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Flex.Molds

Flex.Molds explores the potential of using flexible plastic in conjunction with standard 3D printing techniques to fabricate 3D printed flexible molds for casting concrete.

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INTRODUCTION

New 3D printing materials are currently being developed and released at a rapid pace, including flexible plastic filament that was recently introduced to the desktop 3D printing market. Flex.Molds explores the potential of using this material in conjunction with standard 3D printing techniques to improve the conventional fabrication process of precast concrete. It poses the question: can 3D printing formwork for concrete alleviate some of the problems associated with traditional casting by reducing fabrication steps and increasing geometric flexibility?

The initial research for Flex.Molds was carried out during an elective offered to undergraduate and graduate students at Kent State University, which subsequently led to design development, data collection and the development of guidelines for architects and fabricators who are interested in exploring this new technique. This paper describes the background research, current state of digitally fabricated molds, 3D printing materials, fabrication and casting processes, typical workflow from design to fabrication, design limitations and opportunities, and conclusions.

BACKGROUND: FLEXIBLE MOLDS

In the precast industry, there is a subset of companies that manufacture flexible molds or form liners for architectural applications, such as precast walls. One of the original techniques to create one of these molds is to cast an actual object, such as a brick, using a flexible polymer, such as urethane or rubber. There are now several additional techniques that have been introduced into the market to achieve the same result. They include using a CNC milling machine to mill out the positive of a mold and then casting it with a flexible polymer silicon (Bell 2012), or using a vacuum forming machine, which is very time efficient, to form plastic.

PRECEDENT: COMPLEX FORMWORK

The fabrication of molds for complex geometries is time and material intensive, and therefore steps are taken to control costs, such as maximizing the number of castings per mold (Clark Pacific 2000) or reducing the number of unique molds produced. Unfortunately these efficiencies can lead to the loss of design freedom. One contemporary project that highlights this issue is the concrete façade of Perot Museum of Nature and Science in Dallas, Texas that was designed by Morphosis Architects (Stephens 2013). To create the desired look for the façade, the architects used a set of modularized wax molds for the casting process. Originally, the unique molds were intended to be CNC milled out of wax and then cast out of concrete, however the number of variations was reduced down to 20 to optimize the fabrication process (Doscher 2011).

BACKGROUND: 3D PRINTING AND CONCRETE

Currently, several architects and engineers (Khoshnevis 2006; Buswell 2006) are focused on 3D printing large-scale concrete structures for architectural applications. These projects use a FDM (fused deposition modeling) technique to directly print with concrete-based materials. Large scale prototypes have been realized, however the technique has not yet resulted in a permanent structure. Flex.Molds investigates a different approach to utilizing 3D printing in architecture. Rather than directly printing building components in concrete, which has its own set of opportunities and limitations, this research explores if instead, digital fabrication can improve existing processes in building construction. Flexible formwork can be 3D printed and used to cast concrete with traditional methods, which could shorten the process of prefabricating concrete, while still relying on tested, industry standard processes.

BACKGROUND: 3D PRINTING MOLDS

There are several other projects that are being developed that showcase how 3D printing has an opportunity to offer new design possibilities for concrete casting. For example, the FreeFab project being developed by Laing O'Rourke Construction (Gardiner 2014) is utilizing a large scale 3D printed wax formwork that can be combined with CNC milling, while UCL Bartlett's Clay Robotics project utilizes unfired clay as a temporary mold for concrete (Sun, Kelvin, Wong 2014). These materials offer a unique opportunity to reuse the material from one mold to the next, but both lack the ability to create high resolution or detailed molds, due to the scale of the printing process. The molds themselves also cannot be cast a second time. While PLA flexible plastic is not a natural material, it does offer advantages that increase the accuracy and efficiency of 3D printing molds.

