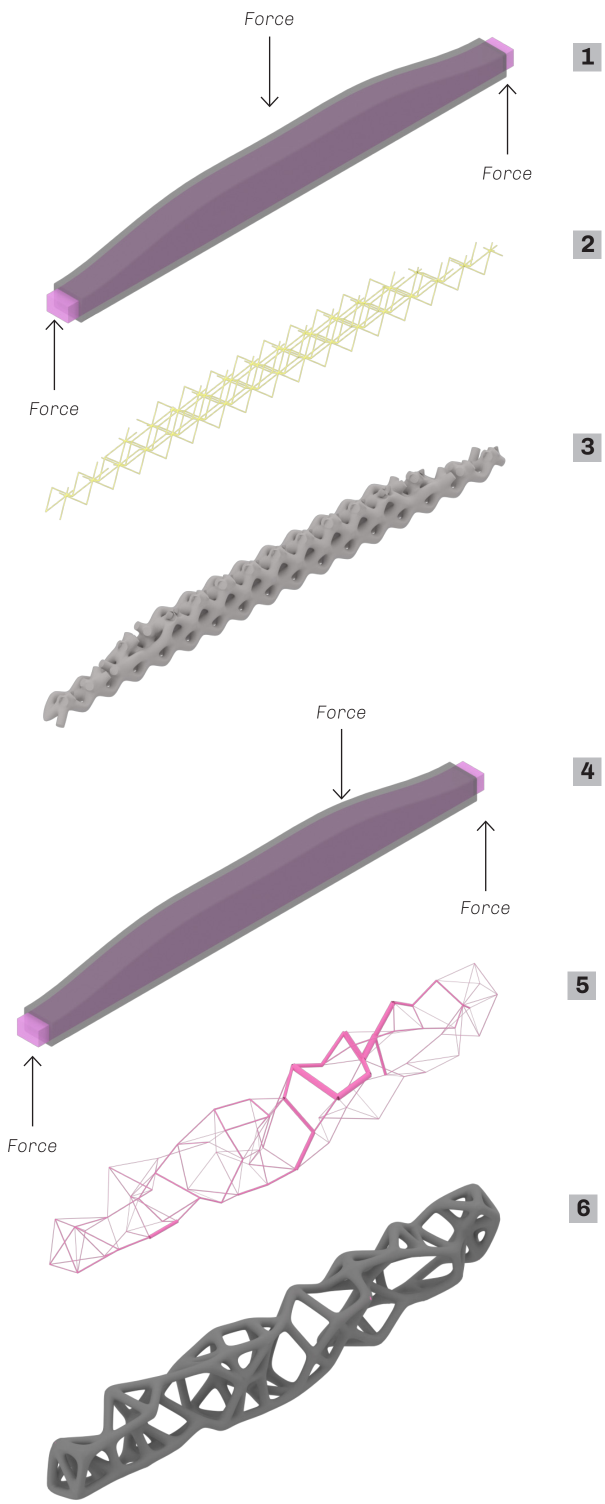
#3 Steel Reinforcement
Radius 0.1875 in
Reinforcement Volume 4.85 in^2
Concrete Cover Radius 1.0 in
Concrete Volume 137.30 in^2

2 times reinforcement radius →
4 times reinforcement volume →
50% reduction in cover radius →
60% reduction in concrete →

Nylon X Reinforcement
Radius 0.3720 in
Reinforcement Volume 19.44 in^2
Concrete Cover Radius 0.50 in
Concrete Volume 56.34 in^2



Research phase 1 structural node diagram and structural testing results.



1 - Beam and reinforcement design space.

2 - Lattice reinforcement design with #3 reinforcement.

3 - Resulting design with 1 inch of concrete coverage.

4 - Beam and reinforcement design space

5 - Variable profile steel reinforcement located with custom definition using Karamba 3D for Grasshopper.

6 - Resulting design with 1 inch of concrete coverage.

