

Experiments with 3D Printing Technologies in
Masonry Construction

by

Adam M. Blakeway

Submitted to the
Department of Architecture
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Architecture (BSA)

at the

Massachusetts Institute of Technology

June 2014

© 2014 Adam M. Blakeway
All rights reserved

The author hereby grants to MIT permission to reproduce and to
distribute publicly, paper and electronic copies of this thesis document in whole or in part
in any medium now known or hereafter created.

Author:
Adam M. Blakeway
Department of Architecture, Computation Group
May 23, 2014

Certified by:
Brandon Clifford
Belluschi Lecturer, Architectural Design
Thesis Advisor

Accepted by:
J. Meejin Yoon
Director of Undergraduate Program
Chairman, Thesis Committee

Thesis Advisor: Brandon Clifford, Belluschi Lecturer, Architectural Design

Experiments with 3D Printing Technologies in Masonry Construction

by

Adam M. Blakeway

Submitted to the Department of Architecture on May 23, 2014 in Partial Fulfillment of the
Requirements for the Degree of Bachelor of Science in Architecture

ABSTRACT

Modern masonry construction finds itself in a cyclical pattern of “more of the same,” insisting on standardized, basic designs consisting of little more than uniform stones laid in regular courses, which do little to add to the variability of the modern world. While these forms attain a surety in structural stability, they offer little in the form of variable aesthetics.

3D-printing, consistently hailed as one of the most promising developments of the 21st century, allowing individuals from every walk of life to create and produce in real time, has, contrarily, failed to grasp our greater aspirations in the field of Architecture. Most attempts at the incorporation of 3D-printing technology in Architecture have simply been to scale the technologies to print larger and larger objects, eventually working up to entire buildings. While these efforts are beneficial in some ways, they consist of numerous drawbacks which make these types of strategies ultimately implausible, at least for the moment.

Modern construction, once thought to be secure in its standards of structure and implementation, is now being challenged to develop designs far more elaborate than their “glass tower” counterparts by pushing the boundaries of what architectural moves are possible. The long held beliefs that stone must be orthogonal and uniform to be utilized in large-scale construction projects are being revamped in the wake of the 3D printing boom.

This thesis seeks to find a synthesis between these two methods of modern construction, unifying the versatility and variability of 3D-printing and the stability and natural aesthetic of masonry, to create viable and aesthetically appealing architectural forms for the 21st century.

Thesis Supervisor: Brandon Clifford

Title: Belluschi Lecturer, Architectural Design

Table of Contents

Title Page.....	Page 1
Thesis Advisor Acknowledgement.....	Page 2
Abstract.....	Page 3
Table of Contents.....	Page 4
Introduction.....	Page 5
3D Printing: Applications in Architecture.....	Page 10
Masonry Construction Practices.....	Page 14
Putting Together the Pieces.....	Page 17
Experiments in Synthesis.....	Page 18
Best Practices.....	Page 28
Future Applications.....	Page 30
Conclusion.....	Page 32
Bibliography.....	Page 34

Introduction

My interest in digital fabrication began at an early age, playing with the simple pieces of my K'NEX and LEGO sets to construct rollercoasters and skyscrapers in virtually limitless collaborations. I remember thinking to myself even then, “Why isn’t everything this easy?” To be fair, I was a bit more whimsical with the scope of the idea back then, but I find the same question echoing in my head today.

As an adult, with working knowledge of the physical environment and memories of that childhood play, I thought long and hard about how such simple methods could be applied on the grand-scale of engineering for the masses. At times, the search proved difficult, always spiraling away from simplicity and into the realms of complexity, but eventually, progress was made and is presented here in this thesis.

I chose the field of digital fabrication as a means of utilizing the ability of digital modeling environments and 3D-printing technologies to accommodate a multitude of variable problems and design choices. As the world presses on through the 21st century, our ability to shape and sculpt the world around us is giving way to more generative methods of environmental impact. Technology is bringing us to a point where subtractive methods of construction, where uniform components are created from natural elements and producing tremendous amounts of waste in the process, are becoming outdated. In their place, additive construction processes, where forms are created through the grafting of smaller constituent parts, generating little, entirely reusable, waste material, are showing to be a better fit for the environment.

With technologies and building methods available that combat waste and utilize reusable products, it was shocking for me to learn that upwards of 90% of the waste produced in the construction industry is the result of renovations and demolitions (Gaisset, 11). Why are we constructing everything around us with materials that cannot be reused or adapted to meet new

demands? The idea of modular building components is not new but, in the modern construction arena with demands for “here and now,” it is highly underutilized in the mindset of reusability.

Given the aforementioned statistics of over 90% of construction waste being produced from renovations and demolitions, it is easy to see why such a concept as reusability in construction has begun to gather steam in the wake of the great “Global Warming” threat. Construction materials are becoming more costly to produce, not only from an economic standpoint, but from an ecological one as well. Most common practices involve designing buildings to maintain resiliency, firmly rooted in their surroundings, as markers of the age in which they were created. Little effort is made to think about the end-of-life of the building; where the materials will go when the building ceases to maintain its usefulness. The act of designing a building to be disassembled allows us an opportunity to get around these boundaries and begin to focus on the recyclability of our building materials and the reusability of the components which comprise them.

The concept of “Designing for Disassembly” incorporates the idea of modularity that we’ve been discussing. By creating building elements in a direct and inter-related fashion, a system can be devised where damaged components can be easily replaced with minimal waste usually associated with renovations. Likewise, the demolition process for a modular building would simply be a matter of disconnecting united parts and relocating them, possibly to be used in another building. The idea is to filter out the waste commonly associated with the natural human desire for new surroundings. Making modular building components that are not only easily replaceable but interchangeable creates an opportunity to expand our surroundings without the added costs and waste of traditional building renovations.

