Cast Stereotomy: A Material-Based Investigation of Stereotomic Modules

NILOUFAR EMAMI
Louisiana State University

PAUL HOLMQUIST
Louisiana State University

Keywords: stereotomy, 3D printing formwork, concrete, topological interlocking modules.

Stereotomy is a traditional construction technique that allows for building architectural structures from discrete stone elements. Stereotomy in this sense is understood as the shaping of solid structural materials to form unique parts that integrally comprise an assembled whole. With the advancement of computational design methods, material properties, and fabrication techniques, the discipline has been "reborn." In particular, stereotomy can be reinvestigated using materials other than stone such as concrete, or the *liquid stone*. Concrete has many advantages over stone. Fiber-reinforced concrete can perform in both compression and tension, as opposed to stone which only performs in compression. In addition, the weight of concrete modules can be reduced by using optimized mixes, as well as by designing molds that create hollow spaces in the modules. Concrete is less expensive than stone, and the equipment for its fabrication is widely accessible. Other advantages include the lower cost of concrete compared to stone, and the general economy of material use.

In this paper, we present research developed at the LSU School of Architecture investigating the design of stereotomic modules and assemblies made of concrete that comprise a topological, interlocking structural catenary arch wherein variability of form is controlled. Digital tools such as Rhino and Grasshopper were employed to push the boundaries of form generation in the design of the arch, while the Karamba plug-in for Grasshopper was used for structural performance assessment. 3D printing was utilized to make formwork for creating the complex voussoirs. In particular, stereolithography (SLA) 3D printers were employed where elastic resin was used. A small-scale assembly of the arch was 3D-printed, followed by the primary experiments of 3D printing formwork for the modules. This research demonstrates the growing potential of 3D printing for creating stereotomic formwork.

INTRODUCTION

Stereotomy is a discipline that has been "reborn" through computational techniques and has new promise in contemporary architecture, especially with respect to new materials and methods. The knowledge embedded in centuries-old techniques holds unique opportunities in the context of digital design and fabrication. The advanced fabrication methods employed for contemporary stereotomy extend traditional subtractive techniques for carving a complex geometry out of a volume by using multi-axis robotic arms to precisely cut curves controlled by a computationally numeric code.

On the other hand, casting concrete using digitally fabricated formwork is a new method that is being explored by many researchers to create complex load-bearing forms composed of discrete units. Here stereotomy utilizes additive fabrication methods to compose the constituent volumes of a form. If cut patterns have been the core concerns of traditional subtractive-based stereotomic design and its extension to contemporary CNC routing technology, 3D printing, casting, and demolding become the focus of a new additive-based stereotomy, which presents its own set of opportunities and limitations.

In this paper we first overview the ways that digital stereotomy has developed up to now as a primarily subtractive method, and the subsequent development of 3D printing formwork for casting concrete. We then examine the parametric design of a topological interlocking catenary arch to explicate how the two stereotomic methods coincide, as well as the ongoing experimental process of prototyping 3D-printed formwork for casting the catenary arch's modules in concrete. We conclude by discussing the advantages of using 3D-printed formwork to cast concrete stereotomic modules, and particularly how this technique 'frees' stereotomy from dependence on as-given solid materials such as stone or wood and allows for customizing concrete materials for material efficiency, weight and structural performance.

STEREOTOMY, MATERIAL, AND TECHNIQUE

The term 'stereotomy' first appeared in 1644 in *Examen des Oeuvres du S.r Desargues* by Jacques Curabelle (1585-16..), a critical commentary on the universal method of stone cutting that had been proposed by the mathematician Girard Desargues (1591-1661) in 1640.[1] The term was a neologism likely in current use referring to the 'science' of stone cutting, rather than stone cutting as a practical art. It derived from the union of the Greek words for *solid*, 'stereo,' and *cut*, 'tomy,' to designate the sectioning of solid bodies. Curabelle's use of the term stereotomy likely drew upon the symbolic significance of geometry in Christian doctrine to evoke the geometry and measure of the divinely created earth.[2] However, medieval stone cutting had long used geometrical operations whose significance was religious as well as structural, and through which the divine order of the world came to be manifest in architectural form. In the Renaissance, these operations became formalized in the use of the *trait géométrique* as seen in the work of Philibert De L'Orme, wherein the architect was called upon to know not only the rules of composition, but also the methods of construction and practice. The *trait* governed the on-site determination of the exact shape of the voussoirs of vaulted systems within a conception of the architectural whole, circumscribed within the particular circumstances of the building. Desargues's method of stone cutting was meant to simplify and universalize the technique for both the architect and the mason through a system of projective geometry, and to replace the embodied knowledge of the practical workshop tradition.[3] It drew upon the universalization of geometry effected by René Descartes and the predominance of *res cogitans* and its truth value over *res extensa* in his philosophy of science. While Desargues's method itself remained obscure and impracticable, the scientific basis for operating instrumentally on the world that it helped to establish came to underlie the subsequent development of stone cutting and projective geometry through the 18th century, culminating with Gaspard Monge's invention of descriptive geometry and the modern development of computational models and operations.