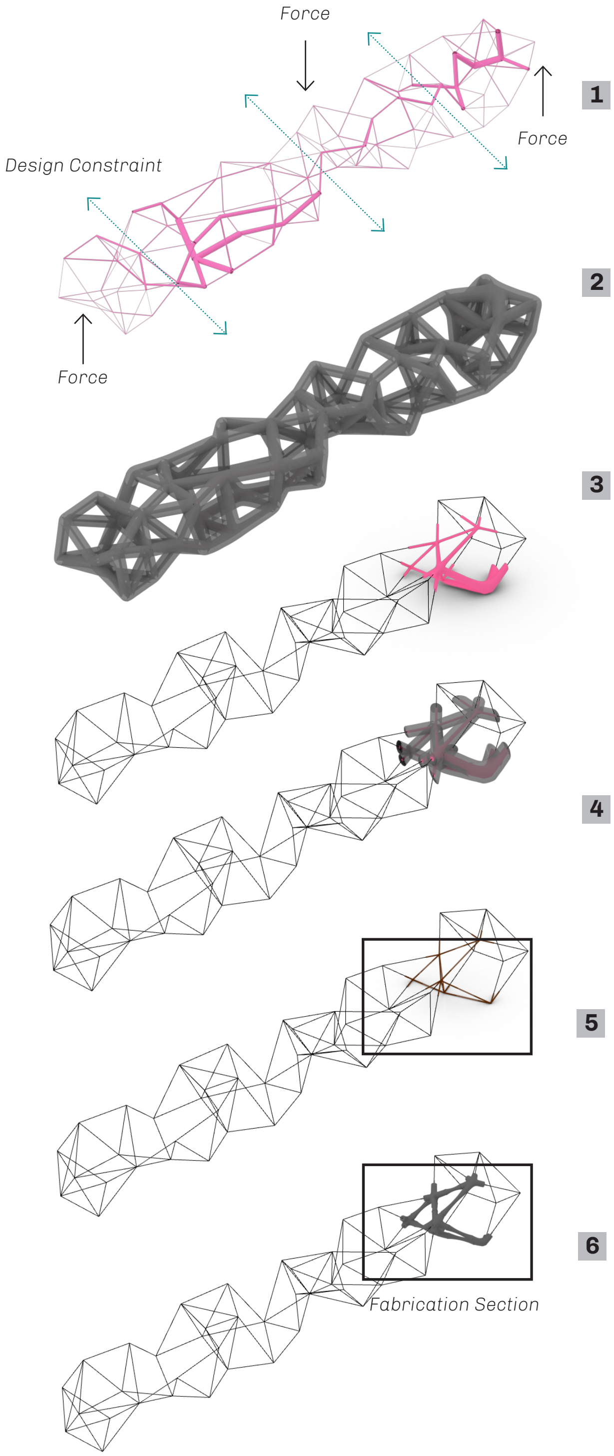
RESEARCH PHASE 2
SOFTWARE TOOLMAKING FOR VARIABLE PROFILE 3D PRINTED REINFORCEMENT

