BRICK PRINTING: FREEFORM FABRICATION OF MODULAR ARCHITECTUAL ELEMENTS WITH EMBEDDED SYSTEMS

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Abstract

We propose the use of modular, printed bricks to enable the integration of building systems and various processing techniques through the use of scalable printer platforms. This is enabled by a novel material platform comprised of clay, gypsum cement, FabEpoxy^{TM}, and SS-26F conductive silicone. On an open-architecture SFF system, a segment of cement wall with embedded electrical and fluidic conduits and various processing techniques was fabricated. Electrical and fluidic tolerances were comparable to traditionally constructed systems.

Introduction

Traditional building techniques tend to create structures with right angles and vertical walls. The majority of buildings are made from discrete parts such as I-beams, bricks, or wood beams. These discrete building elements naturally lend themselves to the creation of simple Cartesian buildings. While bricks have been used or centuries to create curved and complicated structures, the surface retains a certain granularity, and the process is labor intensive and requires onsite modification of the bricks. There are several techniques for homogenous structure creation. Primarily, these focus on casting concrete in various ways. Insulating concrete forms allow for the creation of structures by creating a casing for the structure using preformed parts. Spaces are left for the installations of electrical and plumbing work after the concrete has cured. With shotcrete, a wire mesh or inflated air form provides the shape of a structure which is covered in the concrete. These more naturally lend themselves to curved structures, but lack the resolution that SFF can offer.

SFF presents a solution to this problem by enabling the creation of arbitrary three-dimensional structures. The Radiolaria pavilion, designed by Shiro Studio and D-Shape, is a building being printed on the world's largest SFF system. It is constructed from 5-10 mm layers of artificial limestone (1). The Contour Crafter, developed by Behrokh Khoshnevis, at the University of Southern California, relies on the wet extrusion of cement and other materials to from a square tube and smoothing via a mechanically actuated trowel (2). Both systems create a structure of homogenous and continuous composition. They are incapable of using multiple material processing and printing techniques. While structures of any form could be created, the building systems would be bound by their prefabricated geometry. Any structure printed would be bound to the geometric limitations of its building systems. Additionally the printers for both systems are designed to encompass the built structure. The speed, size and resolution of the printed structure would be limited to that of a single printer – in that sense, the system does not scale favorably with the size of the structure.

A structure made from discrete elements would have the ability to take on any geometry with the added advantage of being produced from many lower cost machines in parallel. The speed of construction would be limited only by the number of printers, and printers could be specialized (at the sacrifice of interchangeability) to create higher resolution building blocks where needed. Lawrence Sass's work with digital home fabrication follows similar principles. His structures are created from laser cut plywood. The laser cutter is significantly smaller than the structure created, and generates structurally sound buildings (3).

All current building fabrication techniques require the installation of building systems, such as piping and electrical work, after the structure has been completed. This separation can lead to construction delays since a wall cannot be completed until all requisite electrical and plumbing work is complete. Often the workers who install the structure are separate from those who install plumbing and wiring. The novel printing materials platform developed could enable SFF to successfully co-install electrical and plumbing infrastructure in arbitrary geometric structures. This could enable a new and uncharted architectural design space. (Figure 1)