FABRICATION PROCESS

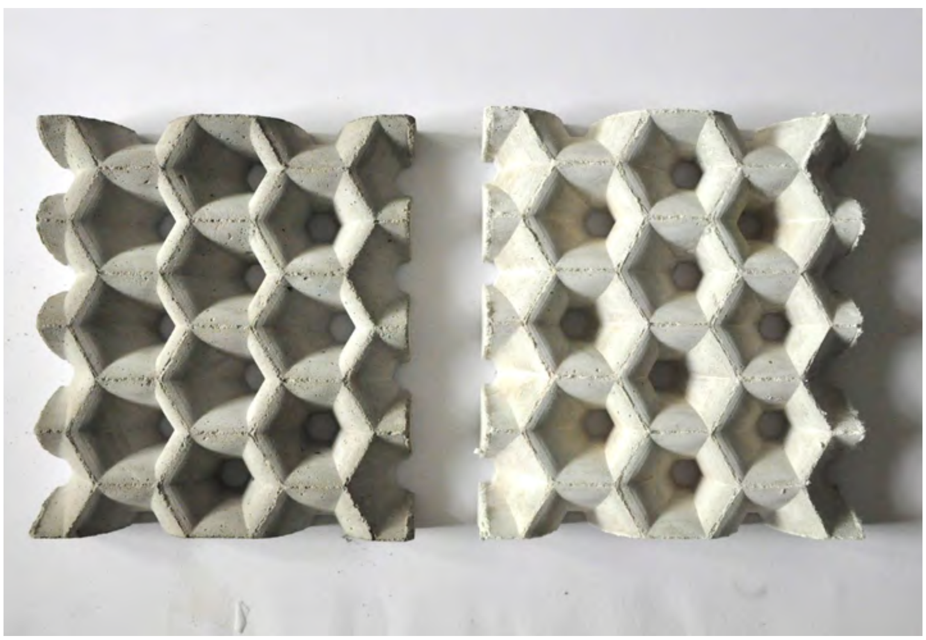
The Flex.Molds prototypes were developed in a single parametric definition that combined the design and fabrication parameters, allowing for the quick development of design iterations. The mold geometry was developed within Rhino's parametric scripting language, Grasshopper®. The initial step of the Grasshopper® definition defines the overall form of the application (e.g. wall panel) through the input of the design parameters of the desired structure. When using a desktop 3D printer, a slicing program is then used to simulate the movement of the printer and generate the tool path code. These simulations are necessary to identify any possible errors prior to fabrication, such as avoiding severe overhangs from one layer to another that can create imperfections in the mold.

Once the design is finalized, the flexible formwork is 3D printed. Research has been carried out using both small and large FDM style plastic extrusion system 3D printers. The project began on a small scale printer, which allowed for the quick identification of the opportunities and limitations of the material and fabrication system. At a larger scale, a commercially available, large desktop 3D printer was used, as well as a 6-axis robot arm. The robot arm had a customized plastic extrusion head end effector attached, which was used to prototype full scale molds up to 6 feet in diameter. Since the extrusion nozzle on the robot arm is larger than both desktop 3D printers, prototypes can be printed in much thicker layers, reducing the overall print time.

Once the print is complete, a release agent is applied to the mold and then the casting material is mixed, placed, and left to cure in the mold. Once the concrete is set, the flexible mold is simply removed and ready for another casting.

MATERIALS: 3D PRINTING

New 3D printing materials for FDM style printers are currently being developed and released at a rapid pace. Flexible plastic filament was recently introduced to the desktop 3D printing market and this project has been exploring its potential in creating flexible molds for concrete. The advantage of this material over standard rigid plastic filament is that a single formwork can be recast multiple times with no damage to the mold itself. Flexible molds hold their form during the casting process, but then allow the concrete to be easily released. It is important to note that while the material is quite flexible, it is not elastic, so it is not possible to stretch and use it in the same manner as fabric formwork. Previous research studied the multiple manufacturers that are currently offering 3D printing filament and can be referenced to identify which material had the highest rate of success (Peters 2014).



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MATERIALS: CASTING

Two materials have been cast during the prototyping process (Figure 1). First, mortar mixtures (sand, cement, and water) that have no additives or composite materials added to the mixture have been used in the small scale molds. The resulting casts have a smooth texture with minimal imperfections. The structural capability of these casts has not been tested in a lab. Concrete mixtures (sand, gravel, cement, and water) will be possible as the system is scaled up and the mold sizes increase.