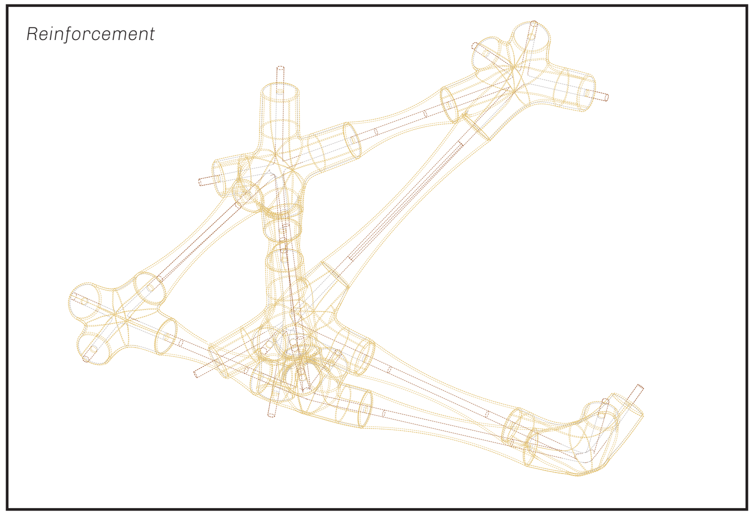
Phase 2

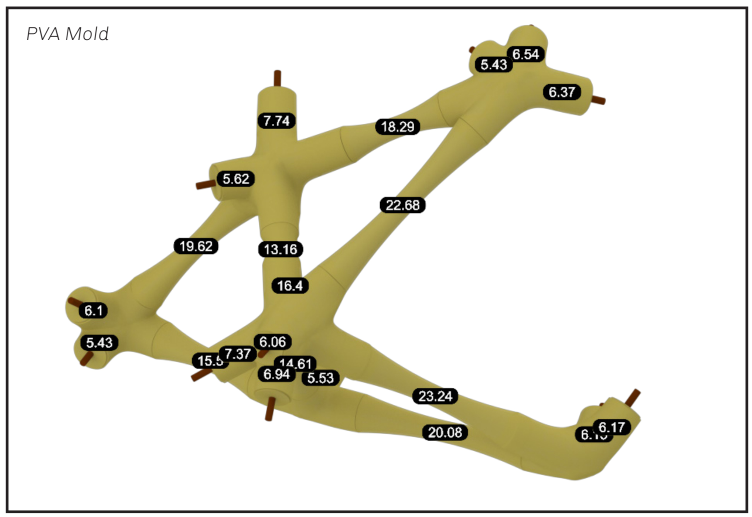
The results of Phase 1 indicated that it was possible to create 3d printed reinforcement with materials such as Nylon filament and that printed reinforcement could be placed and shaped in ways that are difficult or impossible with conventional rebar. Another benefit of using nonmetal reinforcement is a reduction in the amount of concrete cover necessary to prevent rust. Thus, if the dimension and placement of the reinforcement was optimized, it could reduce the volume of Nylon and concrete required and make the structure more efficient compared to conventional materials and designs. To test this idea, the investigators developed custom scripts to facilitate the design of variable profile 3D printed reinforcement.

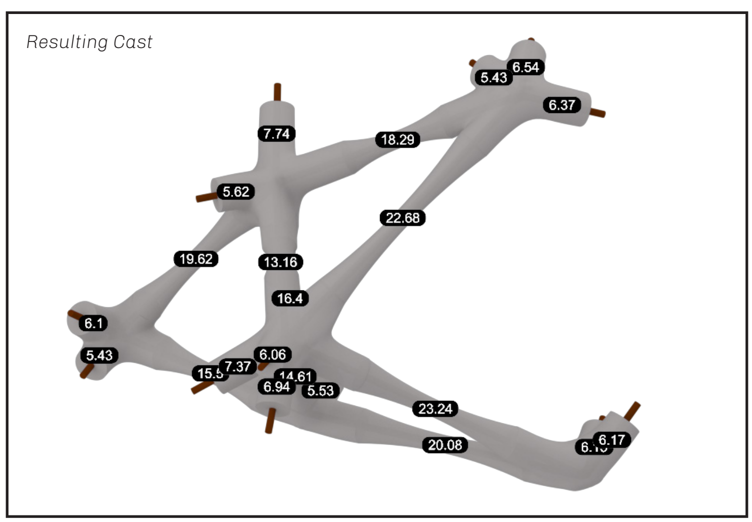
A 20-foot-long concrete beam served as the baseline case for structural analysis and optimization. Using the Karamba 3D structural analysis plugin for Grasshopper, a definition was programmed that allows a designer to create a beam envelope through the specification of structural forces and dimensions. The script generates reinforcement from tension centerlines and adjusts the diameter at nodes and midpoints based upon the selected material and calculated forces. This geometry is interpolated and optimized to create the variable profile reinforcement. The result is a model which requires the least amount of steel (or plastic) reinforcement and concrete to satisfy a design space. With this workflow in place, the script was further improved so it could respond to design constraints commonly found in beam design, such as accommodating openings for mechanical or electrical runs.