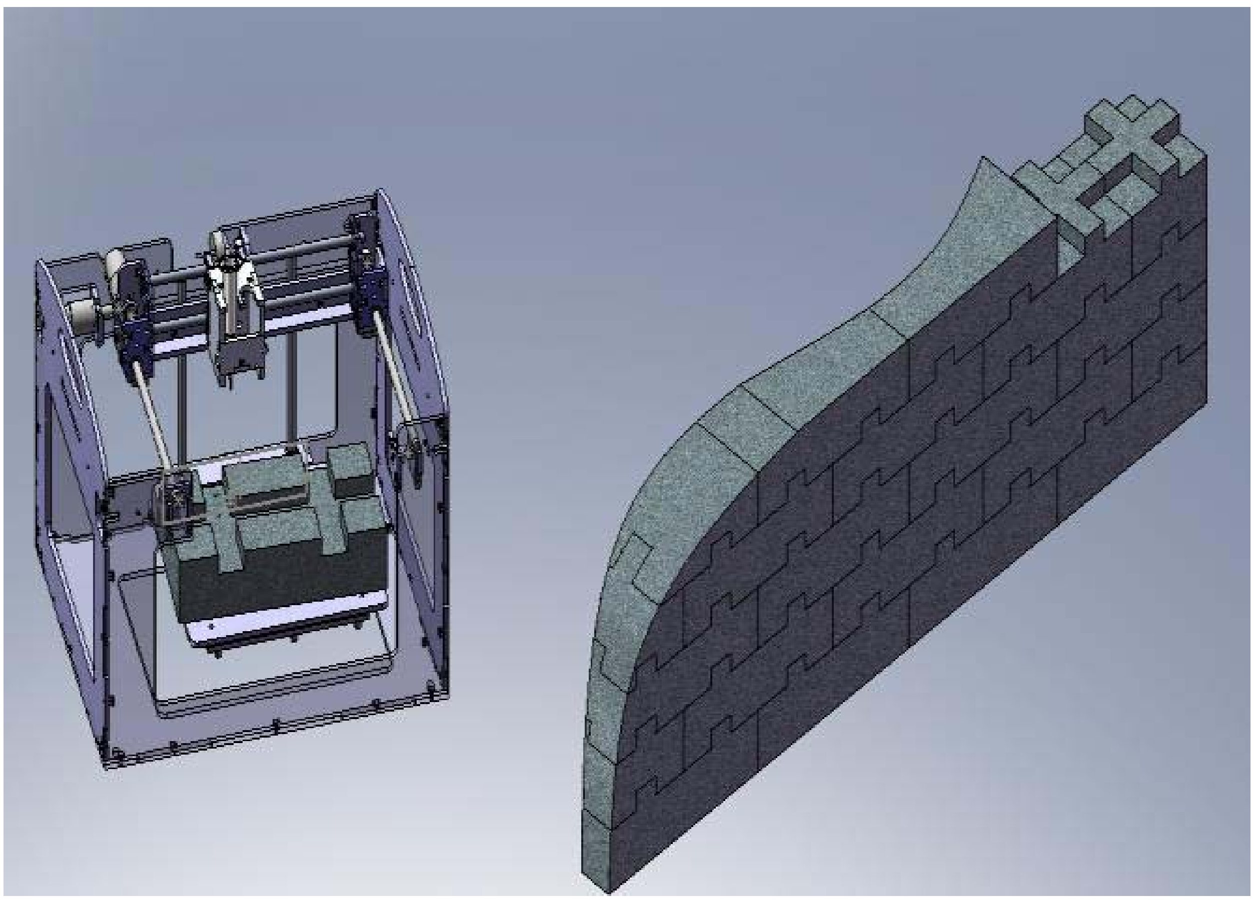


Figure 1: Illustration of Custom geometry, printed, interlocking bricks used to construct a structure larger than the printer. The interference fit of the bricks locks them into position.

Background

The Vast majority of bricks created in the world today are fabricated using extrusion processes where clay is forced into a die and then cut into desired lengths. This mass manufacturing technique is prevalent in the industrialized world. Bricks generated using this system usually have excellent mechanical properties, but vary only in length and cannot take on arbitrary shape without the retooling of the assembly line. The bricks are fired in a rail kiln at temperature ranging from 1000 to 1500 degrees depending on the clays composition. (4) In the more rural settings, brick making is a manual process. Clay is placed by hand into preformed dies. These bricks are then placed in static kilns or Bull's trench kilns. (5) The firing process of both methods is shape independent and would not be affected by the use of SFF'ed bricks.

In order to demonstrate techniques and fabricate with the new materials platform in this paper, a Model 1 Fab@Home printer was used. Fab@Home is an open source, low-cost SFF system. The printer automatically moves the syringe and dispenses material in a process known as "robocasting". Its small reservoir and size limits that scale of prints, however its design allows for the combination of any extrudable materials into a printed object.