In contemporary practice, Giuseppe Fallacara and Maurizio Barberio have put forward the term *digital stereotomy*, aiming to show the capabilities of computer modeling and subtractive CNC shaping techniques when applied to stereotomic design and fabrication.[4] They characterize *digital stereotomy* as the "union between stereotomy and three-dimensional computer modeling techniques in relation to topological transformations and deformations."[5] Recently, an event entitled "Stereotomy 2.0 and Digital Construction Tools" was held at the New York Institute of Technology showing state-of-the-art research on digital stereotomy through physical models, prototypes, and posters.[6] According to Patrick Schumacher, stereotomy has been "reborn" as 'Stereotomy 2.0' by expanding its traditional formal and material range and scope of application to "systematically integrate material logics as well as engineering and fabrication rationales into the very constitution of its tools and processes, and thus of its formal repertoire."[7]

Regarding materials, digitally fabricated stereotomic assemblies have generally been realized in both stone and wood. From a structural point of view, stone assemblies are almost exclusively subject to compression, while those in wood are subject primarily to bending and tensile stresses. There are also stereotomic wall and vaulted systems that are reinforced with metal or wood elements.[8] Although these systems have been criticized by purists who hold that geometrical calculation alone should solve both the aesthetics and static demands with a single, solid material, it was later considered virtuous as it was based on the scientific awareness of the characteristics and behavior of building materials.[9] As an example, Rippmann and Block have focused on approaches that link form-finding and material-driven fabrication in researching the design of an unreinforced, stone-cut vault for the Martin Luther King (MLK) park in Austin, Texas.[10]

Technique is another important piece in this puzzle. The knowledge embedded in centuries-old techniques still hold unique opportunities in the context of digital design and fabrication. Some techniques have been completely replaced by new ones, while others are being practiced in parallel with a digitized version of them, and some new techniques have emerged whichdid not previously exist. Ancient stone cutting techniques have been replaced by robotic multi-axis cutting techniques;[11,12] three-axis and five-axis digital fabrication techniques are widely used for wood cutting; and 3D printing has emerged as a completely new technique.

3D PRINTING FORMWORK, MATERIAL, AND TECHNIQUE

Because stereotomy is widely and historically associated with subtractive processes, we propose the term 'Additive Digital Stereotomy' (ADS), following upon Fallacara, to emphasize the difference between the two approaches. In ADS, as in subtractive processes, the stereotomic module is first conceived or calculated as a virtual geometrical entity whose physical volume is then delimited by 3D-printed formwork, and into which liquid material is poured and solidifies. Both the fabrication of the formwork and the physical volume itself are thus additive processes. Although no 'solid' is 'cut', properly speaking, we argue that ADS is in fact stereotomy because it conceives of a solid whole composed of discrete, structurally interdependent units that must be fabricated separately. We also argue that ADS is a more effective method of stereotomic fabrication, and that additive fabrication processes open the door to exploring a wider range of materials and structural and aesthetic performance.

Additive manufacturing (AM), also known as 3D printing has been hailed as a potentially transformative technology that could usher in a "third industrial revolution."[13] This technology is capable of joining various materials and creating objects from 3D data, usually layer upon layer, in contrast to traditional subtractive manufacturing technologies.[14] AM already offers many distinct advantages over traditional manufacturing techniques such as 'design freedom' for designers, engineers, and consumers, with the capability to produce complex geometries not feasible using other processes. Other advantages include reduced waste and the possibility of using recyclable materials.[15]

On the other hand, concrete is a conventional material commonly used in load-bearing applications. It is one of the cheapest materials with high load-bearing capacity in the building industry and "the single most widely used material in the world."[16] However, complexities associated with casting liquid concrete, especially the creation of forms for casting, not only add to material and labor costs but have also restricted the geometric freedom of built cases.

Architects and engineers have sought to address these limitations of concrete by using 3D-printed formwork. Brian Peters experimented with 3D-printed flexible filaments to design one- and two-part molds in 2014.[17] The advantages of this method are that molds can be used up to five times for concrete castings and afterwards can be reclaimed as 3D printing feedstock. The size of the 3D printer and print bed in Peters's studies, however, limited the ability to scale up the printing process. In 2016, Jipa et al. published their work on 3D-printed stay-in-place formwork for a concrete slab focusing on the topological optimization of the complex geometry,[18] while a year later, Aghaei-Meibodi and Jipa et al. published details of a 3D printed sandstone stay-in-place formwork.[19] This method combines the formal geometric flexibility (such as recesses, undercuts, internal voids, and tubular structures) of 3D-printed sandstone and the structural capacity of concrete. It produces the sandstone formwork using binder jetting, a process in which a liquid bonding agent is selectively dropped onto thin layers of powdered material to bind it. This method can be used to prefabricate large-scale building components since it uses industrial-grade binder jetting. In casting the concrete, it allows for high-resolution details and complex geometry, reduces material use, and facilitates the integration of technical infrastructure. In the same year, Jipa et al. used regular PLA filaments to 3D-print formwork for a concrete canoe named skelETHon, and then used heat guns to melt the formwork to release the parts.[20,21] Meibodi et al. recently expanded upon their method of stay-in-place sandstone formwork to combine it with CNC laser-cut timber formwork to fabricate a 20 mm slab using prestressed concrete.[22] Others have studied an FDM 3D-printed mold that was segmented into parts for easy disassembly.[23] More recently, Leschok and Dillenburger, as well as Doyle and Hunter experimented with dissolvable 3D-printed formwork for creating complex concrete forms.[24,25] The literature is summarized in Table 1.

