Nexus Netw J (2018) 20:645–669
https://doi.org/10.1007/s00004-018-0376-x

NEXUS NETWORK JOURNAL
Architecture and Mathematics

RESEARCH

Lightweight Stereotomy with Glass-Fiber Reinforced Plastic

Justin Diles[1]

Abstract Stereotomy is historically synonymous with stone construction and solid architectural poché. Yet stereotomy need not be limited to dense materials and compression-only structural forms. With the aim of developing stereotomic architecture that employs parts that are exceptionally expressive—rather than exceptionally heavy—this paper explores constructions made from glass-fiber reinforced plastic, a contemporary lightweight material. The research also recognizes that the volumetric parts and networks of joints employed for stereotomy have important visual as well as physical consequences. By focusing on creative applications of descriptive geometry, the projects presented in this paper seek to make explicit stereotomy's unique combination of graphic and constructional qualities. Using a novel system of tessellations derived from digital simulations, the research puts computational techniques in service of stereotomy's formal questions, developing visually animated assemblies of parts. The architectural qualities of these assemblies as well as the constructional feasibility of lightweight stereotomic parts were tested through a series of designs that culminated in large architectural constructions, including a free-standing wall, a pavilion prototype and a free-standing interior pavilion employing lightweight, free-form Cyclopean masonry.

Keywords Stereotomy · Fiber composites · Plastic construction · Cyclopean masonry · Lightweight · Robotic fabrication

---

✉ Justin Diles
diles.8@osu.edu

[1] Knowlton Hall, 275 West Woodruff Avenue, Columbus, OH 43210, USA

Birkhäuser

Introduction

The stereotomic research outlined in this paper grew out of a desire to build architectural constructions from complexly curved, volumetric parts that fit together to form sophisticated patterns. During the 2012–2013 academic year, the author of this paper held the Howard E. LeFevre '29 Emerging Practitioner Fellowship at The Ohio State University. The original focus of the fellowship research was twofold. The first aim was to study the sinusoidal deformation patterns produced by Euler buckling using digital tools. The second was to design and construct free-standing walls that would focus attention on the exceptionally curvilinear forms of buckled surfaces. During the research, a new method for producing tessellations was discovered by overlaying surfaces displaced by buckling. As these tessellations were developed into self-supporting architectural assemblies, a stereotomic construction system was born. In hindsight, pursuing stereotomy would have profound implications for the trajectory of subsequent research. Since the tessellations did not resemble the joint patterns of historic masonry and since the doubly-curved parts would be difficult to cast, a second important choice was made. Lightweight, hollow parts molded from glass-fiber reinforced plastic (GFRP) would be used instead of parts made from stone, brick, concrete or laminated wood—materials that have been historically (and recently) associated with stereotomic assembly. These choices yielded the stereotomic research and constructions that are the central topics of this paper.

Stereotomy and GFRP Construction

In his late nineteenth century textbook on the subject, S. Edward Warren defines stereotomy as "the application of *Descriptive Geometry* which, comprehensively defined, tends to the cutting or shaping of forms, whether material or immaterial, so as to suit certain conditions" (Warren 1875). This definition of stereotomy is remarkable for its emphasis on geometry over issues of stability and material specificity. Various types of stone would have been the only materials available for permanent stereotomic construction in the 19th century, yet Warren downplays the importance of compressive materiality and structural behavior, focusing instead on geometric knowhow and the deployment of techniques to shape forms, both material and immaterial.

Over 140 years later, Warren's definition of stereotomy is prescient and relevant. Tools that allow descriptive geometry to be applied to both immaterial—i.e., "virtual"—forms through 3D modeling and material forms through digital fabrication are now widely available. Not merely an extension of the geometric techniques of the past, contemporary digital tools have ushered in a new paradigm in which everything digital is variable and tunable to specific architectural needs or desires (Carpo 2011). Despite this paradigm shift, there is a noticeable tendency for contemporary projects exploring the subject of stereotomy to do so with materials and structural logics duplicating those of historic structures, even as these projects cultivate the latest in digital tools. These projects often suggest that digital stereotomy and contemporary masonry in general should still be primarily defined by heavy materials and compression-only configurations. For example, the developers of an innovative parametric brick placement tool state in their paper on the topic that the “main feature of masonry construction is its [compressive] structural behavior” (Rajabzadeh and Sassone 2016). The high profile “Armadillo Vault” structure built from large limestone blocks for the “Beyond Bending” exhibition at the 2016 Venice Biennale also unequivocally “advocates for the logic of compression-only forms” (Block et al. 2016). Similarly, the recent MIT Collier Memorial project designed by the Boston firm Höweler + Yoon Architecture is made from granite, weighs 190 tons and is described as a “compression-only, balanced, rigid body system” (Höweler and Yoon 2016).