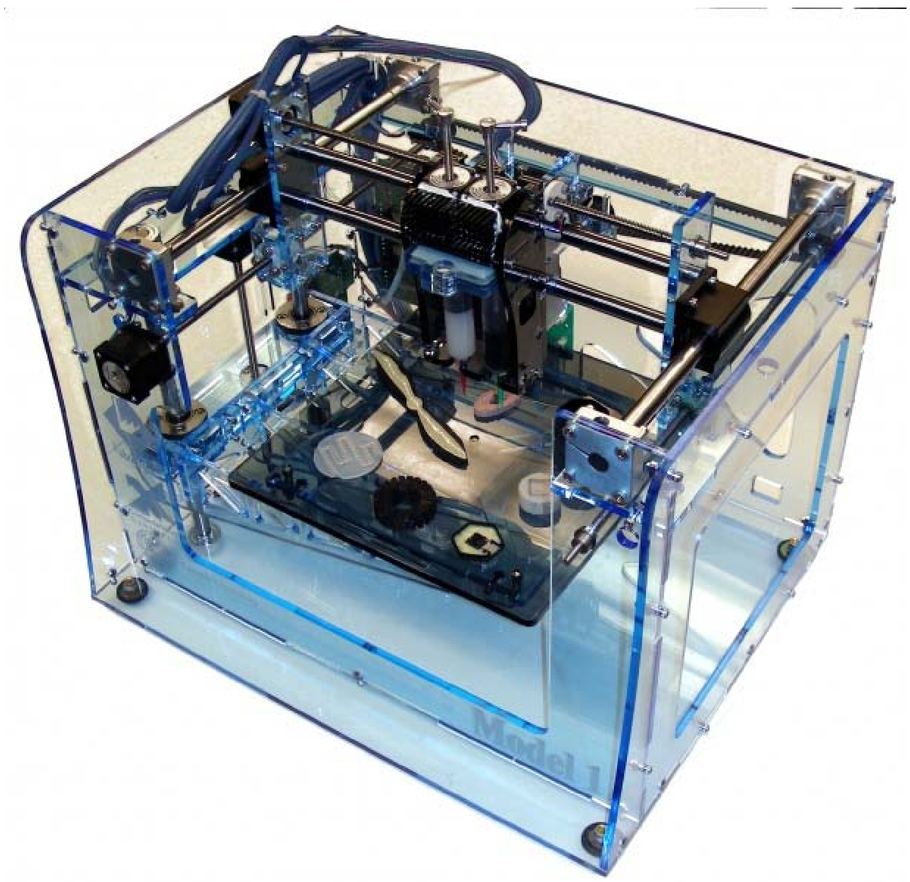


Figure 2: A Model 1 Fab@Home 3D printer with various printed objects

Materials

Hydro-Stone^{tm} Super-X gypsum cement from United States Gypsum was selected as printable cement since it has a fine powder size and high strength, and does not separate under pressure. However its self leveling nature prevents its use in printing without a casing. Xanthium gum was used as a viscosity modifying additive that allowed the cement to retain a given shape while it cures. Xanthium gum was selected because small concentration of the material drastically changes the viscosity of water-based solution. The shape-retaining cement mixture is prepared by adding 0.5 parts Xanthium gum powder by weight to 100 parts hydro-stone super-x powder by weight.

The powders are mixed thoroughly to give an even distribution of materials. This was accomplished by high amplitude low frequency vibration or mechanical agitation. In order to create cement the mixture must be added to 24 to 30 parts water for every 100 parts mixture. Higher water content produces a less dense and lower viscosity material. Hydro-Stone Super X cement is used with 21 to 23 parts water to 100 parts powder (6). The powder must be added to the water slowly while the water is stirred in order to ensure the production of a homogenous material. The mixed cement has a work life of 18 to 25 minutes depending on the concentration of water and uniformity of material.

FabEpoxy by Kraftmark was used as a pipe and conduit material due to its high strength and negligible shrinkage (7). The FabEpoxy used was mixed via a static mixer attached to a two-material cartridge. Once the material had been extruded through the entirety of the mixer, the static mixer was attached to a sealed 10ml Engineered Fluid Dispensing syringe. This minimized the ability of air to enter the syringe and ensured a perfect mixing ratio. Once mixed the material has a work life of 3 hours, and takes up to 24 hours to cure. The cure rate can be increase through the application of heat below 80 degrees Celsius.

SS-26F a 1-part, silver-filled RTV silicone, was selected as an electric conductor because it has been well characterized for use on the Fab@Home platform. It is available in small quantities directly from the manufacturer. It does not form good contact between cured and uncured material and therefore should not be allowed to sit for more than 10 minutes while printing (8).

Kentucky stone ball clay was selected for ceramic brick printing due to is fine powder size. The moisture level of the clay dramatically affects performance of a print and must be controlled. The material is prepared by mixing 70 parts clay powder to 30 parts water, by weight. The water saturated clay must be thoroughly mixed to prevent the formation of non-uniformities. The mixed clay must be stored in a sealed water tight container in the absence of air to prevent the clay from drying out.