It is, however, unreasonable to assume that all building components can be reused indefinitely, and we must ask ourselves “What happens when the component is no longer useful?” One strategy would involve the use of recycled/recyclable materials like plastics and

metals in the construction of these modular building parts. When the component reaches the end of its usable life, it is melted down and separated into its constituent elements to be utilized again. *Eliminating* waste in this lengthy process may prove infeasible, but *reducing* such is not out of the question.

In my search for an answer to this dilemma of waste in construction, I discovered two factions of the architecture craft that, in my eyes, seemed oddly well-suited for one another; namely, masonry construction, and 3D-printing. The concept of masonry construction appealed to me due to its natural allure and timeless strength. I have long since been fascinated by the remnants of ancient monolithic sites, constructed without mortar and modern “by-the-book” procedures, lasting for ages as mankind moves past at an ever alarming rate.

In a very different way, 3D-printing appealed to me for its detraction from the natural, its focus instead being on the endless imaginative capacity of man, this evolution of ordered chaos. It was here where I was introduced to the concept of infinite possibility. To be fair, 3D-printing is still very much in its infancy, and its possibilities are not quite endless, as you will soon read. However, it’s potential for use in the field of architecture is noteworthy, if but done with balance.

In practice, these two construction methods have rarely been utilized in tandem in any efficient manner. In many cases, the two are viewed as wholly separate in their schemas for production. While processes involving uniform masonry construction have met with structural reliability, they often lack the variability and aesthetic appeal of a more randomized look which 3D-printing boasts proudly. Similarly, attempts at large-scale applications of 3D-printing have led to unique forms, but have consistently failed to generate structurally complete or structurally stable forms without added intervention. It is my belief that these construction forms stand to benefit greatly from one another when utilized in tandem, the strengths of each balancing the weaknesses of the other.

This thesis states that 3D-printing and masonry construction are not mutually exclusive methods for the generation of architecture, but can benefit from the strengths and support the weaknesses of the other in the creation of viable and aesthetically appealing architectural forms with the ability to adapt to a changing technological and ecological climate.

3D Printing: Applications in Architecture

3D-Printing works via a methodology known as “additive manufacturing;” the process of building an object from the ground up through addition of parts (the contrary being subtractive manufacturing, such as one might find in stone carving). The benefit of this process is the ability to not only create detailed objects (with accuracy of up to 16 microns), but the versatility to print anything that your imagination can generate. The printers are scalable from a comfortable corner of your desktop to a tower larger than a house, and play host to an ever-increasing number of building materials, ranging from industrial-strength plastics to resin, metals to ceramics. Such versatility is not limited to building materials, but extends to the plethora of industries that are currently benefiting or can benefit from this technology (Volner).



Figure 1 – Radiolaria - The prototype model created in sandstone by the D-Shape 3D-Printer. (d-shape.com)

Presently, the expected potential for 3D-printing in the field of architecture is high, but experiments with the technology on a large scale, tending to show a mindset geared toward 3D-printing as a “beat all, end all” strategy, are proving to be problematic. One such group of experimenters going by the company name *D-Shape*, are working with a stereolithographic process of 3D-printing which fuses sand particles together using a spray adhesive. The system works much like an inkjet printer, the adhesive being sprayed out

on a “sheet” of sand in a designated pattern. The machine then moves up, above the sheet by a miniscule amount, a new layer of sand is laid down, and the adhesive is sprayed again. The result of this additive style of construction produces a sandstone-like material, formed to the designer’s specifications within 10 millimeters of precision (d-shape.com). The prototype design

generated by this machine, christened “Radiolaria,” can be seen in Figure 1. As you can see, the design incorporates a series of flowing curves in a beautiful, eerily natural look that makes one picture the wave-beaten coves of the rocky New England shores.

Despite the elegance of the design and its appeal to natural forms, the construction method itself produces a problem at its core. Considering the construction process creates layer upon layer of stone, the structural stability of the system can be maintained if and only if all of the forces in the body of the building are acting perpendicular to the layer. By generating these curved features in the construction process, the system develops thrust vectors of force that are not perpendicular to the plane of the layer. This produces a sheer force in the body that will show over time as cracking and the separation of layers from one another. From the standpoint of structural reliability, this simple act of physics prevents this technology from reaching its lofty goals.

Other groups with similar goals of scaling 3D-Printing technology to their architectural needs have found solace in the FDM (Fused Deposition Modeling) process, utilizing “filament”-style methods to excrete forms in 3D space, something the D-Shape was as yet incapable of.



Figure 2 - *ProtoHouse* - A model by Softkill Design using FDM processes and algorithms to simulate bone growth. (Fairs)

One London based architecture company called *Softkill Design* is experimenting with the use of extruded material based on the growth patterns of human bones to create structural cantilevers (Fairs). The result is again, a very natural look that solve an interesting problem in architecture; that of the cantilever. But again, we find

ourselves asking questions on the structural integrity of such a structure, particularly considering its precarious design (Figure 2).

Here, we see a natural structural design, that of the human bone. We know from our study of biology that bones differ in size, shape, dimension, and structure depending on the animal, its natural adaptations, and its course of evolution. Taking all of this into account, we see that the transmission of one type of bone to a larger scale, suited for a different purpose, is a very delicate balancing act. While the goal is admirable, the intricacies of developing such a structural system are mind-boggling; the pursuit would take years alone to determine the appropriate structural design, test materials for integrity in design, and ensure structural integrity of the cantilever foundation. This is another example of how simply scaling a project can result in less than advisable structural conditions.



Figure 3 - *Yingchuang New Materials* - A modular wall segment 3D printed from construction waste.

Another attempt at utilizing this FDM style of large-scale construction comes to us from the materials manufacturer *Yingchuang New Materials* in China. Attuned to the problems of waste plaguing the construction industry, this company is

focusing their attentions on cleaning up construction waste and utilizing the materials in the creation of new buildings. Beginning with a process that turns the construction waste into a usable aggregate powder, the team then mixes that powder with cement and water to form a concrete slurry (Figure 3). From here, the slurry is stored in a vat where it is then extruded via a scaled-up FDM printer, into uniform, modular wall segments with a structural stability similar to that of cinder-block construction (Frearson). This process can produce the walls for 10 buildings in a single day. This strength is also its greatest limiting factor.