Yet, as Warren’s definition suggests (by prioritizing “the cutting or shaping of forms” over structural behavior), stereotomy does not need to be narrowly defined as constructions employing heavy elements working in strictly funicular arrangements. Contemporary fabrication technologies—like large CNC routers, hot-wire foam cutters and robot arms outfitted with a variety of attachments—allow many different types of forms to be shaped from an increasingly wide variety of materials, creating the possibility for masonry with hybrid behavior. The work featured in this paper joins a growing collection of projects that employ alternative materials, particularly lightweight foam and GFRP, to achieve lightweight constructions with structural performance that employs both tension and compression. The Periscope Foam Tower by Matter Design Studio is a significant project in this category. The mast-like structure employs large-but-lightweight, stacked foam elements pulled into compression by multiple perimeter tension cables (Naboni and Paoletti 2015) (see also http://www.matterdesignstudio.com/#/periscope/).

Likewise, the RDM Vault—a collaboration between Matthias Rippmann, Silvan Oesterle and Jelle Feringa—is another hybrid structure built from discrete, lightweight EPS foam elements shaped by robotic hot-wire cutting (Feringa and Søndergaard 2014) (see also: http://www.rok-office.com/projects/dragon-skin-vault-1017/). In this project, the elements are ultimately fused together into a monocoque shell structure through the application of a gypsum/acrylic composite material combined with glass fiber reinforcement. Despite the RDM Vault’s funicular form, the low weight of the EPS elements are insufficient to keep the structure stable if significant external forces are applied; moreover, the structure does not use restraining abutments. To make the structure more robust, it was fused into a shell that could accommodate tensile forces.

Although the RDM vault is not viable as a compression-only structure, the volumetric, large and close-fitting nature of its elements make the design thoroughly stereotomic. Importantly, each of the project’s 53 individual components is sculpted by a contoured cutting path to produce a visually striking surface. Once assembled, each element reads as a cascading shingle that overhangs the part below. This visually flowing design could not have been easily achieved by other methods; it requires individual parts with carefully cut surfaces to produce the shingling effect. In this case, stereotomy—the consequential cutting and shaping of discrete elements to be joined in a construction—is what gives the project its architectural character, not simply its ultimate structural strength. Both before and after it is fused with composites, the RDM vault stands as an innovative deployment of descriptive geometry, employing parts that might be characterized as exceptionally expressive.

The development of exceptionally expressive stereotomic parts is also an ambition of the research presented in this paper. Although it is not a consolidated term in the literature discussing stereotomy, the idea of an exceptionally expressive part—whether the part is called an element, component, trait or voussoir—is employed here to refer to stereotomic parts that have designs shaped by concerns that (may include yet) go beyond the requirements of efficient construction, the flow of forces and non-slipping pieces. While it is tempting to use the more known term "ornament," ornamented masonry is strongly associated with carved relief. In contrast, the looser idea of an exceptionally expressive part can encompass both carved relief, parts with special shapes and the complex patterns of joints—the tessellations—that result from tiling special shapes.

Exceptionally expressive parts produce qualities and constructional consequences that are vital to stereotomy. Parts that produce noteworthy qualities are not particular to lightweight plastic stereotomic constructions like the RDM vault and the research discussed in this paper. Historic structures also employ parts that could be identified as exceptionally expressive. Recognizing that significant differences exist between historical and contemporary precedents, there are two cases worth mentioning. These examples suggest that exceptionally expressive parts—masonry elements with unique shapes that produce visually stimulating tessellations or elements that have graphic qualities produced by carved relief—are intrinsically important to the practice of stereotomy.

Exceptionally Expressive Parts in Historic Masonry

The first precedent is pre-Columbian masonry found in South America. In particular, walls made of large blocks like those found at the Sacsayhuamán citadel (located near the present-day city of Cusco, Peru) have exceptionally expressive shapes. These shapes easily acquire nicknames related to their outlines. For example, in his recent publication on Cyclopean masonry, Brandon Clifford (who also designed the Periscope Tower mentioned above) refers to a common shape of one of these polygonal elements as the "Utah," since its boundary resembles that of the political region in the United States (Clifford 2017). Inca masonry serves as a prime example of the idiosyncratic constructional character that emerges when a wall is made from many distinctively shaped parts as opposed to uniform bricks or cuboid, ashlar masonry. The subdivision scheme of this Cyclopean masonry—originally labelled "polygonal" by American archeologist John Rowe—features non-identical shapes, meaning no two blocks in the wall will have exactly the same form (Dean 2010). Each shape can be appreciated for its individual silhouette; however, in aggregate, the shapes interlock precisely along their edges to create a complex cellular pattern that binds the parts into a visually cohesive composition of joints.

The sixteenth century chapel dome constructed for the Château d'Anet in France by Philibert de l'Orme uses an opposite but equally effective strategy of expressive parts. de l'Orme's consruction uses a strictly limited catalog of shapes (Potié 1996). Each of the thirteen horizontal courses of the dome uses only one block-type; however, each courses' block is carved with a relief element that creates a Fibonacci spiral pattern when the blocks are aggregated. Furthermore, the block developed for each course is ingeniously designed to work in two positions—"right-side up" and "upside down"—and the blocks are turned "upside down" every other repetition to create the spiral. In de l'Orme's dome, the joints of the individual blocks are effectively suppressed in order to give priority to the graphic spiral created by the lattice-like "ribs" carved in relief on the surface of each part.