As evident in the amount and variety of recent research, 3D-printed formwork is a leading method for controlling the surface quality of concrete while creating complex geometric forms. However, these methods utilize one mold per part, and the mold is either melted,[26] stays in place,[27,28,29] or is dissolved[30,31] to allow the part to be released. If the process were to be scaled up, printing one mold per part would not be cost effective. We believe that the potential of flexible 3D-printed formwork has not been fully explored, and with the recent availability of large-scale printers and bed sizes, that it holds promise for producing complex standardized molds for casting stereotomic modules in concrete.

TEST CASE: PARAMETRIC DESIGN OF A TOPOLOGICAL INTERLOCKING CATENARY ARCH

Topological interlocking assemblies are made using solid elements. Their overall structural integrity relies on each element being kinematically constrained by its neighbors. This system establishes equilibrium through compression forces where the weight of each block is used against itself to maintain it in the span. Given fixed boundary conditions, the assemblies are able to resist forces without any additional binding material such as mortar. In fact, adjacency replaces mortar.[32,33,34] Researchers have hypothesized that the mechanical response of topological interlocking assemblies is controlled by the geometry of the interlocking elements and their surfaces, as well as local surface patterns.[35] In addition, the global geometry

Table 1. Summary of literature on 3D printing formwork for casting concrete.

Researcher	Material and method	Advantages	Limitations/ potential improvements
(Peters 2014)	Flexible 3D-printed formwork.	Can be used up to five times & then reclaimed as 3D printing stock.	3D printer and bed size are small.
(Jipa et al. 2016) (Aghaei-Meibodi et al. 2017)	Stay-in-place 3D-printed sandstone formwork.	Large building elements with detail and geometrical flexibility can be realized.	Promising, but needs better material properties to become a solution for architectural components.
(Jipa, Dillenburger, and Bernhard 2017); (Jipa et al. 2019)	skelETHon: PLA 3D-printed formwork.	Complex geometry and precise detail can be realized.	Heat guns are used to release the part which is an expensive procedure.
(Aghaei-Meibodi et al. 2018)	Smart Slab: Stay-in-place 3D-printed sandstone formwork combined with timber formwork.	Uses prestressed concrete.	New materials for printed formwork such as dissolvable binder systems can be used.
(Naboni and Breseghello 2018)	FDM 3D printed formwork	Assembling and disassembling the mold's components	Using threads as a joinery type is time consuming.
(Leschok and Dillenburger 2019);	Dissolvable 3D-printed formwork	Complex and non-standard geometries can be created, which is also environment friendly.	Mold is a one-off product.

of the assembly can also be controlled to minimize deflections and increase the efficiency of the system. Osteomorphic blocks are one of the geometric form types used for interlocking modules.[36] Inclining faces to lock the movement of neighboring units is an effective design approach for interlocking units. In osteomorphic blocks, transforming the contact face of two modules into non-planar surfaces is employed to create a curved face that blocks the movement of the blocks in both up and down directions. The blocks are then shifted in each row to achieve interlocking.

We have parametrically modeled a catenary arch after an osteomorphic catenary arch by Fallacara[37] using Rhino and Grasshopper along with the Kangaroo form-finding plug-in. The catenary arch allows uniform load distribution and after it is form-found, the osteomorphic blocks (similar to wave-shaped blocks) were projected onto the arch. All of the blocks underwent a topological deformation, meaning that there were dimensional and angular variations among them. The reason an arch was selected is twofold: first, the single curvature of an arch seemed appropriate for the initial investigations before more complex double curvature forms could be investigated; second, the individual blocks are identical in each row of the arch while half of the arch is a mirrored replica of its first half. This means that when a formwork is 3D-printed, it can be used at least four times for casting in the process of fabricating the vault.

For parametric modeling, a square unit was modeled and mid-points of each edge were then found to construct lines. After the lines were offset, a curve was blended between them to create the lower cross section of the block. By flipping the direction of the blend, the upper cross section of the block was designed. The two cross sections were then lofted, and the blocks were populated in the x and y directions. Finally, they were projected onto the catenary arch. The blocks at the base were cut with a plane to create flat edges (Figure 2).

The parameters that affected the geometry of the interlocking modules varied the contact surfaces of the blocks by changing the offset distance between the two lines (explained in the previous step) and the blend factor between the two offset curves. In addition, the width and length of the blocks in x and y direction were able to be changed. These parameters are illustrated in Figure 3. The constant and variable parameters are summarized in Table 2.