This system as it currently exists only has the ability to generate vertical, uniform, modular wall segments. Each building generated in this style requires additional intervention from modern construction techniques to create the walls lofted over any windows or doors, as well as the roofs. While this method of construction lacks the appeal of more biologically inspired forms like the ProtoHouse, it is acting to solve the very real problem of utilizing construction waste in a responsible manner, reducing the carbon footprint of the buildings constructed this way in the process.

The people at Yingchuang New Materials have stumbled onto a very interesting facet of



Figure 4 - *Yingchuang New Materials* - Completed house using FDM-printed walls from construction waste.

the 3D-printing revolution with their inability to have it be a “beat-all, end-all” solution, namely, the concept of integration. Few attempts have been made on the whole to integrate 3D-printing into modern architectural construction methods, rather, the focus has instead been on seeing it as its own entity, separate and apart from any other construction

method by its incredible differences in approach. Even here, we see modern construction techniques simply being used as filler as opposed to a true integration (Figure 4). But I believe the true spirit of integration and collaboration allows for a much more fruitful opportunity.

To better understand the ways in which 3D-Printing can be integrated into modern building processes like masonry construction, much like we have seen with 3D-printing, we must first understand how it works on its own.

Masonry Construction Practices

Masonry construction can be separated roughly into three unique streams of thought; namely, isodomic carving, precision sculpting, and dry-stacking. Each method is so named for the amount of tooling that goes into the constituent blocks in the construction of each style, ranging from the use of natural “found” stone, to the intricate carving necessary to generate uniform, orthogonal blocks.

Modern masonry techniques have often appealed to the more labor-intensive method of construction found in the generation of isodomic blocks. These blocks, intricately carved to be



Figure 5 - Incamisana - Remnants of a masonry wall at Ollantaytambo, Peru, illustrating isodomic carving.

as uniform as possible in dimension and shape, are often considered ideal for contractors, due in no small part to their monotonous similarity. By reducing building components to simple, uniform, easy to manage regular pieces, contractors could ensure that their buildings would

maintain straight, perpendicular walls with a structural stability based solely on the pressure potential of the chosen stone or brick. This concept is perhaps best illustrated in Figure 5, a snapshot of the remnants of Incamisana at Ollantaytambo in Peru. Here, we see the painstakingly crafted isodomic stones fitting together to create an isomorphic wall (Protzen).

Precision sculpting is a slight detraction from this method that chooses to focus more on the concept of fitting stones through precise chiseling that fits the pieces together in non-uniform alignments that produce smooth surface features, giving the appearance that the stones were melted into one another in place. This unique form of masonry craft, exhibited frequently in the

work of the Incas in Machu Picchu (Figure 6), has a unique aesthetic quality that has excited



Figure 6 - Machu Picchu - Example of precision sculpting in a masonry construction in Peru.

architecture historians for centuries. The stones, while appearing to fit perfectly with one another through the thickness of the wall, are actually merely cut to produce that effect on the surface. When one looks into the inner structure of the walls, you will find a mash of random

“wedge stones” that maintain the structural integrity of the wall. These stones, much like dry-stacking, utilize found stone on the interior to wedge the larger, sculpted stones into place.

Dry-stacking is perhaps the most aesthetically pleasing of the three primary masonry forms, due to its incorporation of natural “raw” stone in the creation of walls. Here, the skill for creating structure is found in the unique “puzzle-solving” attribute of human consciousness. By utilizing natural stone without the aid of mortar to act as a bonding agent, the artisan delicately places stone after stone via ocular alignment. This form of construction allows a single form to be created, dismantled, and then reconstructed in a variety of different stylings, all based on the whims of the artisan, and the structural reliability of certain stone configurations. With great skill comes great reward, and some of the more unique results of dry-stacking efforts can be seen below in Figure 7.



Figure 7 - Various examples of dry-stacking efforts in the creation of aesthetic walls.

At present moment, such creative designs are relegated to low-level retaining walls and aesthetic, non-structural works of landscape art. Due to their naturally incongruous nature, they lack sufficient structural stability to loft their way into larger level construction projects. This is one of the inherent positions where 3D-printing could see itself shine. By uniting these seemingly incongruous parts into a subtle, more structurally reliable framework, we can begin to expand the concept of integration to a point where viable and aesthetically appealing forms can be generated.

Putting Together the Pieces

Given the variety of forms discussed, we can start to see where these two seemingly exclusive methods of construction can become unified in a new form of building practice. Yingchuang New Materials showed us, however inadvertently, that there is viability in the integration of new and old building practices by utilizing 3D-Printing technologies in concert with traditional wood-frame construction to create a low-carbon impact, recycled building. In addition, the versatility of 3D-Printing shows its ability to respond to numerous modes of thinking in the generation of piece-mail modular systems.



Figure 8 - *Randomized Isomorphic Form* - An example of modern masonry attempts at "randomness" in construction.

Modern practices in masonry construction choose to focus largely on the methods invoked in the creation of isodomic blocks; that of uniform, standardized courses in orthogonal and purely perpendicular loading conditions. Even at their most "randomized," modern efforts in the field of masonry construction

have left much to be desired on the order of creativity (Figure 8). Understanding this methodology affords us the opportunity to utilize this same mode of thinking but expanded to incorporate new technologies. In my experiment to follow, I sought to start with the most basic concept of masonry construction that would be easily followed by contractors of the modern day. By utilizing isodomic blocks as a stand-in for the future integration of irregular stones, my goal was to establish a set of basic standards for the integration of 3D-printed parts into masonry construction efforts that could be applied to asymmetric and isodomic stones alike.