A New Method for Shaping Parts

The exceptionally expressive parts described above are historic examples of the types of elements that can now be developed computationally. The initial fellowship research conducted by the author discovered that simulating Euler buckling in digital surfaces can aid in the design and construction of stereotomic architectural assemblies by creating unique templates for parts. Buckling is an instability failure mode that deforms configurations of material through displacement. These deformations are disastrous for actual structures, but, in digital surfaces, buckling produces undulations that are wavelike, with structured patterns of crests and troughs. By overlaying two undulating surfaces, unique, tessellated patterns can be created. These tessellations can be used as the departure point for creating stereotomic parts.

The research of this paper uses the unique patterns produced by overlaying digitally buckled surfaces to develop patterns that can be used to make specially shaped parts for stereotomic construction. To do this, a finite element method (FEM) analysis tool is used to generate catalogs of displaced surfaces that can be overlaid to make various tessellations. To avoid confusion, it should be noted the work presented below only uses the FEM tool to generate tessellations that are subsequently used to derive parts. Thus far in this research, the FEM tool has not been used for funicular form-finding, to evaluate how forces flow through the structure or to determine how parts should be oriented to avoid slippage. These structural and constructional issues are addressed by choosing promising patterns and then evaluating the stereotomic viability of individual patterns with physical models.

Simulating Surface Buckling

In order to design the types of parts used in this research, it is first necessary to simulate surface buckling and then use the deformed surfaces to create tessellations. These tessellations will have integral, doubly curved displacements. Buckling can be simulated with the Karamba digital tool, an FEM analysis plug-in for Rhinoceros©. Karamba can simulate surface buckling using either polyline wireframes or mesh geometries. To generate tessellations, however, NURBS surfaces are more desirable since the intersections between multiple overlaid surfaces can be calculated and used to make parts. Since calculus-based, interpolated topology cannot be processed by FEM tools, meshes are used and then converted to NURBS surfaces. Since hundreds—even thousands—of virtual buckling modes can be produced from relatively simple models, the research was originally confined to simple planar, single-layer gridded meshes with square cells. Karamba's simulation algorithm moves from simple cases of buckling to increasingly complex cases. Our tests show that simple cases have relatively few surface undulations, whereas complex cases have many undulations (Fig. 1).

Complex Tessellations

Further tests revealed that overlaying two buckled surfaces produces tessellations. To make these patterns legible, one surface was toned black and the other white. This technique reveals surprising variety. Some surface combinations produce a sense of directionality across the surface while others produce repetitive figures (Fig. 2). Like any system that tiles a 2D plane, the graphic tessellations made using this technique can be used as a general subdivision strategy for "panelizing" architectural surfaces. But the tiles produced by these tessellations

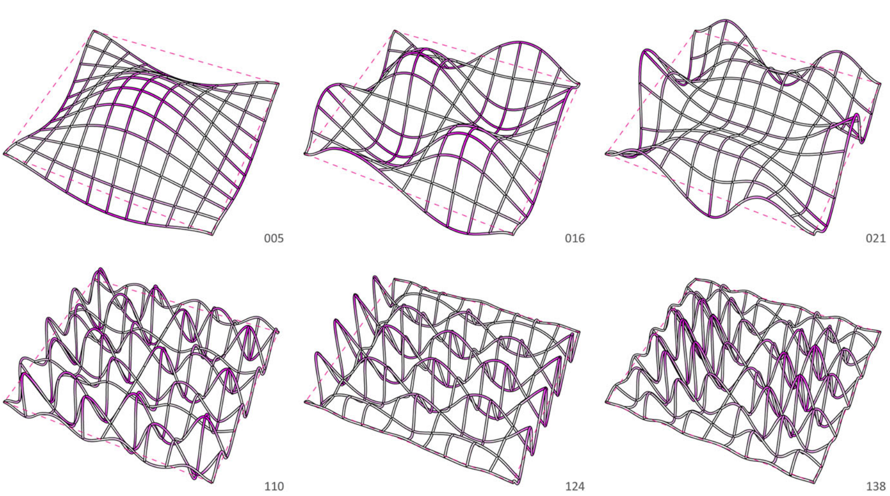

Fig. 1 Wireframe models showing simple and complex cases of Euler buckling simulated computationally