It should be noted that the dimensions of the catenary were constant, and a definite shape was form-found. The catenary arch was structurally simulated in the next session and different thicknesses were tested to understand how they affected the performance of the arch.

STRUCTURAL SIMULATION OF THE TOPOLOGICAL INTERLOCKING CATENARY ARCH

The catenary arch was designed to span 240 cm (7.8’) with a rise of 260 cm (8.5’) where the width of the arch is 120 cm (3.9’). After the parametric model was constructed, a series of structural simulations were conducted using the Karamba plugin for Grasshopper. The goal of the simulations was to understand how changing the thickness would affect structural performance, namely maximum displacement and von Mises stress. The thickness of modules was varied from 5 cm (2”) to 10 cm (4”) and then to 15 cm (6”). The arch was subject to self-weight only, and an isotropic concrete material was applied to it. The material properties are summarized in Table 3. The simulation results are presented in Figure 4 and summarized in Table 4.

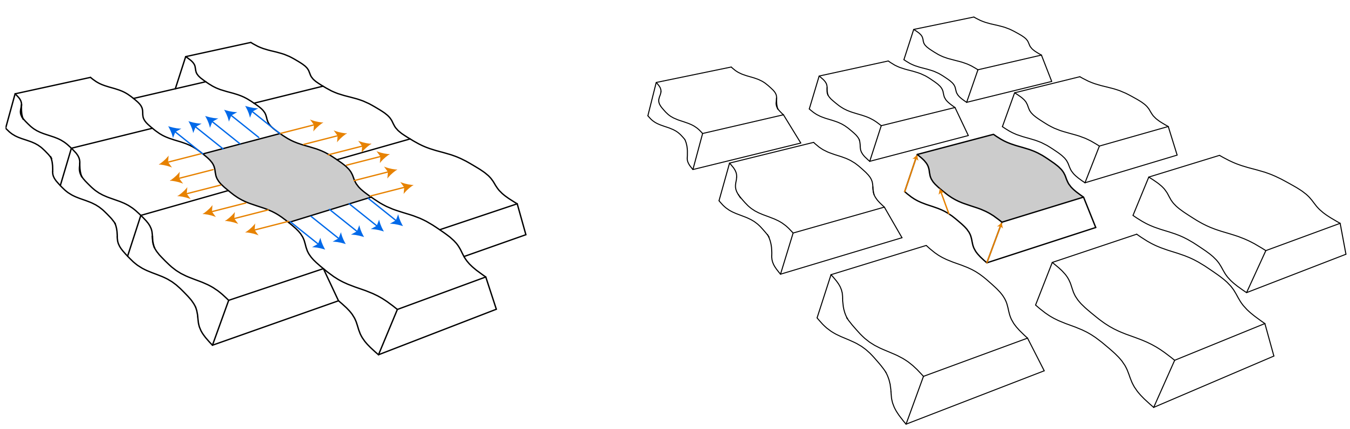


Figure 1. Interlocking mechanism in x, y and z direction in osteomorphic blocks: shifting each row (left); curved contact faces (right). By authors.

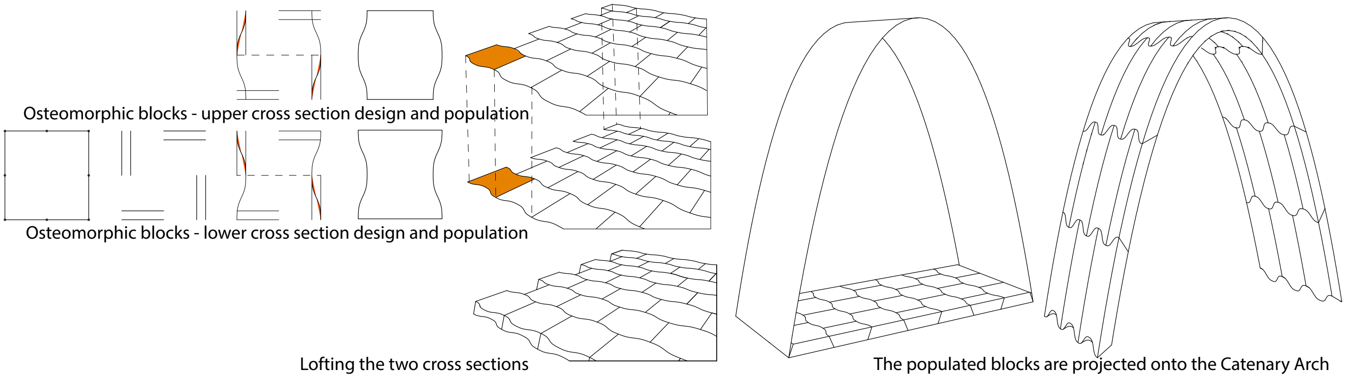


Figure 2. Parametric modeling process of the cast osteomorphic catenary arch. By authors.