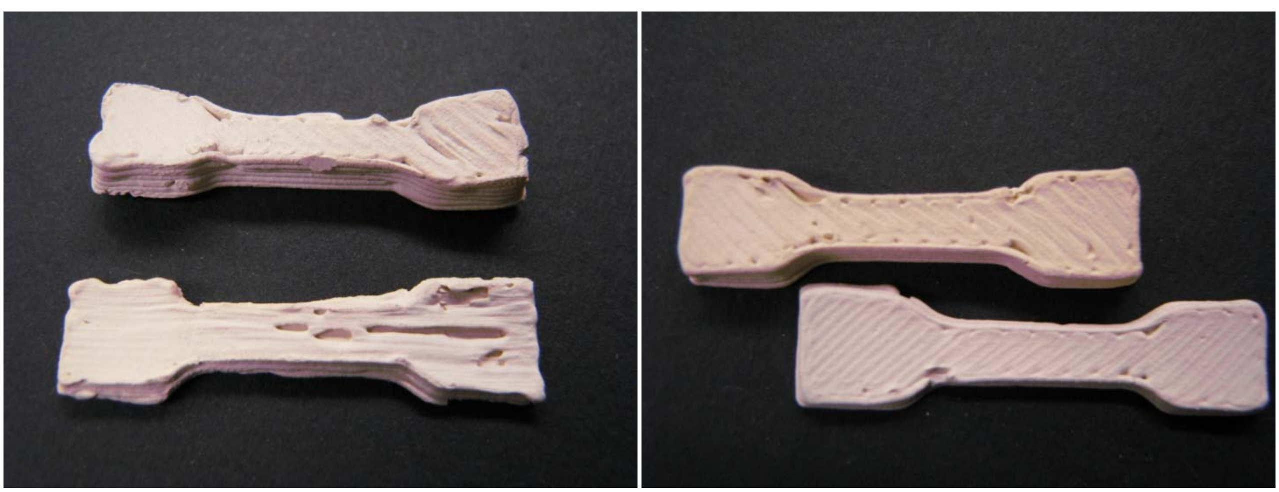
Printing Process

The fabrication was done using a two-syringe, Model 1, Fab@Home printer. Each material needs to be calibrated to give the machine a list of parameters. Primary parameters affect the path planning of the software and determine the resolution and feature size. Secondary parameters, such as "suckback" and "pushout", affect the machines ability of produce a product that matches the geometry and ensures a good finish to the part. For the novel materials, a series of trial and error modifications are needed to determine the parameters (9).

For materials other than FabEpoxy, the wiper piston was removed from the syringes and material was added through the top opening. Material was spread across the top to create an air tight seal. While adding material, pressure is applied on the material to force it down into the syringe. While the material is even with the top opening, the wiper is re-inserted to prevent air form being trapped between the material and the wiper. Air is trapped in the bottom of the syringe by this procedure and requires that the first cubic centimeter of material is extruded through the bottom opening before use. Large air pockets affect the material's print parameters, and small pockets create imperfections in the printed object.

The minimum feature size obtainable on the Fab@Home is determined by the smallest EFD tip that can be used in extrusion. Since Fab@Home motors produce a force less than average human strength, a material must be extrudable by hand for it to be printed. Materials are placed in the syringe using a method described above. Pressure is applied after successively smaller tips are used. The last tip to successfully allow extrusion without clogging is used. If there is significant clogging during printing of homogenous materials, the next largest tip is used.

While the printer deposits the clay, a humidifier moistens the surface of the printing object to promote interlayer bonding. Without the additional humidity, the material will extrude improperly and form regions where the material will not bond (see Figure 3).

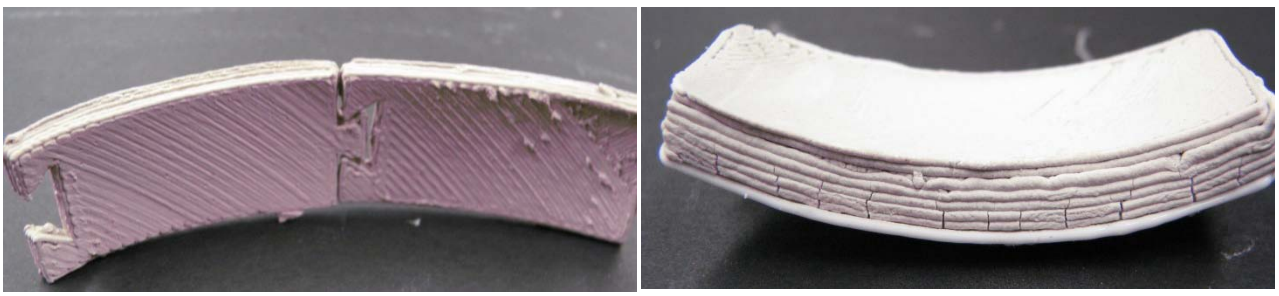


(a) (b)

Figure 3: Parts printed without additional humidity(a) tend to bond improperly between layers compared with those printed in a humid environment(b)

After an object is printed using clay, it must be dehumidified. This can be accomplished by either letting the object sit under a halogen lamp for 12 hours, or heating the objects to 50 degrees Celsius for several hours. Once dehumidified the clay is heated up to 1000 degrees C at a rate of 300 degrees per hour. The clay is held at that temperature for 24 hours. After the clay has been fired, it is cooled at a rate of 300 degrees Celsius per hour until it reaches room temperature.

A significant source of error in the printing of objects is uneven drying. This can be due to a non-uniform heat source or a barrier to moisture. When the sides of a sample dry or cure at an uneven rate the result can significantly change the geometry of the object form its intended state. Figure 4 shows the results of a moisture barrier on the shape of a printed cement object.