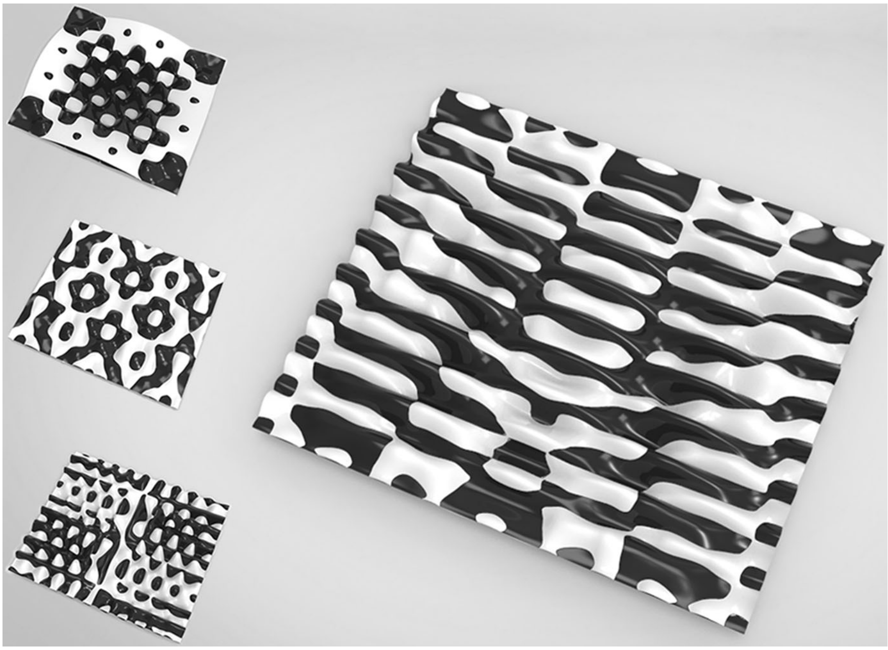

Fig. 2 Tessellations created by overlaying two buckled surfaces

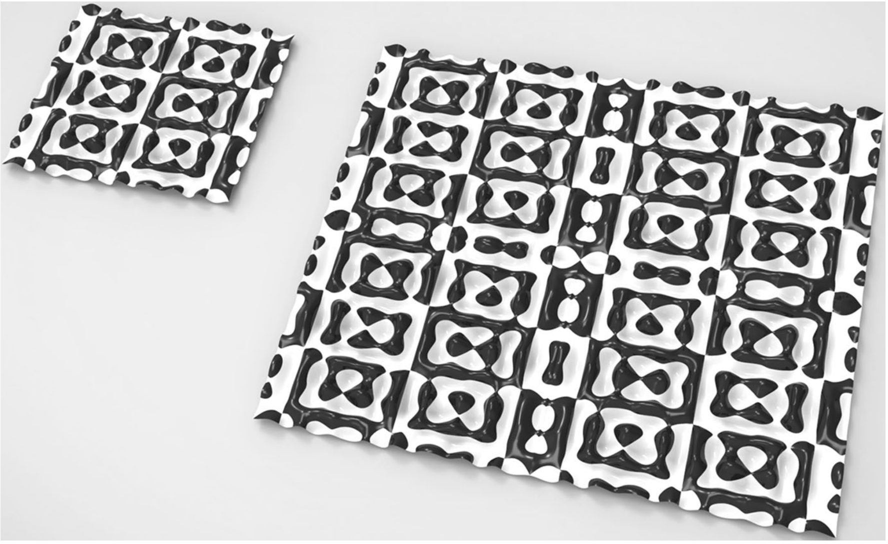

Fig. 3 Volumetric tessellations tile the two-dimensional plane with integral relief

exceed the requirements of simple 2D subdivision; as fragments of an undulating surfaces, these tiles are inherently volumetric and have integral depth in relief (Fig. 3). Consequently, these tessellations are ideal templates for making exceptionally expressive parts.

Stereotomic Walls

After discovering that buckled surfaces can be used to design tessellations, pairs of overlaid surfaces were selected to test as templates for further development as stereotomic walls. At this point, the surfaces of these templates required further editing to become self-supporting assemblies. To accomplish this, the following technique was developed: split the surfaces along their lines of intersection to make four sets of surfaces, and designate two of the sets as the front side of a wall assembly and two as the back. Two related stereotomic wall types can now be developed.

Type 01

To develop a Type 01 wall, the two sets of surfaces originally designated as the back of the wall are deleted. The edges of the remaining surface tiles—the surfaces designated as the front of the wall—are extruded perpendicularly from the overall plane of the wall. This operation produces structural flanges that are joined to the

Fig. 4 Stereotomic wall design Type 01 with stacking and nesting parts

original surfaces. To give the individual pieces thickness for fabrication, the joined surfaces are offset. The final pieces stack and nest into a free-standing stereotomic assembly (Fig. 4).

The structural viability of this wall type was tested with a model 3D-printed in ABS plastic. The resulting prototype was self-supporting and consisted of interlocking, friction-fit stacked volumes (Fig. 5). The prototype measured approximately 16.5 cm (tall) × 30.5 cm (wide) × 5 cm (deep with an average wall thickness of 16 mm. The final assembly had masonry-like “courses” that are overall horizontal in orientation. On first inspection, each part seems unique (like the parts of pre-Columbian masonry). However, on closer inspection, reflected symmetry is part of the overall composition; each part in the wall has a secret “double” with the exact same outline but slightly different surface relief (Fig. 6).