A second set of testing has used glass fiber reinforced concrete (GFRC). This material offers the potential of creating thin, detailed panels that have structural integrity without

Figure 1: Concrete (left) vs. GFRC (right)

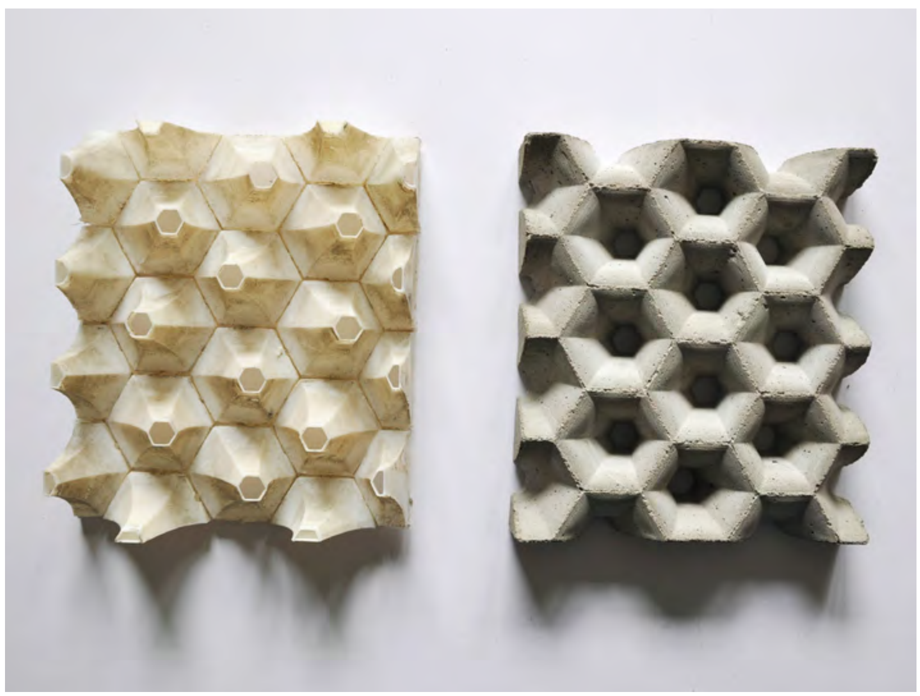
additional reinforcement. The GFRC casts also have a smooth texture with minimal imperfections.

The intent of Flex.Molds is to develop a mold fabrication technique that can rely on conventional casting processes. The material tests have shown that industry-standard casting materials work well with the system.

PROTOTYPING

All the prototypes for this research were 3D printed in-house. This direct link between the digital models and physical tests was essential for the Flex.Molds research, since working with and controlling the printers ourselves led to a better understanding of the material and fabrication opportunities and limitations presented by this system. Optimal printing parameters could only be determined through several rounds of prototyping and casting. The following factors were examined when prototyping: structural stability, permeability, printing speed, and surface delineation.

The prototypes were made on 3D printers with single extrusion heads, however dual extrusion printers could also be used. This system allows for the use of dissolvable PVA materials to be printed simultaneously with the flexible material. The dissolvable material acts as a support during the printing process, allowing for the fabrication of otherwise difficult geometries, such as large overhangs between layers. While this system eliminates some design limitations, it significantly increases the overall fabrication time and post-production of the prints. Therefore, the prototyping has focused on a single material extrusion system.



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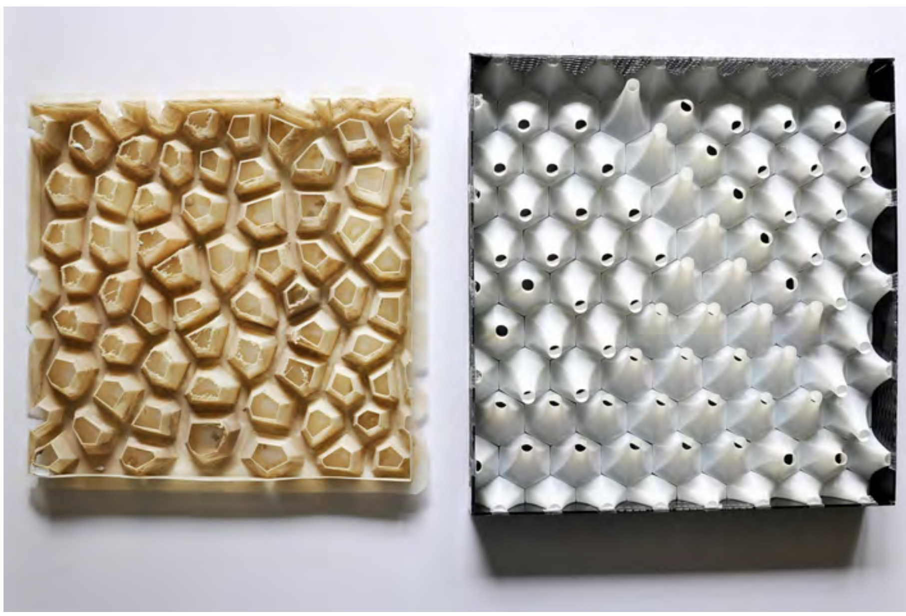
DESIGN