To test fabrication methods, a prototype beam was generated using the method above and a structural section was extracted for further processing. See Phase 3: robotically 3D printed concrete formwork and standard reinforcement; and Phase 4: robotically 3D printed concrete and 3D printed reinforcement.









1 - Beam and reinforcement design space. Variable profile steel reinforcement located with custom definition using Karamba 3D for Grasshopper.

2 - Resulting design with 1 inch of concrete coverage.

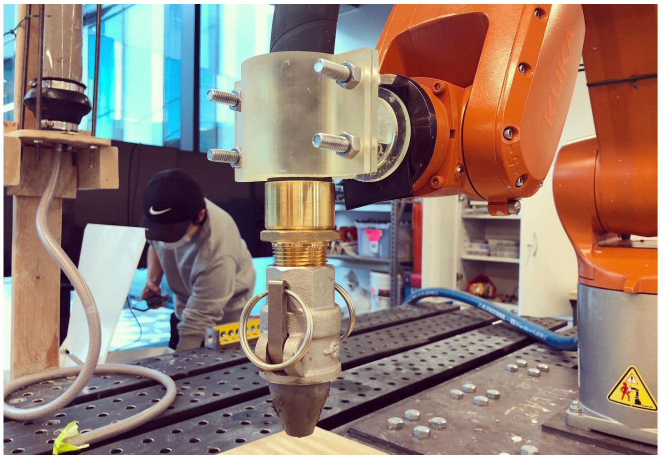
3 - Reinforcement adjusted for Nylon X geometry

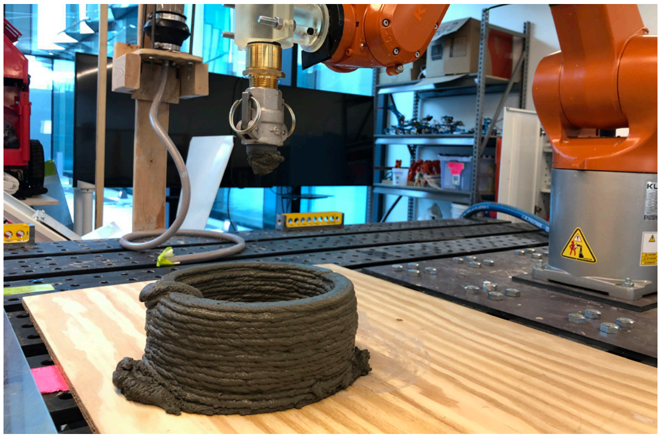
4 - Resulting design with 1 inch of concrete coverage.

5 - Reinforcement using #3 steel

6 - Resulting design with 1 inch of concrete coverage.

Resulting structural section cast in Rockite using PVA formwork and off the shelf #3 reinforcement. Bottom left - reinforcement is held in place by 3D printed jig. Bottom right: molds dissolve in a bath of water.





RESEARCH PHASE 3
HARDWARE AND SOFTWARE TOOLMAKING AND WORKFLOWS FOR ROBOTICALLY CONTROLLED 3D PRINTED CONCRETE

Initial experiments using a dual-extruder to print PVA and other materials simultaneously led to inconsistent results. The temperature difference between the materials was too great. As an alternative to 3D printed formworks, a new set of experiments was conducted to determine whether it would be possible to use a robotic arm to extrude concrete around conventional steel rebar held in place or manipulated by another robotic arm. While this method would limit the range of geometries possible, in comparison to molded forms, it has other potential advantages such as speed and dependable calculation of forces.

The goals of this phase were:

1) To create a software and hardware workflow for 3d printing concrete with the robotic arm.