Type 02

Encouraged by the results of the first stereotomic wall model, an additional wall prototype was designed and 3D-printed from ABS plastic. This design became the basis of stereotomic wall Type 02. To create a Type 02 wall, instead of discarding the surfaces affiliated with the “back” of the wall, these surfaces are translated, perpendicularly, away from the front sets to make a gap. The gap is then bridged by “lofting” the edges of corresponding surface sets from each side of the wall. This technique produces both structural flanges and closed, volumetric solids with relief on both sides of the wall (Fig. 7). These geometric solids can be 3D-printed without further editing. However, for the test model, some of the surfaces were “cut open”

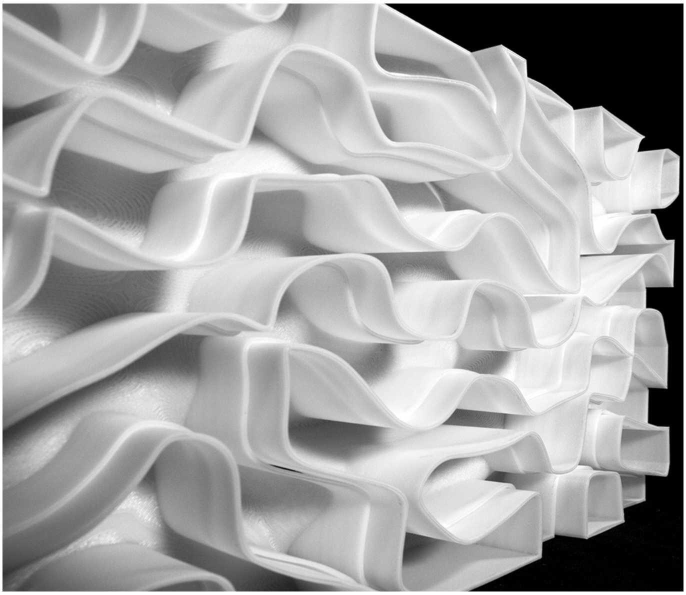

Fig. 5 3D-printed model of initial stereotomic wall design Type 01

Fig. 6 The wall design features hidden symmetries

on the back of the wall and on its ends. This revealed interiors of the parts which (in the 3D-printed model) are all still hollow volumes.

Stereotomic Wall from GFRP

The initial phase of stereotomic research concluded with the construction of a full-scale, freestanding wall. Approximately the height of a person, the wall measured 1.8 m (tall) × 3.2 m (wide) with a variable depth. This self-supporting wall consisted of 32 interlocking elements made from E-glass—a common type of glass-fiber reinforcement—and a high-strength epoxy resin matrix. The composite surfaces were laid-up in open-face, CNC-milled foam molds that were coated in plaster and wood filler to protect and further smooth the molds' curved surfaces. Prior to beginning the composite lay-up process, the molds were also coated with several release agents.

Once the molds were built and prepared, the composite parts were made. To give the wall an alternating black-and-white color scheme, pigmented polyester gel-coat resins were sprayed into the molds first. After the gel-coat layer was dry, it was roughened with sand paper. Several structural layers of reinforcement and high-strength epoxy resin were then laid-up to an average final thickness of only 3 mm. When the pieces were de-molded, the color gel-coat layers pulled away from the faces of the molds, creating a finished surface.