Combining parametric design tools, such as Grasshopper®, with 3D printing, allows for the creation of unique 3D prints and infinite design outputs for concrete panels. Not only are the molds flexible, but the design opportunities are flexible as well. The initial designs produced for the research focused on two primary application categories, interlocking

Figure 2: Reconfigurable mold layout

blocks and wall panels, to understand the opportunities and limitations of the material and fabrication system (Peters 2014). The interlocking blocks have intricate exterior patterns and are intended for wall or roof applications. The wall panels include both solid and perforated panels. The solid panels are intended for wall veneer applications and the prototype designs study various patterns and effects that could be applied. The casting technique for these panels is similar to that used for form liners. The perforated panels could be used in shading or rain screen applications and various geometries were developed to test their feasibility.

Since then, the research has focused on identifying geometries and applications that highlight the potential of the technique. For example, the new tests are exploring the use of "under cuts" and complex geometries that can only be achieved with advanced fabrication techniques, such as 3D printing and multi-axes milling machines. The new prototypes also highlight the use of intricate interlocking joints, which could not be fabricated using any other tools. Finally, prototyping has also extended to the design, fabrication and casting of two-part molds. The success of these tests points to the possibility of casting large and complex geometries that would far exceed what is possible to 3D print in a single mold that uses a form liner technique.



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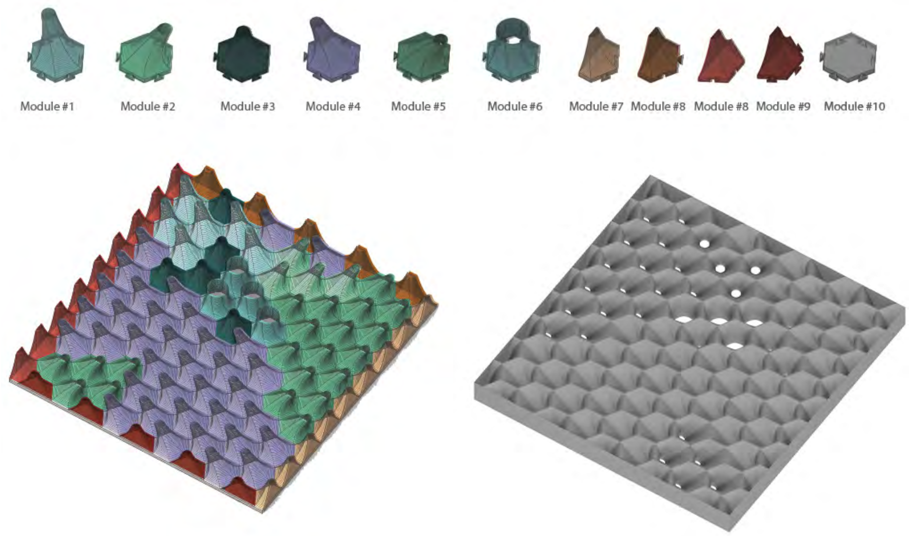
RECONFIGURABLE MODULES

Currently, fabrication time is one of the disadvantages of this system. Experimentation led to an innovative method for efficiently producing large panels: reconfigurable modules (Figure 2). For example, to produce a 24in x 24in x 2in panel, option one would be to 3D print a large scale mold in one piece and option two would be to 3D print several small interlocking modules that assemble to form a mold at the desired size (Figure 3). Comparing the initial fabrication time of these two options, the single mold is faster to produce (42 hours vs. 50 hours), however, if a design calls for 20 unique panels across a surface, the calculation changes. Since the small modules are reconfigurable, after they are cast and the concrete is removed, they can be reassembled into countless combinations to create unique variations. The mold fabrication time then becomes 840 hours for 20 unique, monolithic molds and still 50 hours for 20 unique molds made from the small reconfigured modules.