Experiments in Synthesis

In order to better understand the nature of asymmetric stones in dry-stacking efforts, I sought to try my hand at this form of ocular alignment to see where 3D-printed parts might fit best in the construction of such walls. I began by laying a foundation row of stones roughly 2"x6" in area, and started stacking stones up in a semi-coursed structure (Figure 9). Here, I was



Figure 9 - Attempts at small-scale dry-stacking to discover pathways for 3D-printed part integration.

able to quickly see the numerous crevices where 3D-printed parts could make their way into the structure as a means of unifying the pieces for a more stable finished product. Each course met the next with an uneven nature that was very hard to predict, and exceedingly more difficult to establish a stable course upon. I soon realized that the benefit of 3D-printing was in establishing a layer that each course would be able to “graft” itself to, creating a more stable footing for each stone, and a stable foundation for all of the stones above.

Taking this concept into the digital realm, I began to experiment with asymmetric ocular

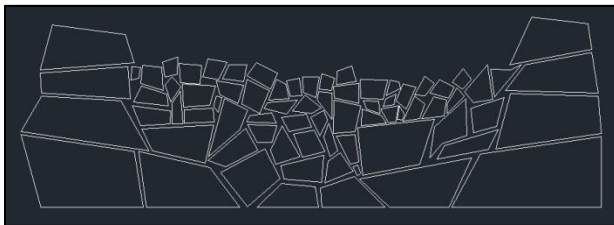


Figure 10 - 2D framework for intuiting lines of 3D-printed part interface.

alignment in a 2D format to better illustrate the effective locations of 3D-printed parts in concert with “found stone” (Figure 10). As

one might come to expect from the collapsing of a 3D concept into a 2D framework, this detraction provided little in terms of spatial understanding behind the methods at work in dry-stacking and how 3D-printing could find a place within it. While an understanding regarding the lines formed between the constituent parts

was attained, this only sought to solidify the understandings from a “precision sculpting” methodology where the sole focus of attention is the outer surface of the wall. Here, a semi-accurate 2D representation of a dry-stacked wall is developed without consideration of the volumetric qualities of each stone. Following this line of logic to an end would be to assume that each individual stone is uniform in the y-direction, into and out of the screen. This would lead us to such results as the “isodomic randomness” featured in some modern attempts at masonry construction.

In order to better understand the ways in which these blocks were interacting, I decided to focus my efforts on the generation of 3D models, utilizing isodomic blocks as space-holders for more asymmetric forms in order to establish a simple set of “best practices” that could govern the generation of both styles. I began with a simple 9-block grid system as a stepping stone for this path of integration.

9-Block Grid Models

My first three attempts at solving the problem of integration utilized this simple grid system composed of nine isodomic blocks (2” cubes), placed in planar, single-curve, and double-curve alignments (Figure 11). In this manner, via manipulation in the digital environment of AutoCAD™, I was able to test a variety of different topics of consideration in these three configurations alone.

“Prospero” (Figure 11a) was my first attempt at a basic, planar grid using a “guided” 3D-printed accompaniment. This printed part provides a “lay-down” framework design to allow construction workers an easy guideline for the laying of masonry blocks. When using

asymmetric stones, each block would be labeled according to a signifier on the printed part itself to confirm accurate placement.

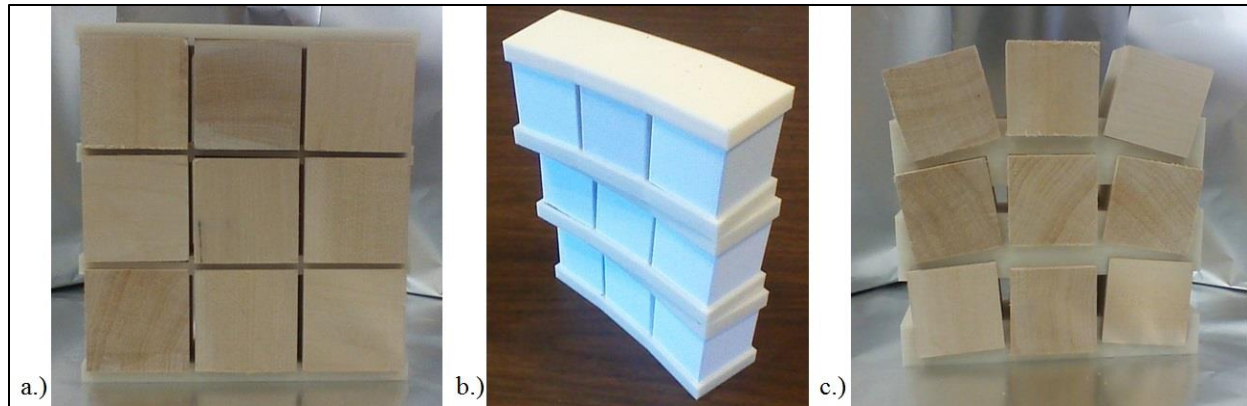


Figure 11 - *9-Block Grid Models* - 3D-printed plastics with ceramic and wood cubes; a.) "Prospero," standard grid test, guided formation; b.) "Alonso," double-curve cantilever test, cupped formation; c.) "Ariel," single-curve test, cradle formation.

This test provided for an interesting series of insights into the nature of this endeavor. The first and foremost comes in the form of security. Considering the sheer heft of the design (0.1276:1 Plastic to Block Volume Ratio), it proved to provide one of the sturdiest forms in my experimental designs, linking each of the tiers together through a simple “tooth and gap” style of unification. The “teeth” of this design were equivalent to 1/16 of the total height of each individual block, which allowed for a fairly easy fitting between the blocks and the 3D Printed Parts (Figure 12a).