(a) (b)

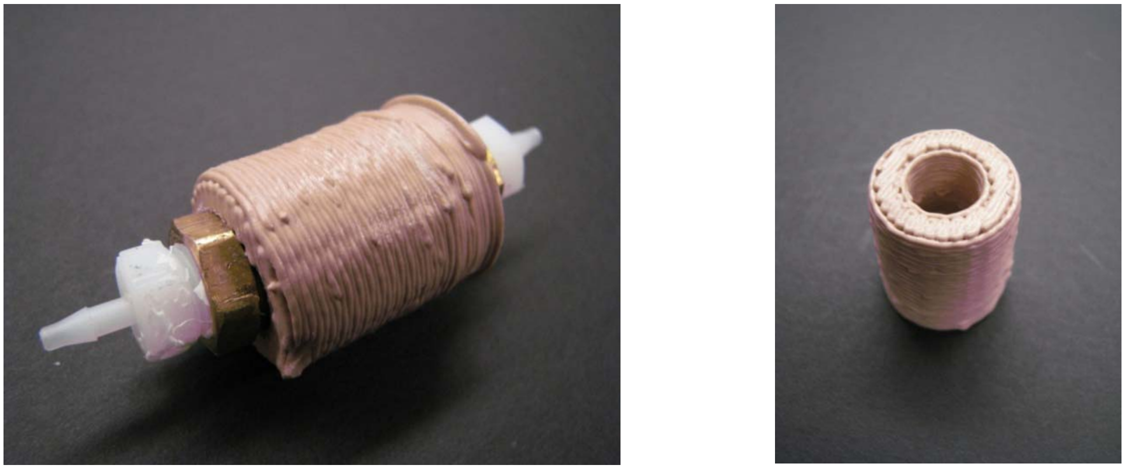
Figure 4: Results of uneven drying on clay(a) and cement(b) due to non-uniform heat source(a) and a moisture barrier(white silicon) (b)

Results

Property	FabEpoxy	Gypsum Cement	SS-26f Silicone	Ball Clay
Tip diameter(mm)	0.8382	0.8382	1.36	0.8382
Path speed(mm/s)	8.0	12.0	7.0	10.00
Deposition rate	0.0039	0.0035	0.0020	0.0045
Path width(mm)	0.80	0.8	1.0	0.91
Path Height(mm)	0.70	0.70	0.49	0.88
Pushout (s)	0.70	0.24	0.1	0.1
Suckback (s)	0.70	0.24	0.1	0.1
Suckback delay (s)	0.7	0.01	0.0	0.0

Table 1: List of Fab@Home Model 1 printing parameters.

FabEpoxy can be successfully printed on a Fab@Home using a 0.8382 mm diameter nozzle. FabEpoxy machinable nature lends itself easily to joining a printed fluidic channel to existing plumbing infrastructure. National Pipe Thread (NPT) inserts can be screwed into a FabEpoxy tube while wrapped in Teflon tape. This creates a water and air-tight seal which is an ideal joint between traditional and SFF'ed components.



(a) (b)

Figure 5: A FabEpoxy pipe (b) can be joined to standard plumbing and pneumatic fixtures via NPT plumbing inserts and barb adapters (a).

The Uniform Plumbing Code (UPC) calls for water to be delivered to homes for domestic use at between 50 to 70 PSI. Valves and supply lines as well as appliances are designed to withstand up to 80 psi (10). In order to determine the viability of using FabEpoxy as a fluidic conduit, a test sample was produced using an inner diameter of 12mm and a wall thickness of 6mm. The sample was allowed to cure over night under a halogen lamp, to speed curing, in order to ensure maximum strength had been achieved. NPT inserts were used to attach the pipe to an air supply, and to seal the pipe. The pipe was allowed to pressurize up to 100 PSI and drained repeatedly. The 12mm inner diameter pipe was able to successfully survive pressurization up to 100psi, without any noticeable deformation. FabEpoxy can withstand temperatures up to 121 degrees Celsius, well above home water temperature.

FabEpoxy piping was successfully embedded into a printed cement structure by inserting a preprinted pipe into a printed section of cement, and by simultaneously printing both materials. The outer diameter of the pipe was .2mm smaller than the inter diameter of the cement in order to account for inaccuracy of the tip heads and printing errors.