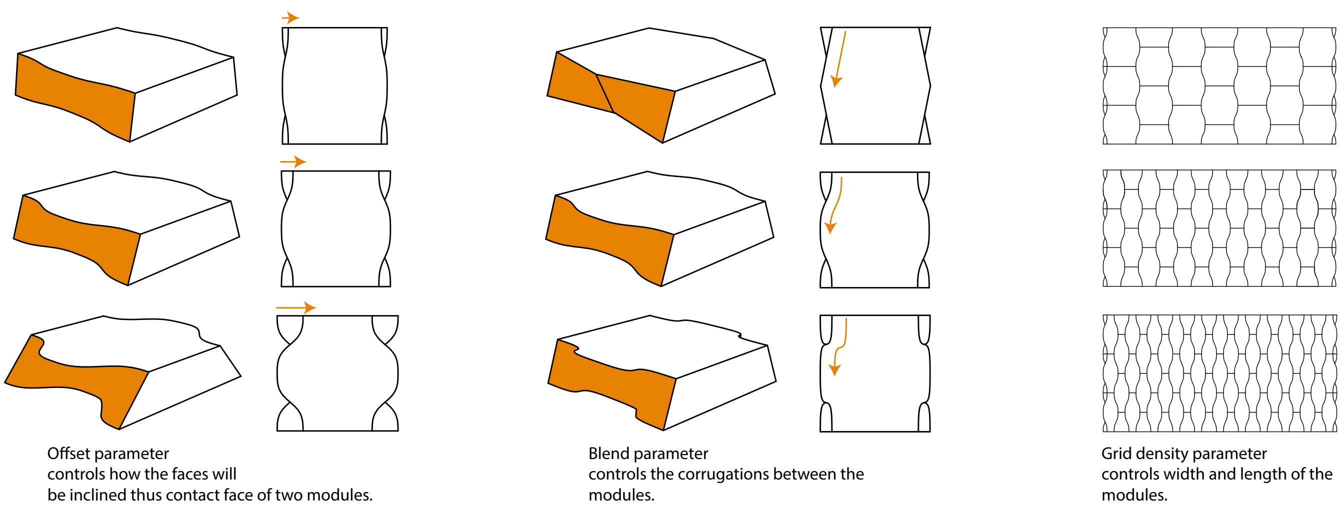


Figure 3. Parameters that can be varied. By authors.

Table 2. Variable and constant parameters in the parametric model.

Parameter	Value/ Range	Constant/ Variable
Catenary span by width	240 cm by 120 cm	Constant
Catenary rise	260 cm	Constant
Interlocking module thickness	10 cm	Constant
Interlocking module offset	4 to 18 cm; 1 cm intervals	Variable
Interlocking module blend factor	0 to 1; 0.1 intervals	Variable
X-direction replication	7-19, intervals of 2 (always an odd number to maintain a key stone)	Variable

An important takeaway of the structural analysis was observing how increasing the thickness decreases deflection. However, it should be noted that the analysis here was done under dead load only. Were a live load added to the applied loads, the weight of the modules would become problematic and induce more deformation. The analysis suggests that reducing the weight of the modules while having a higher thickness (thus higher stiffness due to the higher moment of inertia) will improve the performance. This initial simulation further confirms the need for customizing the module's geometry for reducing weight and for customizing the concrete material for higher structural efficiency. This is in line with the ability in 3D printing formwork to allow for hollow space in the modules, which, along with the use of low-density concrete mixes, would reduce the weight of the modules. These are the future steps of this research study.

On a separate note and for future analysis, Discrete Element Method (DEM) analysis should be conducted to account for the

Table 3. Material properties used for structural simulation.

Load [KPa]	E (Elastic Modulus) [MPa]	G (Shear Modulus) [MPa]	Fy (yield strength) [MPa]	Density [Kg/m^3]	Specific Weight [KN/m^3]
Gravity	26,000	10,800	30	2400	23.5