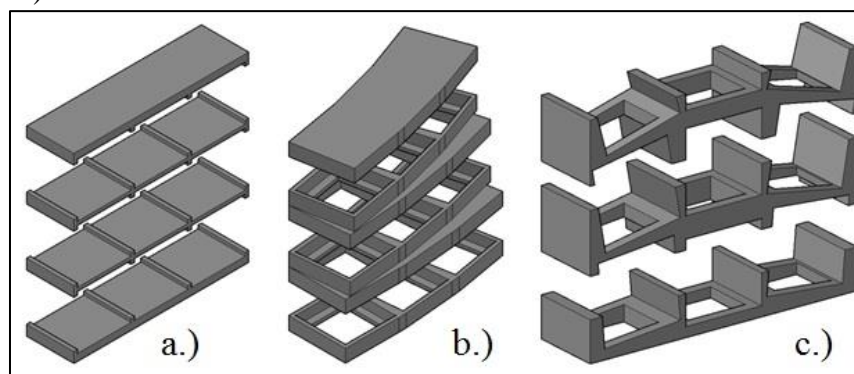


Figure 12 - *3D Printed Parts* - a.) "Prospero," standard grid test, guided formation; b.) "Alonso," double-curve cantilever test, cupped formation; c.) "Ariel," single-curve test, cradle formation.

One of the drawbacks from this hefty construction came as a factor of cost of production. At this early stage in the 3D-printing industry, materials are still quite expensive and often times infeasible in large scale applications, though steps are being made to bring prices down and they are falling by the day. In an effort to mitigate this expense, this heft must be reduced to minimum standards. Extensive research will need to be conducted to determine these safe minimums, but efforts were made in this thesis to find an agreeable minimum standard.

The second of the three grid models, entitled “Alonso” (Figure 11b) explored the possibilities of a double-curve with this integration style. In response to the demands of “Prospero” to limit the amount of printed material, I made sure to hollow unnecessary areas in the prints for “Alonso” as much as possible, though the plastic to block volume ratio still ranked in higher at 0.1740:1. This is likely due to the complexity of the design. As we will see, more complex designs demand more from the printed plastics in terms of their dimension.

Here, I found that in order to achieve the optimal recommended cantilever (not to exceed $\frac{1}{3}$ of the girth of the object), a slightly more invasive form of coupling was required. By encompassing the entire bottom plane and $\frac{3}{16}$ of the overall height of the connecting planes ($\frac{3}{8}$ ”), with corresponding encompassments on the tops of the stones, I was able to produce a “cupping” style of connection that would allow the blocks to cantilever over one another while remaining firmly grounded to those stones beneath (Figure 12b).

The direct drawbacks of this building style, while unnoticeable in the realm of the digital workspace, is most obvious when the pieces are united in the physical realm. When attempting to assemble the blocks into their respective “cups,” the pieces met with a stern resistance. While this particular circumstance is likely due to the nature of ceramic Z-Corp prints (blocks) to

expand while cooling, and for ABS plastic prints (printed shims) to shrink, the problem still posed an interesting insight into how a large-scale production site might experience similar results.

Quite succinctly, the rigidity of the prints and blocks coupled with the static coefficients between the surfaces of the two kept the objects from uniting properly. This caused the blocks to sit awkwardly in their “cups,” generating an overall unstable structure. While the simple thought would be to simply increase the size of the cradle-positions, sadly, this would create gaps in the structure that would lower its overall structural reliability, and throw off the dimensions of the final construction. The concept of cradling presents far greater problems than 3D-printing can effectively and efficiently solve at this time and should therefore be avoided as a construction tactic at present moment.

“Ariel,” the third in our grid series, was an attempt at creating a single-curve in a splayed feature, utilizing a “cradling” formation to hold the blocks (Figure 11c). Like “Alonso,” I made sure to adhere to the wisdom from Prospero, gutting as much of the unnecessary printed material as I felt was possible (Figure 12c). In retrospect, more could have been done to eliminate excess material, as is illustrated in my later models.

The production of “Ariel” revealed several of the same lessons learned from the two previous models. Surface area again proved to be an issue with regard to easy assembly, though to a lesser degree than the “cupping” method exhibited in “Alonso.” While an effort was made to eliminate excess material, it was noted that the overall design was still too bulky (0.1683:1 Plastic to Volume Ratio) to be a fiscally sound option.

The simple lessons learned from these first basic attempts were applied to the four designs to follow in the experiment series. These next two models were designed in the vein of experimentation without limitation, creating intricate forms that sought to find how complexity alters the interaction between the 3D-printed parts and the stone.

Complex Form Models

This next set of designs is inspired by forms that one is not usually accustomed to seeing in masonry construction. The idea is to show the ability of 3D-printed parts to situate stones in a method which is considered highly improbable with modern masonry techniques.