(a) (b)

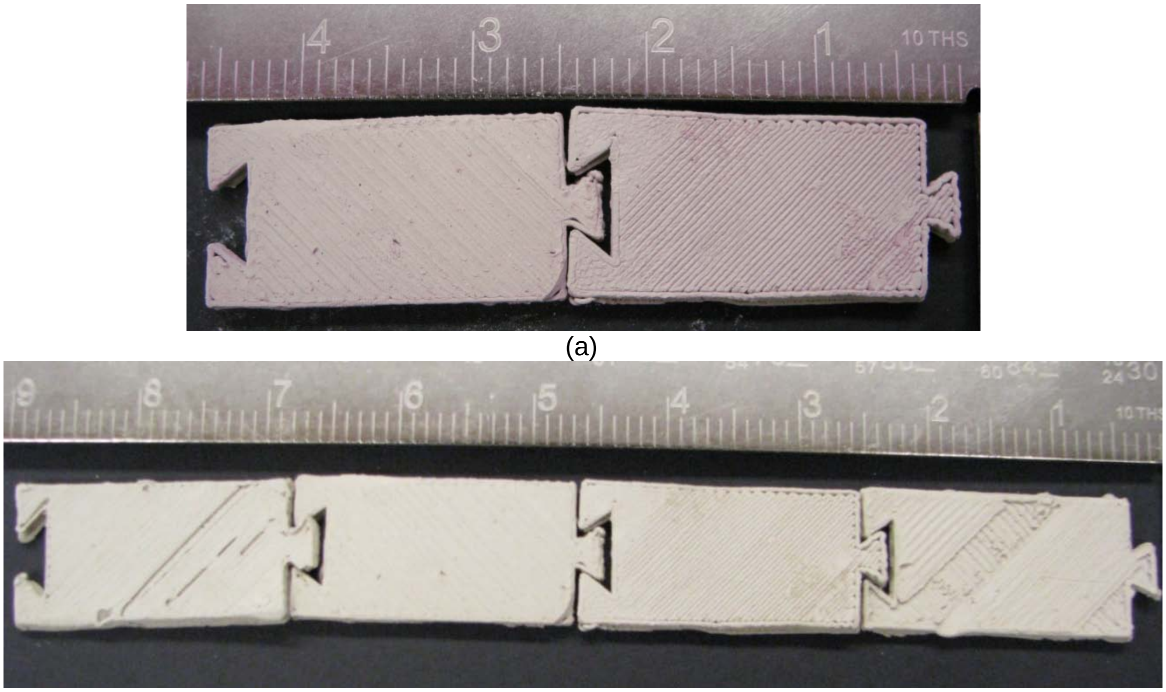
Figure 6: FabEpoxy pipes can be embedded into cement structure by simultaneously printing the materials (a) or by mechanical insertion after successful printing (b).

In order to demonstrate the ability to SFF an electrical conductor inside of cement, a section of SS-26F was printed inside of a gypsum cement casing. After allowing 24 hours for curing, the sample's resistance was measured. The sample had a resistance of 0.2 Ohms. SS-26F has a build resistivity of 5.0×10^{-6} Ωm, while copper has a resistivity of 17.2 x10^-9 Ωm (8). Therefore a printed wire would need to have a radius 17.04 times greater than an equivalent copper wire. A 14 gauge copper wire would correspond to a 13.87mm diameter printed wire.

Figure 7: A section of printed electrically conductive silicone embedded in a printed cement structure.

Ball clay has a notoriously high shrinkage rate that makes is a poor choice for most potter applications. In SFF this can be advantageous since it allows for the fabrication of parts which have a smaller feature size post firing. 10 samples of bricks printed with a geometry of 20mm x 20mm x 4.4mm. After firing the part shrank by 14.68% with a standard deviation of 1.47% in the plane of the layer, and by 16.33% with a standard deviation of 2.52% in the direction perpendicular to the layers of the object. Using this as a directional scaling factor, it should be possible to account for shrinkage by rescaling an object at printing time to ensure it meets the intended geometry.

An interlocking chain of bricks was fabricated using Kentucky clay. Since the clay shrinks considerably, an interlocking dovetail design was selected since it allows for limiting 2 degrees of freedom without the need for extraordinarily high geometric fidelity. Figure 5 shows a series of bricks with dovetail interlocks before firing in a kiln. The Fab@Home printer used to make the bricks has a build space of 17.8 cm x 17.8cm. The one dimensional structure has a length of 22.9 cm.



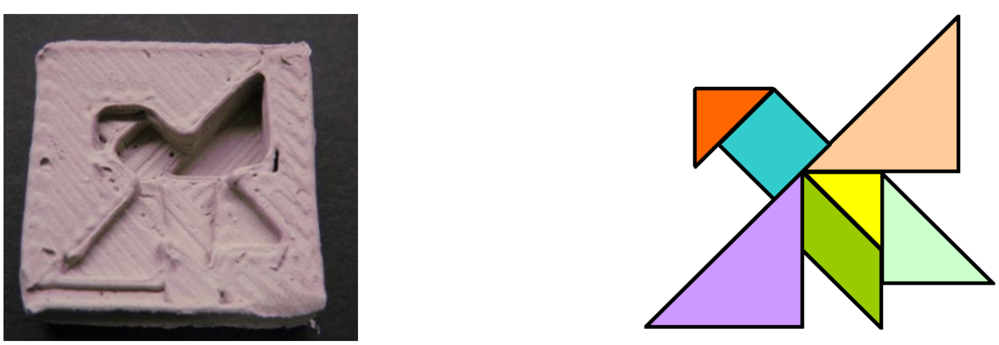
(a)

(b)

Figure 8: Interlocking Ceramic bricks (a), next to standard ruler, formed into a structure(b) on the scale of the printer.