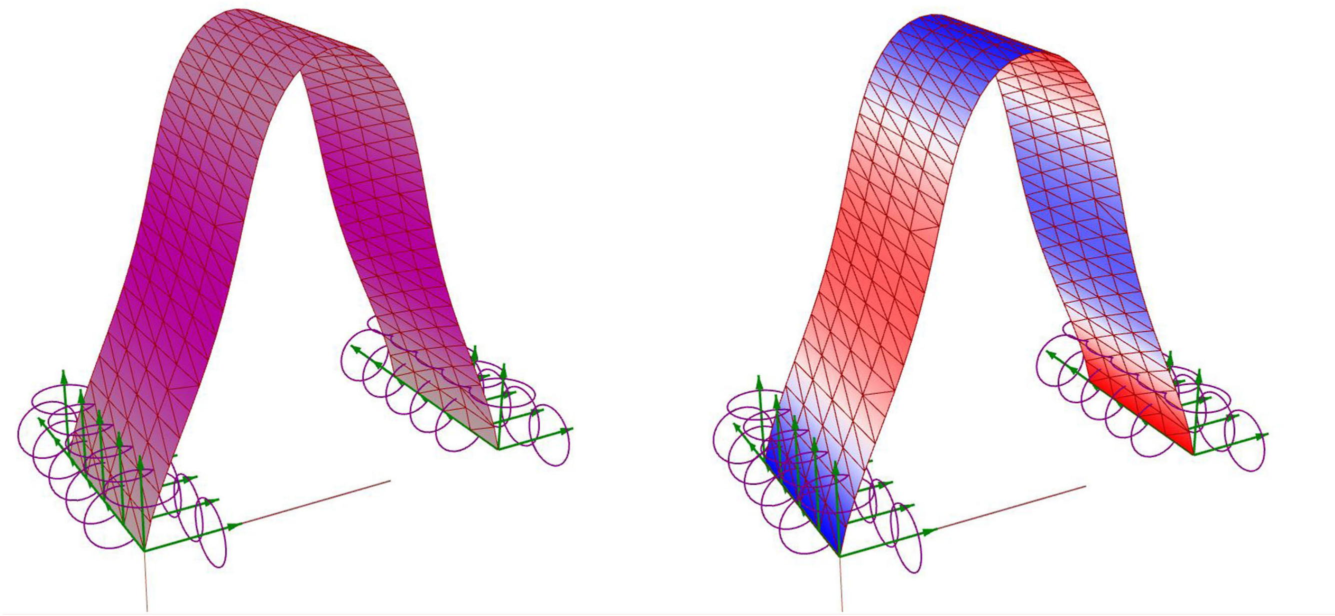


Figure 4. Structural analysis of the arch. By authors.

Table 4. Deflection and stress levels in the catenary arch with different thicknesses.

Thickness	Mass [kg]	Deflection under D.L. [cm]	FMaximum Von Mises [MPa]
5 cm (2")	8.43	56.73	11.2
10 cm (4")	16.87	14	5.66
15 cm (6")	25.31	6.3	3.8

friction between modules and the ways they might slip due to the applied loads. The offset variations affecting the surface area on the module's sides can be studied for comparing the effect of design parameters. These variations can later be combined with a changing blend parameter to better understand the complex interrelationships.

FABRICATION PROTOTYPING

To test the assembly of the modules, they were 3D printed using clear resin and then assembled using a false formwork to keep the units in place. The arch was created at a scale of 1:10 with a span of 24 cm and a rise of 26 cm (Figure 5- left). During assembly, it was noted that greater adhesion could be achieved in future iterations by making deeper undulations in order to increase contact surface area between the modules. In addition, small gaps were noticed between modules. This was traced back to the slight difference between the catenary arch output from Kangaroo that was used for routing the false formwork and the actual catenary on which the modules were populated. In future iterations, the small variations in Kangaroo's form finding should be considered and a catenary arch should be fixed for the rest of the script. On a separate note, for future prototyping, having a groove across the arch similar to the one seen in the built vault by Fallacara[38] will be considered. This would help to align the units.

After testing the assembly of the interlocking modules, a series of experiments with 3D printed 'elastic resin' was conducted. The key takeaways from the experiments are summarized below:

-There is a tolerance of 0.8 mm for 3D printing embossed sections in the formwork if any keys are to be utilized. This means that the engraved keys need to be 0.8 mm larger than the diameter of the embossed keys. It should be noted that scaling up will present much greater tolerance issues when building full-scale structures and this issue needs to be resolved.

-The supports generated by Formlab 3D printers require careful consideration as they might not be able to support the weight of the 3D-printed piece. Many experiments failed due to this problem. The diameter and number of touchpoints should be increased, while the thickness, and thus the total weight of the printed formwork, should be optimized. When the thickness of the 3D print was less than 2 mm, the surface cracked. Therefore, there is a limit on how thin it can be.

-The elastic resin might be slightly distorted due to its material properties. The cast plaster model reflects the distortion and if it is beyond the tolerance, the distortion will affect the assembly of modules. Therefore, optimizing the shape and thickness of the formwork is crucial.

3D printing formwork was an efficient construction method for the catenary arch design that was studied. In particular, 3D printing formwork for constructing a stereotomic vault proved to be a viable technique. According to the designed catenary arch, the modules repeat in each row, and half of the vault is a mirrored replica of its first half. Therefore, only six formworks needed to be 3D printed for the scaled catenary arch design (Table 5).

CONCLUSION

While the term *digital stereotomy* aims to characterize the capabilities of computer modeling and subtractive CNC techniques, we are proposing 'Additive Digital Stereotomy' (ADS) to describe the way that formwork can be 3D printed for casting topological interlocking modules. We argue that in calculating and fabricating discrete, structurally interdependent units, ADS is an innovative and true form of stereotomy. ADS is furthermore a potentially more effective method of stereotomic fabrication since it allows for optimizing the weight of modules by geometric design, using low density concrete for casting, as well as reusing formwork for multiple castings.