Reconfigurable molds also solve another problem. Molds can break or delaminate during the casting or removal process, rendering the mold unusable. When using reconfigurable

Figure 3: Monolithic vs. reconfigurable



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molds, only the individual module that was damaged needs to be reprinted, thereby creating less waste and reducing additional fabrication time.

The panel system shown highlights the design potential of such a system (Figure 4). The application is a sunscreen façade that can be configured to respond to specific sun angles, controlling the quantity of sun exposure in the interior at certain times of day throughout the year. The various modules each represent a specific time of day during the year, so that sun exposure can be tailored to the building's site, façade orientation and desired interior effect. Several parameters of the design can be modified, including the sun angle, the size of the perforation (or no perforation at all), the shape of the perforation (circle, square, etc.), and the depth of the panel. Additionally, the outlining frame can be changed to create a different size panel or to create a different shape, such as an octagon or triangle, all while using the same modules. The system is also easily scalable, meaning that the reconfigurable modules can easily be designed for larger or smaller panel sizes, perforations or thicknesses. The modules use an interlocking snap fit connection that allows them to be held together temporarily during the casting process, but then easily released after, allowing them to be reassembled and reconfigured into a different casting pattern. The snap fit connection is a custom detail, and therefore several rounds of prototyping we necessary to achieve the ideal tolerance that leads to a tight fit between the modules, but that doesn't cause damage when they are separated.

ONGOING RESEARCH

Flex.Molds began with research into both the printing and casting material with the goal of identifying important parameters to create a reliable fabrication system. While this research is still ongoing, the focus is currently on the design outputs that can be achieved with this technique, as well as the development of the interlocking and reconfigurable modules. The durability of the formwork during the casting process also merits further experimentation, as stresses put on the molds include the placement of reinforcement and the use of release agents. To date we have cast several molds up to five times and have seen very limited damage to the mold, however this will continue to be monitored.

The research has been focused on small scale prototypes, and therefore the next step of the project will be to cast large scale panels (Figure 5). These will test the limits of the fabrication process, as well as the structural capability of the molds and panels.