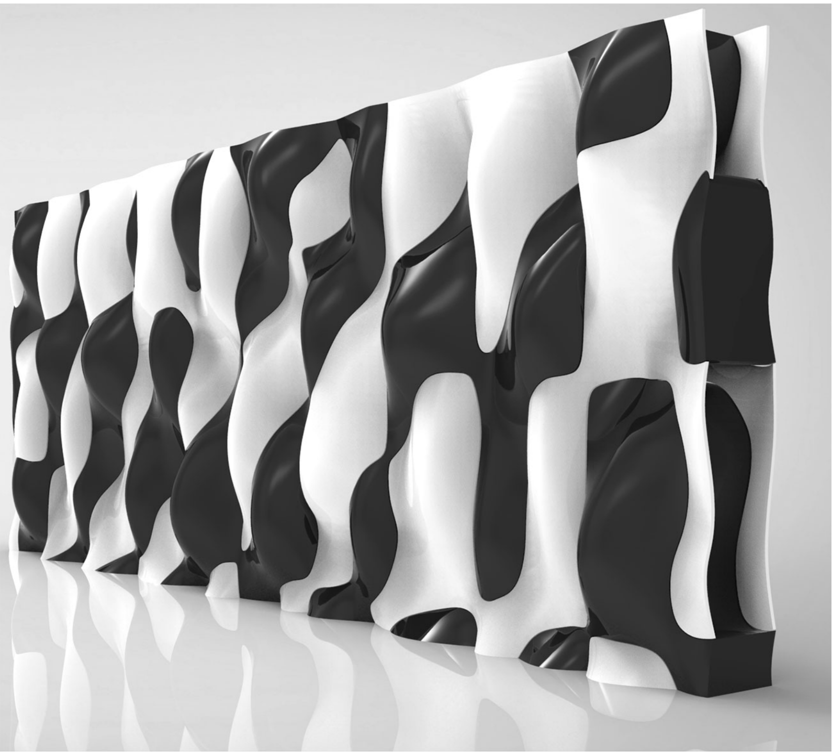

Fig. 7 Type 02 stereotomic wall design with relief on both sides of the wall

Parts with a white tone were left open on the rear side of the final wall; each piece only required one open-face mold for fabrication. Black parts remained closed volumes; each of these parts required two open-face molds to produce halves that were fused with adhesives into a closed, hollow part. Both the black-toned parts and the white-toned parts appear massive on the front side of the wall (Fig. 8). But on the rear of the wall, the open-faced white parts reveal the thinness of the wall's stereotomic elements and the overall lightness of the construction (Fig. 9).

Observations on Initial Research

This research shows that stereotomic walls with exceptionally expressive parts can be developed from the voluptuous tessellations that form when digitally buckled surfaces are overlaid. 3D-printed models and the large-scale wall made from GFRP show that these designs can be self-supporting. More importantly, the interplay of open and closed parts in the GFRP wall revealed the perceptual shifts that are possible to achieve with a thin-walled approach to stereotomic construction. What might appear to be solid and heavy on one side of the wall can be revealed to be light and thin on the other side. This thin-walled approach to stereotomy produces a

Fig. 8 Full-scale, free-standing stereotomic wall made from molded GFRP parts

new type of architectural poché, termed here “laminar poché.” Laminar poché realized with plastic parts adds something new to stereotomy: parts that provide structure and define significant volume without requiring great mass.

The initial phase of research also raised interesting questions. The walls that were designed and built all used perpendicularly extruded or lofted flanges to make parts; however, stereotomy also employs more complex projection systems to design parts with the angled faces necessary for building spatial structures like vaults. The next logical question was whether a spatial structure could be realized with lightweight GFRP parts developed from the tessellation system we discovered. The next project, the *Plasticity Pavilion*, extended the research to answer these questions.

Stereotomy from Large GFRP and Foam Parts: The Plasticity Pavilion

In 2014, the Texas Digital Fabrication Alliance (TEX-FAB), a non-profit organization dedicated to promoting advancements in digital design and fabrication, organized an international competition called “Plasticity”. The brief sought design proposals that joined state-of-the-art digital design and fabrication technologies with GFRP composite construction. The competition had two stages. The first was an

Fig. 9 The rear side of the wall reveals the thinness of the construction

open call for schematic designs from which four finalists were selected. In the second stage, each of the finalists produced a proof-of-concept prototype, and a winning proposal was selected for full-scale construction with the assistance of Kreysler and Associates, a leading fabricator of GFRP building components.

The author's entry *Plastic Stereotomy*—ultimately realized as the *Plasticity Pavilion*—was selected for construction from an original field of 70 entries. Developed in stages, each iteration of the pavilion design featured a self-supporting structural system made from large parts, precisely stacked into an interlocking arrangement to form a spatial structure. Winning the competition also provided the opportunity to work with an industry partner and test the feasibility of realizing GFRP stereotomic construction in a factory. The effort proceeded in the three phases described below: schematic design, prototype production, and final design and construction.

Schematic Design: Overview

Relative to the original stereotomic walls constructed in 2013, two advances were made during the schematic design phase of the Plasticity Pavilion: buckling tessellations were applied to a fully three dimensional volume, and a spherical projection system was adopted to ensure that neighboring parts could be joined along adjacent faces in the structure. Prismatic geometry—an octahedron—was selected and slightly elongated to serve as the overall form for the pavilion. The shape was selected for its simplicity, visual dynamism and because it cannot work structurally in pure compression. Since the *Plasticity Pavilion* is built from GFRP, its overall shape shows that "plastic stereotomy" can have parts and joints between parts that carry load in both tension and compression. An octahedron, resting on one of its faces, has a flat top that must carry load in bending, i.e., flexure, instead of pure compression.

The pavilion was given an exterior octahedral shape with a volume of 40 cubic meters that fit within a bounding box measuring 5 m (wide) × 6.4 m (deep) × 2.5 m (tall). An interior volume of 20 cubic meters was located inside the octahedron to make occupiable void that would also define the interior faces of the pavilion's parts (Fig. 10).