Creating flexible 3D printed formwork using the Fused Filament Fabrication (FFF) as well as Stereolithography (SLA) methods allows designers to incorporate the fabrication parameters of 3D printing into the design of concrete building components and narrow the gap between design and construction. The

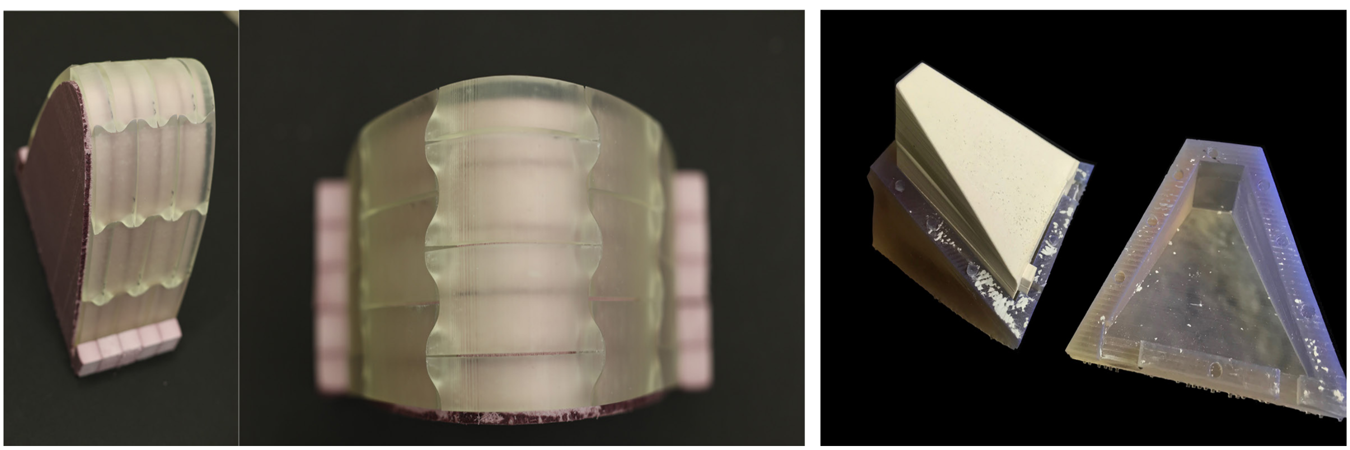


Figure 5. Scaled model of the units and the arch (left and center); 3D printed formwork prototypes (right). By authors.

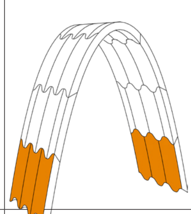
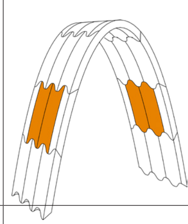
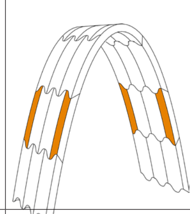
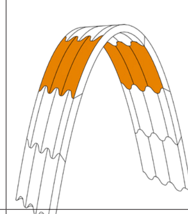
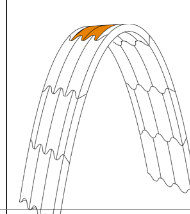
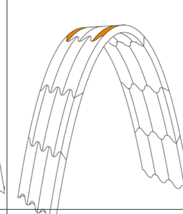
Formwork type	A	B	C	D	E	F
						
Number of uses	6	4	4	6	2	2

Table 5. Deflection and stress levels in the catenary arch with different thicknesses.

unique advantages of 3D printing allow for making formwork that enables the fabrication of structural building components with complex geometries, while concrete, a material which is already widely used in the building industry, can be cast and employed more efficiently to realize more creative forms. The geometry of the formwork can be precisely controlled, while the flexibility of the formwork allows for easy release of concrete and potential reuse. Depending on the scale of the 3D printer, an array of formwork sizes can be designed and fabricated. This can ultimately decrease cost and increase efficiency in the building industry while allowing the construction of more complex geometries.

This is an ongoing project where the opportunities and limitations of 3D printing formwork for casting interlocking stereotomic modules are being investigated. After the effect of geometric variations on the structural performance of the assembly is further understood, fabrication limitations will then be applied, tested and analyzed. In addition, the potential for reducing weight by creating openings in the modules will be explored while monitoring their structural performance, which we believe will maximize the benefit of 3D fabrication techniques for cast stereotomy.