2) To develop a custom concrete mix that combined flowability and printability

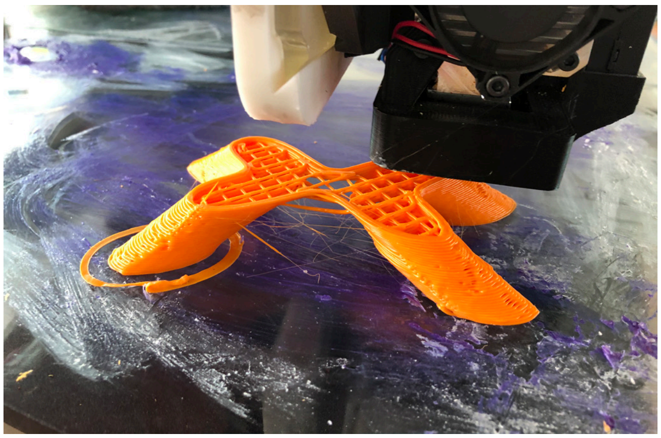
3) To print a beam section using this method.

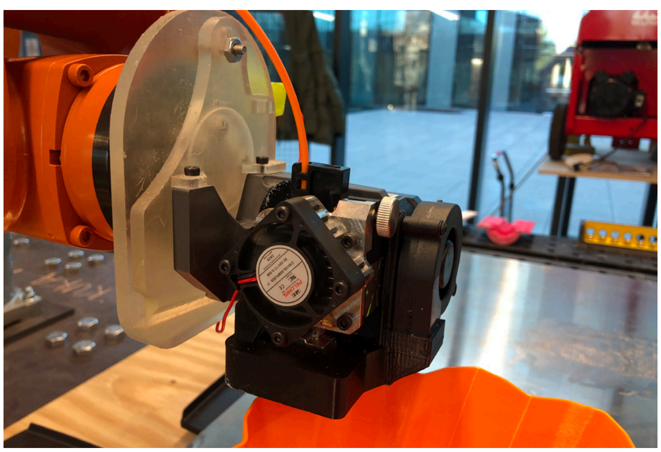
Goal 1 was achieved by designing and fabricating custom hardware to allow the robotic arm to deliver concrete to a specific location with consistent flow. This involved a custom 3D printed end-effector and nozzle, connected to a concrete hose and a Spray Buddy concrete pump. Toolpaths for the robotic arm were generated using Grasshopper and KUKA PRC and calibrated through a series of iterative tests.

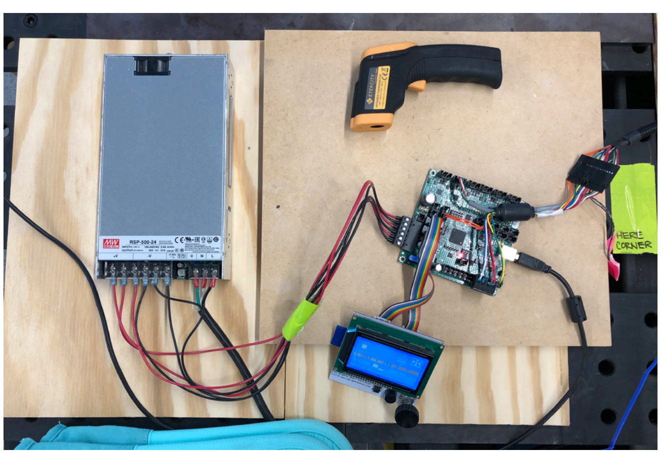
Goal 2 was unsuccessful. Early material tests conducted with our collaborators in Construction Engineering, Structural Engineering, and Material Science were promising but inconsistent. The project then moved to a new lab space which was not set up for concrete casting (no sink, poor ventilation, etc) and it was not possible to obtain the results necessary in a timely manner.

Therefore, instead of continuing to pursue Goal 3 at this time, the focus of the research effort turned toward the development of plastic 3D printing for the remainder of the grant.

From top to bottom: Custom end effector and nozzle for printing concrete, successful flowability and buildability test, set up with Spray Buddy pump, and a less successful test print.