Schematic Design: Parts from 3D Tessellations and Spherical Projection

Like the planar geometry used for the initial stereotomic walls, the exterior form of the pavilion was initially modeled as a polygon mesh. This mesh could be buckled using the same FEM simulation algorithm used previously for 2D mesh planes. Hundreds (or more) buckling "frequencies" with undulations of lesser or greater density were generated. Representative examples of these displaced meshes were converted into NURBS surfaces and intersected with the original octahedral shape to make tessellations. We discovered that this process can create tessellations that fully wrap any original 3D mesh shape (Fig. 11).

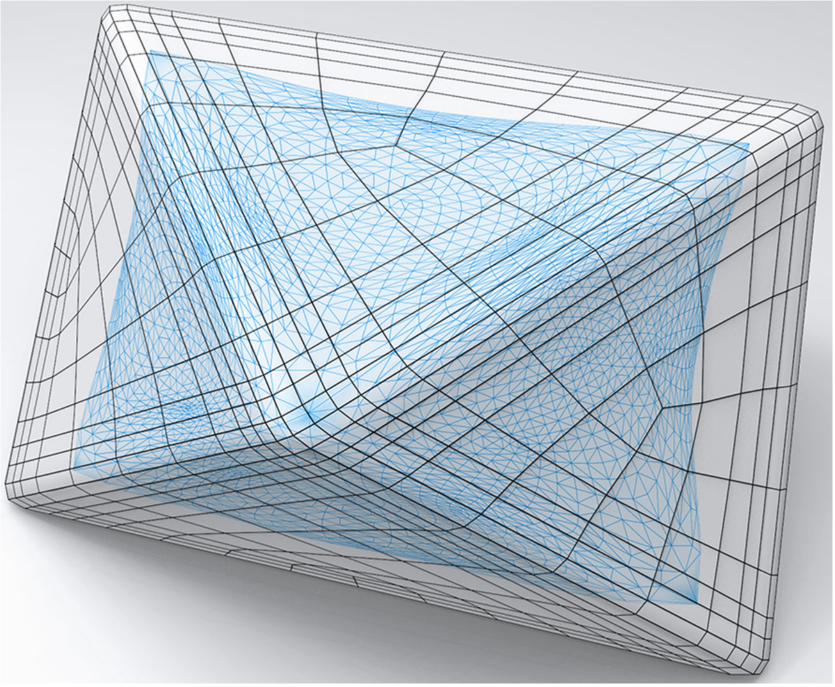

Fig. 10 The octahedral base shape of the Plasticity Pavilion has a void on the interior that is not simply an offset of the exterior form

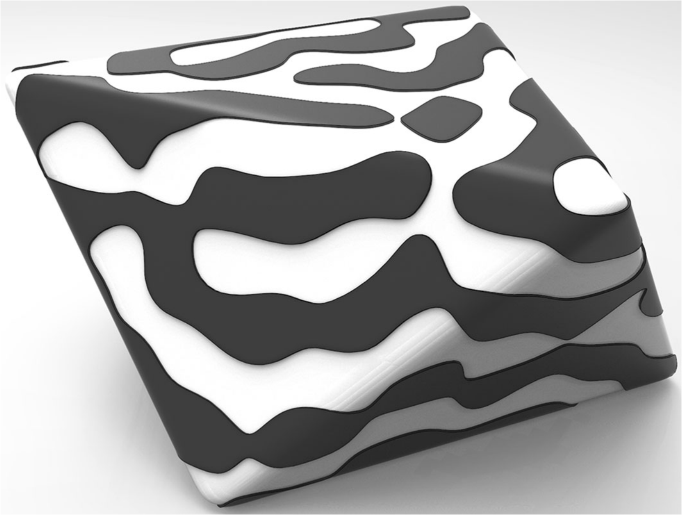

Fig. 11 The author's tessellation system derived from surface buckling applied to a three-dimensional volume; the pattern completely tiles the form

For this design, surface undulations that passed above the boundary of the original shape were deleted while undulations that passed below the boundary were kept (The areas of the original shape that covered the interior undulations were also deleted). The resulting tessellations had alternating zones of flat and highly undulating surfaces. To make the tessellations more visible, flat zones were toned black and undulating zones white; tessellations of varying densities were tested.

While the tessellation system made patterns that wrapped the pavilion's exterior shape, individual parts could not be made by simply extruding the edges of the patterns. It was also not possible to three-dimensionally scale or otherwise offset curves made from the edges of tessellation (in order to make a second set of curves from which interior "flanges" for the parts could be lofted). Scaling the curves resulted in unacceptable distortion and corrupt surfaces for the parts. The problem of making parts was solved by locating a sphere at the centroid of the pavilion's volume. Using the "Pull" command in Rhinoceros©, the curves of the tessellation were projected onto surface of the sphere. Next, using the "Fin" command, the curves (on the sphere) were extruded outward, using the sphere's surface normals as guides for the extrusion (Fig. 12). This process created a set of surfaces that intersect all of the original surfaces of the design; these surfaces also exactly align with the original tessellation pattern (Fig. 13).