Figure 4: Reconfigurable mold design

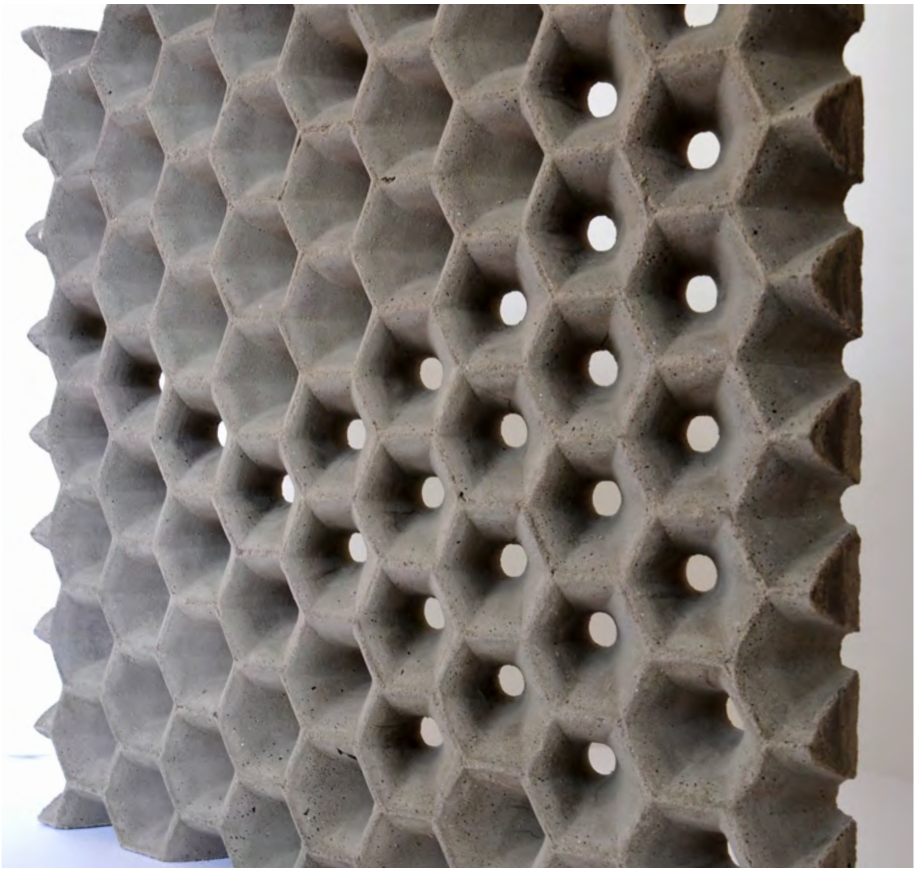

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Figure 5: Concrete cast

CONCLUSION

Flex.Molds offers a new pathway for 3D printing to improve an aspect of architectural construction. Unlike directly 3D printing a structure, this method has the potential to be implemented immediately into the construction industry because it improves upon an existing, well-understood technique and material. This research also serves as another example of transforming 3D printing from a prototyping tool to a manufacturing tool that produces functional objects. There are several benefits that we see to using this system in comparison to directly 3D printing a panel or using typical precast methods. These include highly detailed surfaces, fine surface finish, complex geometries (under cuts), reconfigurable modules through the use of interlocking joints, high material efficiency and the potential to recycle the mold after its usefulness. At the same time there are several limitations to this technique, which include slow fabrication time, limited printer sizes, and the durability of 3D printing (delamination between layers).

Another important advantage is that 3D printing unique molds does not increase the cost of fabrication. This allows for the production of highly complex or intricately detailed forms, which greatly increases the design possibilities for architects. Designs that would otherwise be simplified to fit a small number of molds can remain as the architect intended them to be. Additionally, this technique directly 3D prints the form that will be cast, and therefore the traditional step of CNC milling a form from which to make the mold is not needed. Eliminating this step helps to compensate for the main disadvantage, which is that 3D printing is a slow process.

GUIDELINES

These guidelines are for architects and fabricators to reference when using flexible filament to 3D print forms for casting. Through several rounds of prototyping, several key parameters were identified for working with the technique, however note that these guidelines are in reference to FDM style 3D printers only.

PRINTING SPEED

The recommended printing speed for flexible filament is 30mm/s. This is significantly slower than the printing speed for standard PLA filament (50mm/s), to reduce the amount of printing failures during the fabrication process. Additionally, this significantly increases the overall fabrication time compared to typical a typical filament.

OVERHANGS

One of the biggest limitations of using a FDM style 3D printer is the minimal tolerance for overhang between layers. Through our research we have concluded the maximum angle for the overhand between layers with a single extrusion system is approximately 45 degrees.

LAYER HEIGHT

The surface finish of the concrete is directly related to a printing parameter: the layer height. For example, when printing with desktop 3D printers, a layer height of 0.1mm should be used to create a relatively smooth surface finish, with the printing process almost undetectable. However, the surface finish for molds created using robotic arms with a larger printing nozzle is slightly rougher, since it is necessary to have a layer height of 1.8mm.

The layer height affects both your surface finish and your overall fabrication time. The smaller the layer height, the finer the print resolution and surface finish and longer the overall fabrication time. The larger the layer height, the rougher the print resolution and surface finish, however the quicker the fabrication time. The majority of the Flex.Molds prototypes were fabricated with a 0.1mm layer height.

WALL THICKNESS

Prototyping has led to a recommended wall thickness of .8mm to 1mm. This allows for the layers to properly adhere, producing a fairly durable mold that withstands repeated castings.

SURFACE DIVISION

Large, flat surfaces tend to warp during the printing process due to the properties of the material, which can ultimately lead to a print failing during the printing process. To avoid surface warping, large surfaces should be subdivided into smaller geometries. An additional benefit to this approach is that the vertical sides of the mold also become stiffer, which is important during the casting process. The correct amount of surface division depends on the overall scale and design of the mold to be fabricated; therefore it is not possible to provide definitive guidelines for the size of the subdivisions.

PRINTING MATERIALS

The previous research on this topic studied the multiple manufacturers that are currently offering 3D printing filament to identify which material worked the best (Peters 2014). Generally speaking, there is a much higher rate of print failure when using flexible material compared to a standard hard plastic, such as ABS or PLA plastic filament, because of its sensitivity to the parameters noted above. It is necessary to be patient with these prints and expect a certain level of failure during the prototyping process. FlexiFil™ filament produced by FormFutura has been the most reliable, however results will continually vary as manufacturers update the materials.

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