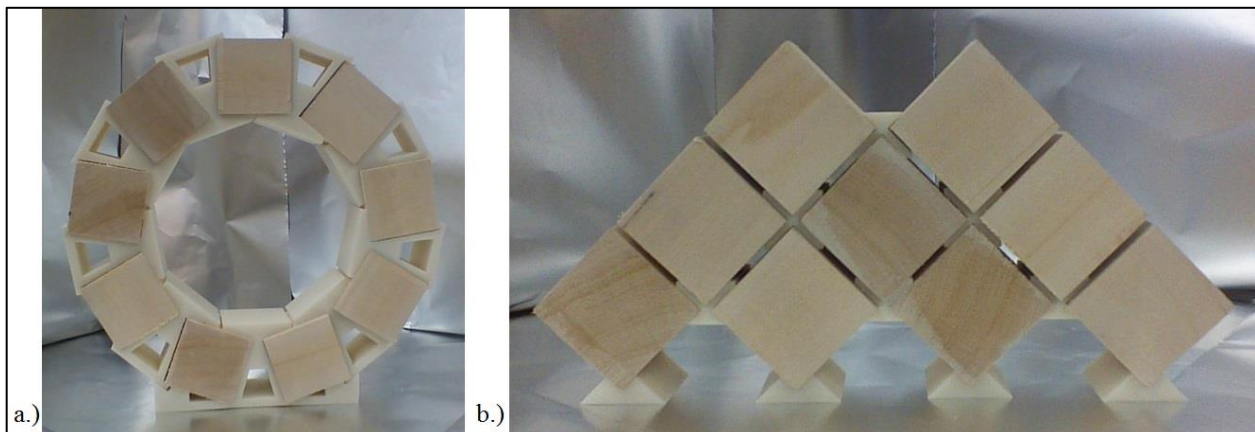
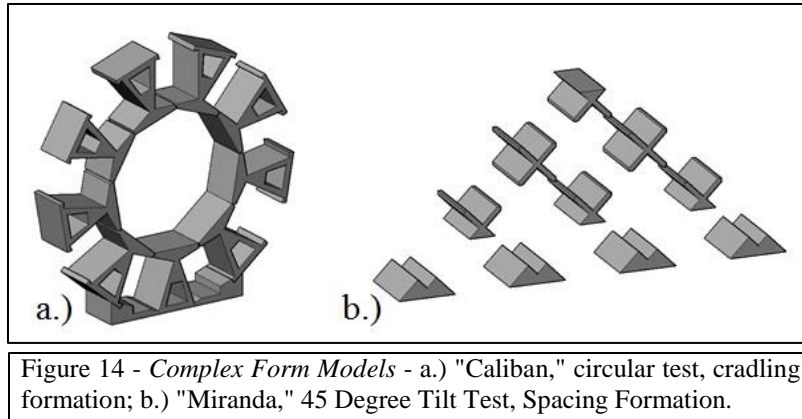
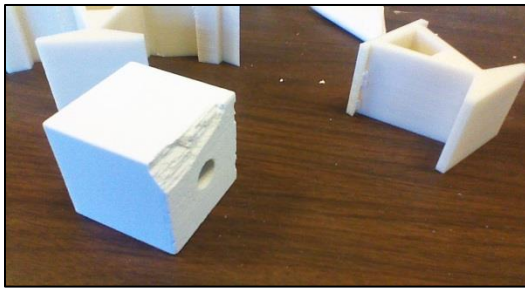


Figure 13 - *Complex Form Models* - Examples of less common masonry forms; a.) "Caliban," circular test, cradling formation; b.) "Miranda," 45 Degree Tilt Test, Spacing Formation.

"Caliban" was an overzealous attempt at something truly groundbreaking, namely, the generation of a circular array of stones (Figure 13a). Most masonry construction employing curves will usually adhere strictly to funicular shapes in pure compression, and hardly ever produces full-circle designs. 3D-Printing allows us to play with the roles of gravity and funicular design in a way that detracts from age-old stereotypes and best practices, and allows us to generate truly groundbreaking forms.



While the design itself proves to be novel, interesting, and evocative to the eye, the application in the real world met with difficulties in the process of assembly. Here, the noted differences between the two mediums of 3D-printed material, namely their traits of either



expanding or shrinking, met poorly in the attempt to generate a curved structure. The blocks did not fit uniformly as was intended, and this experimenter was forced to put off full construction due to the rapid degeneration of the Z-Corp blocks as seen in Figure 15. Later attempts to construct the form using wood

blocks met with success, thanks in no small part to the pliability of light wood.

Overall, the v-shaped members (Figure 14a) produced an overwhelming static friction due to their awkward and prolonged interactions with the blocks along the inner-perimeter of the circle which, all-told, added up to over 50% of the usable surface area of each block being covered by the 3D-printed shim. In addition, the complexity of the design led to a whopping 0.4924:1 plastic to block volume ratio, our highest recording yet, illustrating the clear correlation between complexity and material demand. A possible fix to these problems would be a thinning

of the constituent 3D-printed parts to minimize the surface area of interaction between the blocks and the shims. This could be done by exploding the geometry into a wireframe-style of construction as will be demonstrated further on in this thesis.

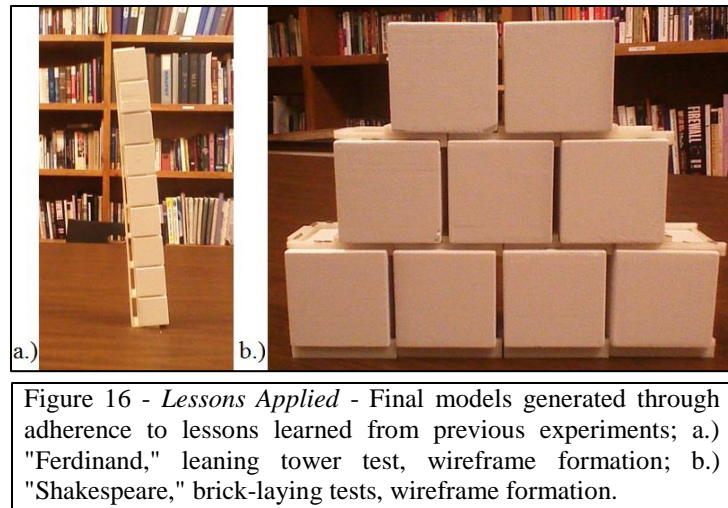
“Miranda” followed a fairly simple process of rotation that became increasingly complex in its integration of printed parts. By rotating the basic grid structure by 45 degrees along the plane of the face, and resituating the blocks to act in supportive rolls, a generation of a form featuring isodomic blocks on their edges was conceived. Here, an attempt at utilizing 3d-printed parts as “spacers” in the structure, to maintain proper spacing between the blocks, and as footings to stabilize the base blocks on their edges, meets with surprisingly attractive results (Figure 13b). The spacers, acting as merely space maintainers and guides for the stones, do not “cup” or “cradle” the blocks here as our other methods have (Figure 14b).