RESEARCH PHASE 4

HARDWARE AND SOFTWARE TOOLMAKING AND WORKFLOWS FOR ROBOTICALLY CONTROLLED 3D PRINTED PLASTIC FILAMENTS

A second alternative explored in this research involved mounting a single extruder to each of the robot arms so that one arm could print the PVA mold and the other could print the reinforcement. This avoids the earlier problem of the temperatures difference between the filaments with the dual-extruder. The immediate challenge of this method is coordinating the motions of the robot with the extruders. On a typical 3D printer, the X/Y/Z system is synchronized with the rotation of the extruder gear, but a six-axis robot has a different type of motion and there is no software available that can process the necessary translations. And so, the first problem to solve was developing a method for six-axis printing with these constraints in mind.

The goals of this phase were:

1) To create a software and hardware workflow for 3d printing plastic filaments with the robotic arm

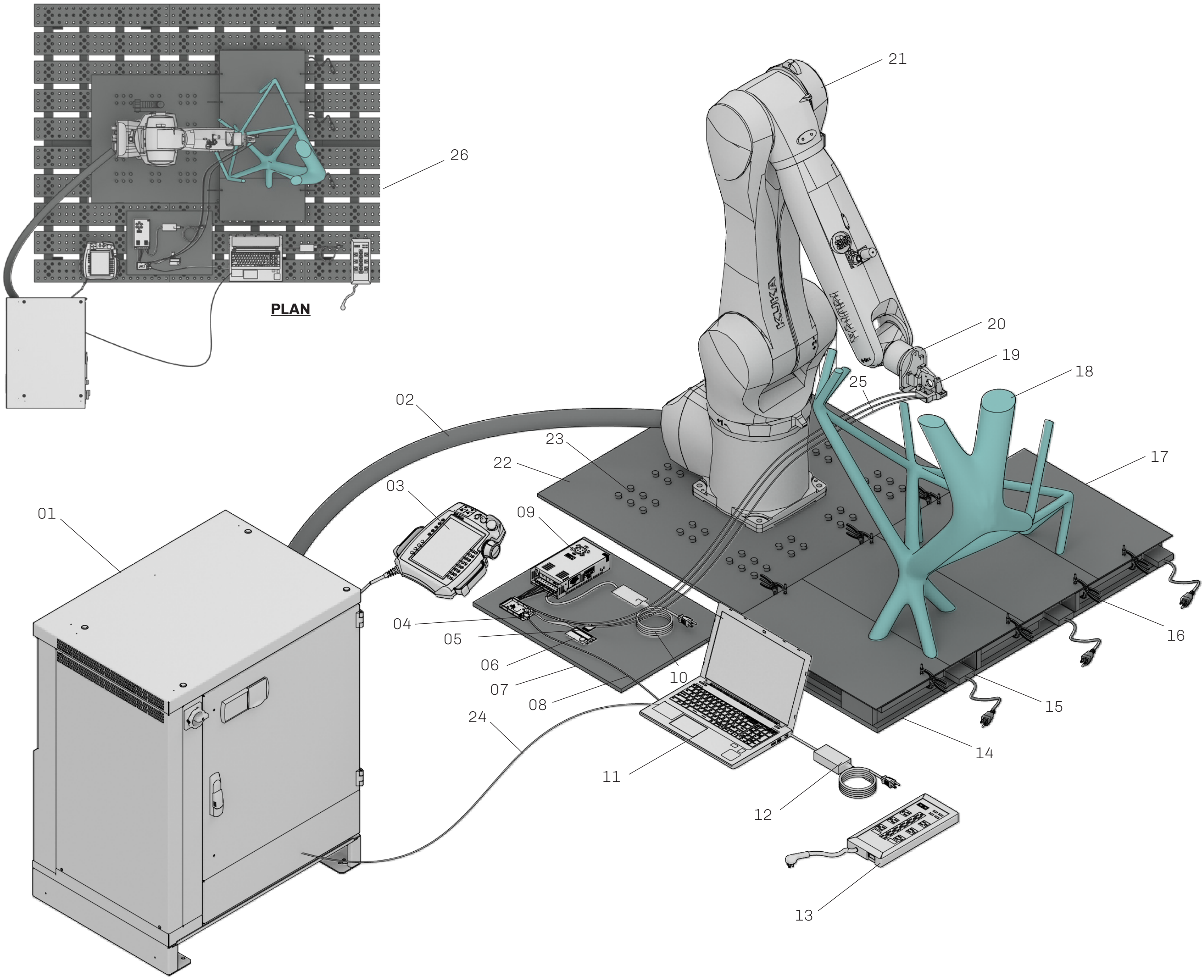
2) To develop the workflow using only readily accessible / off-the-shelf electronics and software