ENDNOTES

1. Giuseppe Fallacara and Maurizio Barberio, "An Unfinished Manifesto for Stereotomy 2.0," *Nexus Network Journal* 20, no. 3 (2018): 519–43.
2. Fallacara and Barberio, 519–43.
3. Alberto Pérez-Gómez, *Architecture and the Crisis of Modern Science* (Cambridge, MA: MIT Press, 1983), 229, 232.
4. Giuseppe Fallacara, "Digital Stereotomy and Topological Transformations: Reasoning about Shape Building," in *Proceedings of the Second International Congress on Construction History*, Queen's College, Cambridge University 29th March - 2nd April 2006, vol. 1, 2006, 37.
5. Giuseppe Fallacara, "Toward a Stereotomic Design: Experimental Constructions and Didactic Experiences," in *Proceedings of the Third International Congress on Construction History*, 2009, 553–60.
6. Micaela Colella, "Stereotomy 2.0 and Digital Construction Tools," *Nexus Network Journal* 20, no. 3 (2018): 769–88.
7. Patrik Schumacher, "Stereotomy 2.0: High-Performance Eloquence," *Nexus Network Journal* 20, no. 3 (2018): 515–17.
8. Fallacara and Barberio, "Unfinished Manifesto."
9. Giuseppe Fallacara and Maurizio Barberio, "Stereotomy 2.0: The Rebirth of a Discipline That Never Died," *Nexus Network Journal* 20, no. 3 (2018): 509–14.
10. Matthias Rippmann and Philippe Block, "Rethinking Structural Masonry: Unreinforced, Stone-Cut Shells," *Proceedings of the Institution of Civil Engineers: Construction Materials* 166, no. 6 (2012): 378–89.
11. Brandon Clifford, Wes McGee, and Mackenzie Muhonen, "Recovering Cannibalism in Architecture with a Return to Cyclopean Masonry," *Nexus Network Journal* 20, no. 3 (2018): 583–604.
12. Philippe Block, *Beyond Bending: Reimaging Compression Shells* (Munich: Detail, 2017).
13. "A Third Industrial Revolution," *Economist*, April 21, 2012.
14. Ruth Jiang, Robin Kleer, and Frank T. Piller, "Predicting the Future of Additive Manufacturing: A Delphi Study on Economic and Societal Implications of 3D Printing for 2030," *Technological Forecasting and Social Change* 117 (2017): 84–97.
15. Olga S. Ivanova, Christopher B. Williams, and Thomas A. Campbell, "Additive Manufacturing (AM) and Nanotechnology: Promises and Challenges," 2011, 733–49.
16. James Mitchell Crow, "The Concrete Conundrum," *Chemistry World*, no. March (2008): 62–66.
17. Brian Peters, "Additive Formwork 3D Printed Flexible Formwork," in *Acadia 2014: Design Agency*, 2014, 517–22.
18. Andrei Jipa et al., "3D-Printed Stay-in-Place Formwork for Topologically Optimized Concrete Slabs," in *TxA Emerging Design + Technology*, 2016, 97–107.
19. Mania Aghaei-Meibodi et al., "The Smart Takes from the Strong," *Fabricate*, 2017, 210–17.
20. Andrei Jipa, Benjamin Dillenburger, and Mathias Bernhard, "SkelETHon Formwork 3D Printed Plastic Formwork for Load-Bearing Concrete Structures," in *SIGraDi Congreso Internacional de La Sociedad Iberoamericana de Gráfica Digital*, vol. 3 (Concepción, Chile, 2017), 345–52.
21. Andrei Jipa et al., "Formwork Fabrication Freedom for a Concrete Canoe," *Design Management and Technology* 14, no. 1 (2019): 25–44.
22. Mania Aghaei-Meibodi et al., "Smart Slab," *ACADIA 2018: Re/Calibration: On Imprecision and Infidelity*, 2018, 328–35.
23. Naboni and Breseghello, "Fused Deposition Modelling Formworks for Complex Concrete Constructions."
24. Matthias Leschok and Benjamin Dillenburger, "Sustainable Thin-Shell 3D Printed Formwork for Concrete," in *Impact: Design With All Senses. Proceedings of the Design Modelling Symposium*, ed. Christoph Gengnagel et al. (Berlin: Springer International, 2019), 487–501.
25. Shelby Elizabeth Doyle and Erin Linsey Hunt, "Melting: Augmenting Concrete Columns with Water Soluble 3D Printed Formwork," in *ACADIA: Ubiquity and Autonomy*, vol. 6, 2019, 92–97.
26. Jipa, Dillenburger, and Bernhard, "SkelETHon Formwork."
27. Jipa et al., "3D-Printed."
28. Aghaei-Meibodi et al., "Smart Takes."
29. Aghaei-Meibodi et al., "Smart Slab."
30. Leschok and Dillenburger, "Sustainable Thin-Shell."
31. Doyle and Hunt, "Melting."
32. Oliver Tessmann, "Topological Interlocking Assemblies," in *Physical Digitality—Proceedings of the 30th International Conference on Education and Research in Computer Aided Architectural Design in Europe* (Prague, Czech Republic, 2012).
33. Oliver Tessmann and Mirco Becker, "Extremely Heavy and Incredibly Light: Performative Assemblies in Dynamic Environments," in *Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA): Open Systems*, 2013, 469–78.
34. Oliver Tessmann, "Interlocking Manifold: Kinematically Constrained Multi-Material Systems," in *Advances in Architectural Geometry*, ed. Lars Hesselgren et al., 2013, 269–78, https://doi.org/10.1007/978-3-7091-0309-8.
35. Lee Djumas et al., "Deformation Mechanics of Non-Planar Topologically Interlocked Assemblies with Structural Hierarchy and Varying Geometry," *Scientific Reports* 7, no. 1 (2017): 1–11, https://doi.org/10.1038/s41598-017-12147-3.
36. Y. Estrin, A. V. Dyskin, and E. Pasternak, "Topological Interlocking as a *Material Design Concept*," Materials Science and Engineering C 31, no. 6 (2011): 1189–94.
37. Fallacara and Barberio, "Unfinished Manifesto."
38. Fallacara and Barberio.