This addition, while doing a phenomenal job at reducing the overall plastic to block volume ratio (0.0842:1, the lowest yet), the structural stability proved to be less than adequate for maintaining the form. Gravity, a feature often left out of the digital modeling environment, played hell with the weights stacked atop one another, forcing the overall structure to splay out toward the edges, caving-in at the center. As a makeshift brace, I was able to incorporate the top and bottom “guide formations” from “Prospero” in an effort to unify the sides of the design, allowing it to maintain its form. Further efforts should be made in future models to ensure unity of the printed foundation formations as well.

Lessons Applied

My final two experiments were generated as an application of the lessons learned in the previous five models, with the first bearing emphasis on maintaining structural stability with

height, and the second focusing on the utilization of these lessons in a basic brick-style coursing design. Above all, these following models sought to reduce unnecessary printed material, minimize the plastic to block volume ratio, experiment with minimum tolerances for printed parts in stable construction, and exhibit the usability of 3D-printing in masonry construction efforts.



"Ferdinand" was a bold endeavor to create a leaning tower, built to the specifications of the great Leaning Tower of Pisa (Figure 16a). The blocks rest at an angle 5.5° to the ground surface, the same as the Tower of Pisa before its most recent renovation, with the 3D-printed assemblage maintaining an angle of 4° , the corrected angle after renovation. The printed form is exploded to its wireframe constituents with each edge being no more than $1/8''$ square (Figure 17a). This low-volume print returned an astonishing 0.0857:1 plastic to block volume ratio, on par with the construction of "Miranda" but far more structurally sound. A few of the members did break during printing and assembly, but the compression exhibited between the stones and the printed parts was able to maintain cohesion.

This construction, while appearing to be in the process of falling, actually maintains its structure remarkably well barring any severe motions of the table, comparable to a high-level

earthquake at scale. While the breaking of the members may prove a breach of the lower thresholds of the plastic's potential, at scale, it is easy to see that members would be significantly larger and less apt to fracture in these same ways.

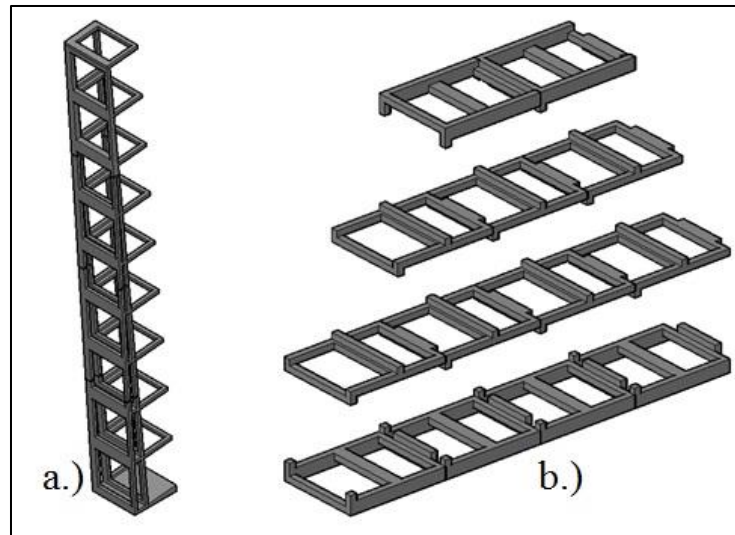


Figure 17 - *Lessons Applied* - a.) "Ferdinand," leaning tower test, wireframe formation; b.) "Shakespeare," brick-laying tests, wireframe formation.

The seventh and final model, dubbed “Shakespeare,” is an attempt at a bare-bones meeting of the minds between 3D-printing and modern masonry construction techniques, utilizing the lessons learned in my experiments with the integration of these two building methods (Figure 16b). Here, an exploded wireframe structure structures the blocks into offset courses often characterized by standard brick buildings. Here, the plastic to block volume ratio, as a testament to concepts of increasing material requirements with increasing complexity, and of limiting the amount of unnecessary plastic printed, rings in at 0.0419:1, cutting its closest competitor in “Miranda” by more than 50%. These simple pieces snap onto their assigned blocks and slide together to create a structurally stable and uniform, isomorphic wall (Figure 17b). All of the pieces fit perfectly snugly in their respective positions, creating the best print yet in terms of reliability and plastic consumption.

Best Practices

The generation of these forms in a physical environment provided the opportunity to grasp the basic concepts behind the integration of 3D-printed parts into masonry construction forms. Bringing together the lessons learned from each of these methods of integration, I have compiled a basic set of “best practices” for the utilizing of 3D-printed shims to work in tandem with various forms of masonry construction. They are as follows:

- 1.) Static friction is perhaps the biggest hurdle when establishing custom-fittings for randomized stone pieces. In order to reduce the effect of this during the construction process, it is advised that the designer seeks to minimize the surface-area interaction between the stone and the 3D-printed part. This will allow smooth fitting of the stones in their correct place and limit the amount of “bowing” experienced by the printed shims.
- 2.) Ensure a level of connectivity between individual blocks that allows them to be united to one another. In order for a structurally stable construction to be properly executed, there needs to be a model for “form-fitting” the blocks so as to ensure that a seal is formed between the stone and the printed shims.
- 3.) Utilize the 3D-printed parts as a method for lofting the blocks in random ways that adds to the randomness of the chosen stones, and as a secondary support mechanism for the wall. This will allow voids to be filled with traditional filler material (smaller stones, cement, or mortar), creating a more traditional-looking style coupled with a revolutionary structural implementation.
- 4.) Avoid pro-longed “printed part to printed part” connections. Due to the nature of 3D-printed materials to expand or contract upon completion of printing, it is important to

limit the interaction between constituent printed parts to eliminate “sum-total effects.”

This will ensure that the variance between the designed form and the constructed form are as minimal as possible.