3) To print reinforcement with similar print resolution as the desktop Lulzbot Taz

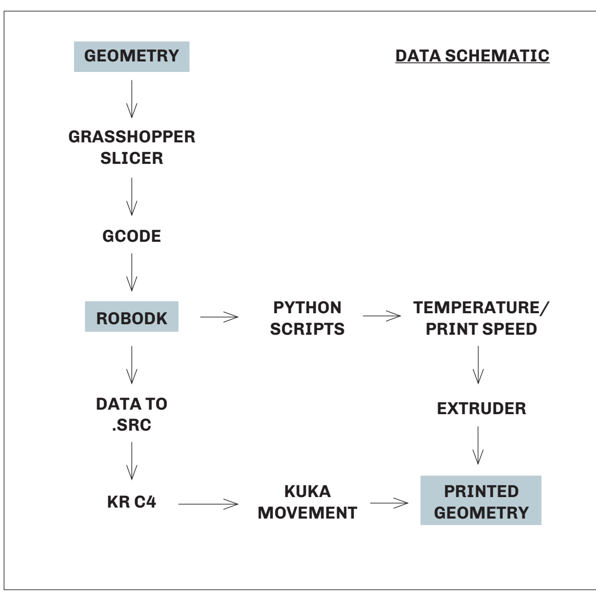
Goals 1 and 2 were achieved resulting in a software and hardware set up with a total cost of less than $1000 in equipment and materials. A custom Grasshopper slicer was developed for creating specially-formatted G-Code. RoboDK simulation software translated this code into synchronized robotic path movements and commands for the custom firmware loaded on the extruder. A diagram of this set up can be found on the following page.

Goal 3 is ongoing but, as can be seen in the images at left and on the following page, the printing workflow is now well-established. Future work will include eliminating non-printable geometries or those that require support materials and the reduction of print times through path manipulation and, eventually, a significantly larger print nozzle.

From top to bottom: Comparison of reinforcement printed on the Lulzbot Taz desktop print (left) and the KUKA KR-10 1100 robotic arm (right), testing for printability and bridging, custom end effector attachment, electronics set up.



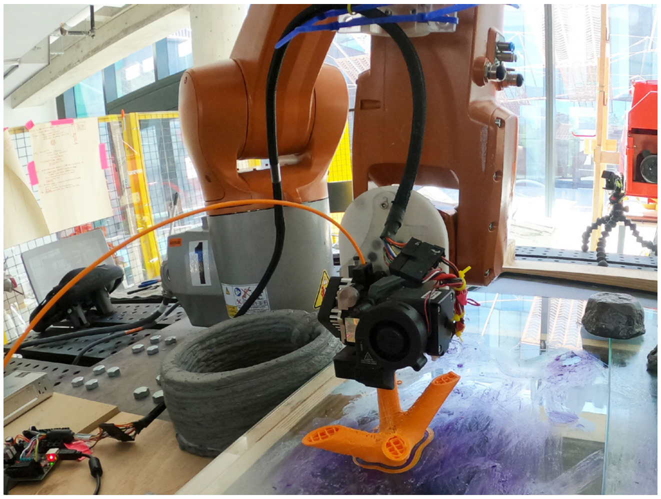
PHASE 4: Hardware and Software Configuration for Robotically-Controlled 3D Printing