Discussion:

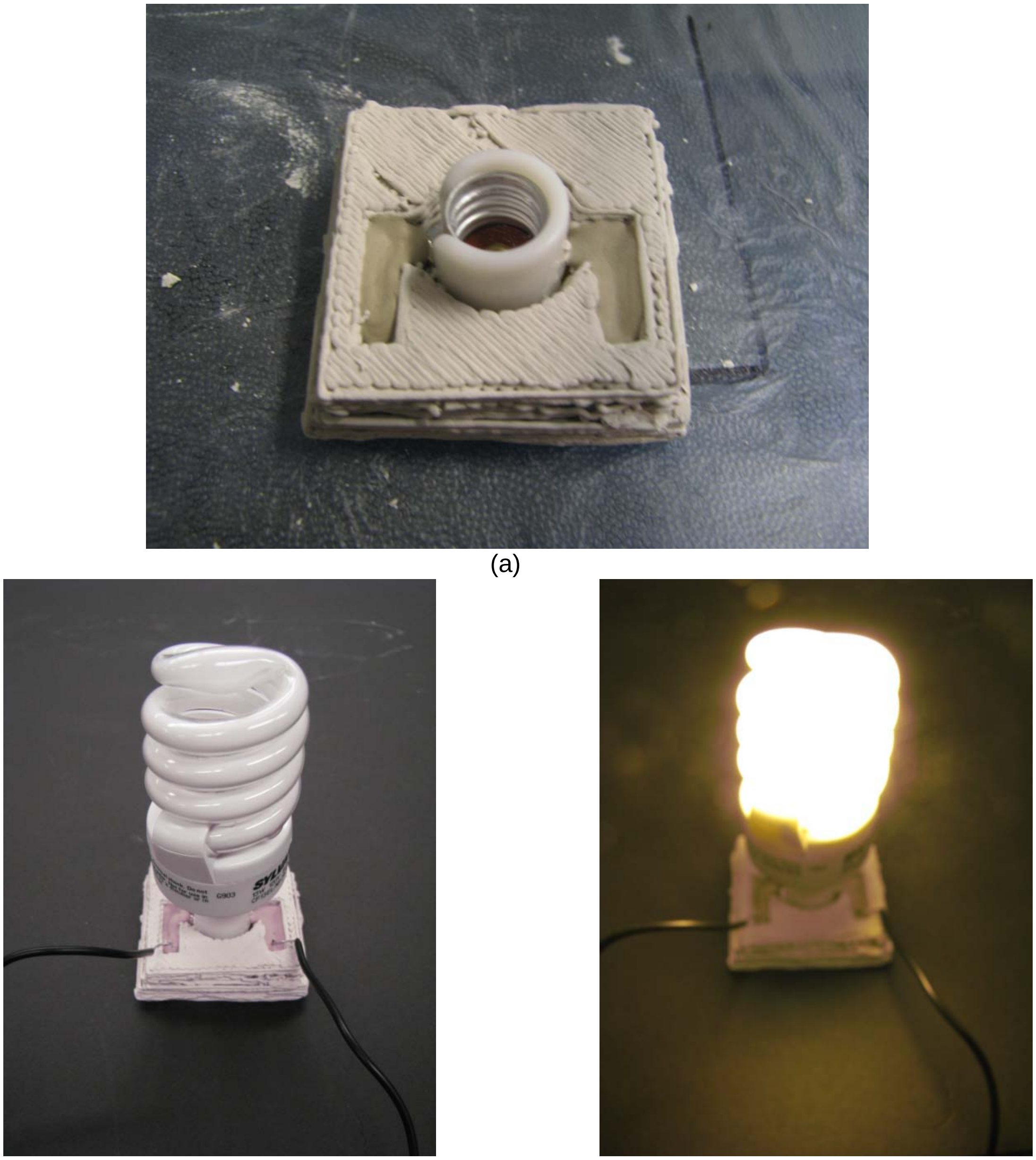
The printed superstructure, comprising individually printed bricks, successfully demonstrates a printer's ability to generate architectural structures of arbitrary scale using parts bound by the build size of the printer. As a demonstration of the ability to fabricate decorative objects, a brick was created with the Cornell Computational Synthesis Lab logo embedded as a relief. Each shape in the tangram logo was placed at a different depth in the brick. The minimum tip size affected the fidelity of the print since it forced all corners to be rounded with a fillet of radius 0.4191mm. Using this technique it should be possible for any design to be placed onto the bricks used to make a building. Often in classical style architecture, figure heads and text are added to the structural design of the building as decoration. The technique would greatly reduce the cost of such architectural flourishes by removing any skilled labor or work by hand.