- 5.) Minimize the usage of material in the printed shims. Considering the present expense associated with 3D-printed objects, often charging by volume of material printed, reducing the amount of material used to its safety minimums will allow the project to be driven by design rather than fiscal accounting.
- 6.) An overall recommendation for the design of 3D-printed shims consists of a “hugging” principle whereby at least 3 “sides” of the block or stone in question is fitted to a single printed piece. Illustrated in Figure 18, this basic concept is illustrated in green, showing the necessary interaction to fix a stone comfortably in alignment. The printed part in white illustrates a similar principle of “snap-together” fitting, where 4 “sides” are united and “snapped” into place. This method produces a stronger cohesion between the printed part and the stone.

As further work is done on the integration of 3D-printing technologies into modern construction efforts, it is exceedingly likely that more standards for collaboration will be imposed to govern the construction processes, as is customary with nearly all forms of modern construction after the appeal grabs hold. These key best practices, however, can act as a simple guidepost for future architects wishing to expand on this topic, allowing them to avoid many of the more serious pitfalls in the medium before they crop up.

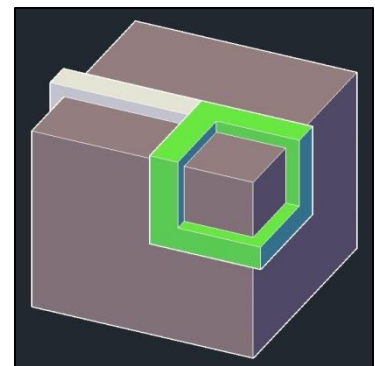


Figure 18 - *"The Hugging Principle"* - An illustration of the "Hugging Principle" in action on an isodmic block.

Future Applications

While the models presented in this thesis focused on isodomic blocks in the generation of these basic principles for the utilization of 3D-printed materials in modern construction, the real of 3D-printing is not limited to such uniformity, nor is this thesis an attempt at stating such. In order to grasp the truest art of found stone modeling, several applications of this mode of thinking would need to be experimented upon before arriving at a final determination on the effectiveness of such practices. Luckily, modern technology is rife with opportunities for exploring this topic in even greater detail.

The development of 3D-scanning technology allows us to work in seeming opposition with 3D-printing, as this technology allows us to take objects from the physical world and place them in a digital environment for manipulation; the exact reverse process behind 3D-printing. However, these technologies can be utilized quite efficiently in tandem. In a study utilizing asymmetric stones, an experimenter could scan numerous “found stones” into a digital environment, tagged with appropriate identifiers, and assemble them in digital space without the need for the painstaking process of ocular alignment in a physical sense. Here, the experimenter could even devise a computer algorithm to arrange the imported stone forms into a specified pattern governed by basic spacing and alignment principles.

Using this practice, the experimenter would have the ability to govern the generalized placement of the stones and establish a set of 3d-printed parts to fill the voids in a structurally viable way that increased the stability of the structure as a whole. The finished product would then bear all of the natural beauty of a dry-stacked construction with the structural stability of an isomorphic form. While this is not the only direction this research could head in the future, it

bears stating that the integration of 3D-scanning technology would prove invaluable in a production of this caliber.

Conclusion

This thesis sought to answer a simple question: “Can masonry construction and 3D-printing technologies be combined to offer a viable form of architecture?” In response, I believe that the potential for such a collaboration of ideas is definitely not far from a reality. I have shown that masonry construction in a modern sense lacks the aesthetic variability that one would come to expect from 21st century constructions. Similarly, we have seen that 3D-printing technologies require more than a simple “scaling-up” procedure to work effectively in the generation of complex architectural forms demanded in the modern construction arena.

Combining these two seemingly diametrically opposed methods of development into a single-stream of unified cooperation provided an interesting glimpse into the facets of both forms which drive the current designs in each. Masonry construction, focused at its heart on a drive for structural surety, sacrificing natural aesthetic appeal in the process, creates forms that stand the test of time. 3D-printing in its architectural adaptations provides for a variability in design unmatched by any other construction form currently in existence, though its ineptitude in the development of structurally stable forms remains a stumbling block for users wishing to see its grand potential.

Bringing these methods together proved to provide an alternative viewpoint for the future of architectural design and construction. Through a careful abiding of the “best practices” established in this thesis, experimenters can begin to delve into the curious questions surrounding asymmetric stone construction and the methods by which 3D-printing might find its place in architecture as a mutual benefactor as opposed to a sole-contributor. We can now see the viability of 3D-printing as a supporting material, foregoing the standardized drive toward a “beat-all, end-all” strategy.

By uniting these two factions of development, I have exhibited an earnest attempt at the generation of viable architectural forms inconsistent with either technology when referenced as mutually exclusive practices. More work is required to bring these ideas into a fully usable form for integration into modern construction, but the foundation for this revolution in architecture has been laid, and my desire to see it through is only beginning.

Bibliography

Gaisset, Ines. *Designing Buildings for Disassembly: Stimulating a Change in the Designer's Role*. Thesis. Massachusetts Institute of Technology, 2011. Cambridge, MA: MIT, 2011. Print.

Dini, Enrico. The Technology of D-Shape. *D-Shape.com*. Monolite UK Ltd. Web. <<http://www.d-shape.com/tecnologia.htm>>

Fairs, Marcus. ProtoHouse by Softkill Design. *Dezeen Magazine*. Web. Dezeen Ltd. (Oct., 2012)

Volner, Ian. The 3-D Printing Revolution. *Architectural Digest*. Condé Nast. (Oct. 2013)

Frearson, Amy. Chinese Company 3D Prints 10 Buildings in a Day Using Construction Waste. *Dezeen Magazine*. Web. Dezeen Ltd. (Apr., 2014)

Protzen, Jean-Pierre, Who Taught the Inca Stonemasons Their Skills? A Comparison of Tiahuanaco and Inca Cut-Stone Masonry. *Journal of the Society of Architectural Historians*. Vol. 56, No. 2 (Jun., 1997), pp.146-167.