HARDWARE KEY

01 KUKA KR C4 CONTROL SYSTEM
02 220 V POWER CORD
03 KUKA SMARTPAD TEACH PENDANT
04 RAMBO V1.4 BOARD
05 LCD CONTROLLER
06 SD CARD
07 12" X 18" BOARD
08 USB DATA SYNC CABLE
09 24V POWER SUPPLY
10 110 V POWER CORD
11 LAPTOP
12 110 V POWER CORD
13 SURGE PROTECTOR
14 24" X 48" PLYWOOD BOX
15 ELECTRIC GRIDDLES
16 CLAMPS
17 12" X 24" TEMPERED GLASS
18 PRINTED GEOMETRY
19 1.2MM TOOL HEAD
20 SLA PRINTED ATTACHMENT
21 KUKA KR 10 R1100-2
22 24" X 24" STEEL PLATE
23 BOLTS
24 ETHERNET CABLE
25 HARNESS
26 BUILD PRO WELDING TABLES

RESEARCH NEXT STEPS



The findings of this research are listed in the Executive Summary section of this document. At this point in the project, the premise of Polycasting remains valid: successful prototypes have been cast and demonstrate the biodegradable properties of PVA; suitable materials for molds and reinforcement have been identified; and there is a solution-in-principle for transitioning from desktop scale dual-extrusion to the scale of the robotic arms.

The next steps of this research will be to:

1) Advance the 3D printed concrete workflow,

2) Combine this will the plastic 3D printing workflow

3) Explore simultaneous printing between two KUKA KR10-1100 industrial robotic arms with mounted extruders

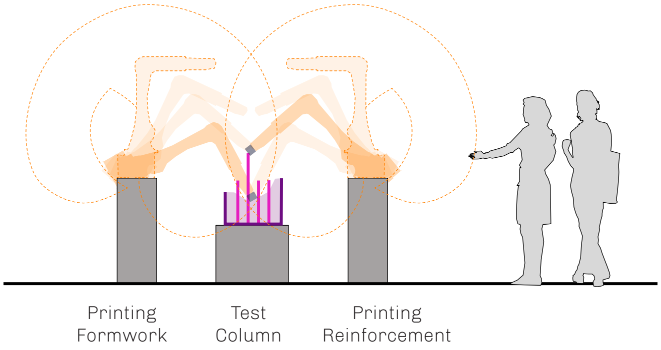
4) Test the design applications of these technologies in future studios and seminars

5) Meet with industry partners to discuss applications in the construction industry

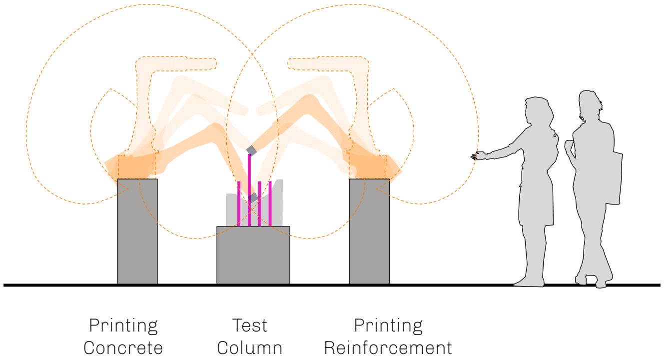
6) Pursue additional grant funding for a new series of experiments and implementation at a larger-scale

7) Submit the methods and findings to relevant conference and journals

Printing plastic formwork and reinforcement



Printing concrete with plastic printed reinforcement



KUKA KR 10kg Payload Industrial Robotic Arm (Payload refers to amount of weight the arm can hold fully extended in this case 22 pounds)

Dashed line indicates the envelope or boundary of the robotic arm's movement. Each joint moves in 6 axes.

The boxes on the ends are Custom End of Arm Tooling (EOAT), in this case 3D printer heads

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