(a) (b)

Figure 9: The CCSL logo (b) printed as a relief in a ceramic brick.

In order to demonstrate the effectiveness of the printed cement with electrical conductor, a candelabra bulb socket was embedded inside a printed cement object along with wires attached to the socket. The printed wires were then connected to 120 volt AC power via a standard power cord. When the cord was plugged in, the printed wires successfully carried current to the socket and activated the bulb. The conductive silicones pliable nature easily lends itself to merging traditional and printed electronics since it can adapt to the unique geometry of the coupling wire or lead.



(a)

(b) (c)

Figure 10: A light bulb attached to a socket, embedded in a cement structure(A) and powered via printed conductor before (B) and after(C) current is applied

As a test of the feasibility of the brick printing platform, the flow rate of material was determined for various drive systems. Material was loaded into a 10ml EFD syringe and placed in various deposition systems. The time to empty the container of its volume of material was record, and flow rate determined (See Table 2). A circular room with 100 square foot (9.29 m^2) interior and 3 inch (7.62 cm) thick 10 ft (3.048 m) tall walls requires 90.58 cubic feet (2,565,013 cm^3) of material. A current Fab@Home design would take almost 10 years to print the clay needed to build the structure, provided it worked non-stop with constant material feed. However a more advanced printer with a single, 1.524 mm tipped, tool 90psi driven tool would take 5 days and 11 hours. 6 printers with sufficient path speed would be able to print the material in less than a day using the same tools.

There are tradeoffs between time and resolution and parallelization. One can sacrifice resolution for build speed. Normal construction techniques do not provide 0.8mm resolution. With printed structures, the high resolution is only needed for exteriors and interfaces with building systems. Using a dual-resolution printer, one could balance the need for resolution and print speed. If a structure is made using 50% high resolution and 50% low resolution it can achieve the needed precision with increased build speed (See Table 3).

Material	Tip Diameter (mm)	Drive	Flow rate (cm^3/hour)
Clay (70% powder)	0.8382	Fab@Home	31.48
	0.8382	90 psi air supply	628
	1.524	90 psi air supply	1044
	1.524	100 psi air supply	1166
	2.78	100 psi air supply	2262
Gypsum Cement (27 parts water)	0.8382	Fab@Home	29.38
	0.8382	90 psi air supply	7880
	1.524	90 psi air supply	19,700
	1.524	100 psi air supply	19,700
	2.78	100 psi air supply	19,700

Table 2: The drive and resolution of the deposition tool determines the tools build speed.

Number of Machines	Tip Diameter (mm)	Output rate (cm^3/hour)
1	1.524	19,700
100	1.524	1,970,000
100	0.8382	788,000
50/50	0.8382/1.524	1,379,000

Table 3: Number and resolution of printers affect build speed. Values are for machines using 90 psi tools to deposit gypsum cement.

A potential application of brick printing is the use of local materials for the construction of unique structures in remote and impoverished areas. The small size and scalable nature of the brick printing system allows for a minimal upfront capital investment. A person or organization could start with several printers, and reinvest their earnings into more machinery, directly increasing productivity. The clay based printing could use local earthen material to fabricate the structure. Kilns based on the Bull's trench design allow for the firing of large amounts of bricks with minimal resources.

Future Work

A logical next step in this research is to print and entire wall power socket and lighting fixtures into a cement superstructure. In order to accomplish this, a more rigid printable conductor would be needed. In order to create larger superstructure using this material platform a new deposition tool would also need to be developed. While a large material reservoir would allow for the easier creation of larger models, the short work life necessitates the creation of a mix-on-demand tool that would mix the powder and water of the gypsum cement shortly before printing. This new tool would not be constrained by the pressure and tip size limitations of the current Fab@Home tool and could increase the resolution of cement printing.

Conclusion

Solid Freeform Fabrication has great promise in the field of building construction. While most arbitrary geometry structure fabrication techniques rely on the use of large scale printers, small size printers with high resolution could prove to be equally useful. . Current large scale printers can create structural elements but cannot embed building systems during the printing process. The combination of cement structures with FabEpoxy pipes and extrudable conductor can allow for the seamless integration of building systems into the printing process. Printed bricks can be used to create structures not bounded by the size of the printed. The printed bricks could be used as both structural support and decorative flair. In addition to possibly enabling new ways of constructing classical designs, this approach opens entirely new design paradigms in which designers are less constrained by the limitations that current fabrication technologies impose.

Acknowledgements

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