Trimming these spherically projected surfaces with the exterior and interior design surfaces of the pavilion created the necessary, hidden surfaces from which stereotomic parts could be made. Furthermore, the curves on the sphere were offset; these offset curves were used to create a second set of flange surfaces. These flanges trimmed (and were trimmed by) the original surfaces of the pavilion to create construction joints in the form of gaps between the parts.

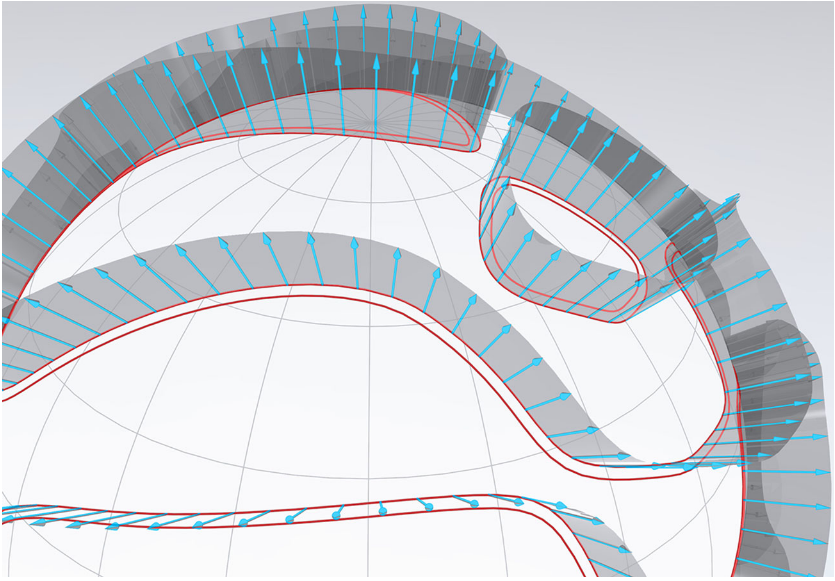

Fig. 12 Curves of the desired part pattern are mapped onto a sphere and then projected outward using the sphere's surface normals

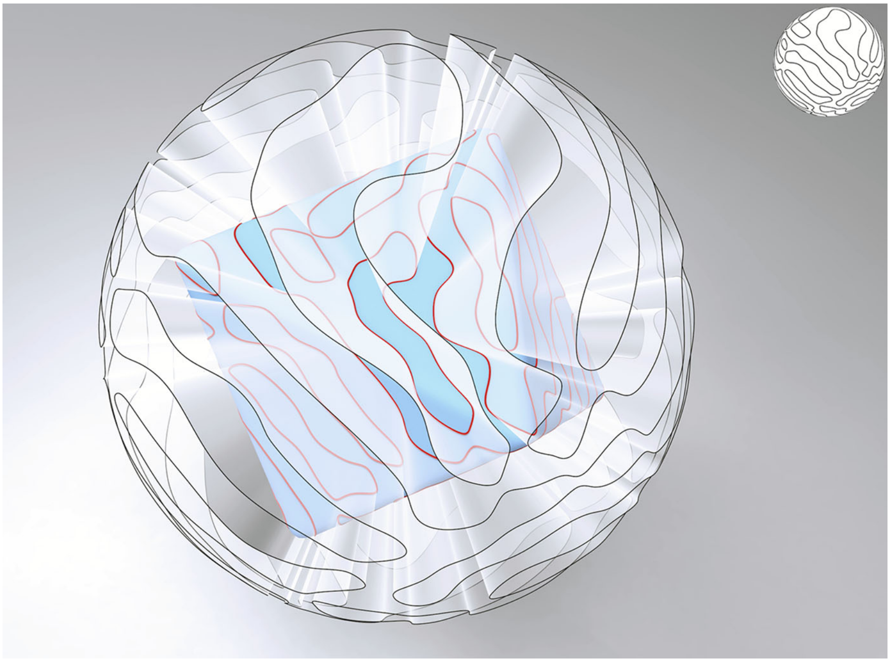

Fig. 13 The outer and inner surfaces of the base geometry for the pavilion are split into parts with spherically projected flanges

Final Schematic Design

Using the techniques described above, a final schematic design was developed using a relatively dense tessellation pattern as a template for the parts. The result was submitted to the first stage of the Plasticity competition (Fig. 14). The striated design has 24 masonry courses that are approximately parallel. Each course is approximately 0.35 m (tall) × 0.35 m deep (thick). Originally, half of the parts were proposed to be made from EPS foam wrapped in GFRP and half of the parts were to be made as thin-shells, open to the interior of the pavilion (Fig. 15).

Prototype Fabrication

The schematic design was selected as one of the four finalists in the Plasticity competition; a physical, proof-of-concept prototype was then built for the final round of judging. The prototype captures a representative section of the proposed pavilion (Fig. 16). The prototype scale is 25% smaller than the full-scale proposal, standing 1.875 m tall rather than the full height of 2.5 m. The prototype has 10 parts total, and shows the viability of three unique part types made from GFRP (Fig. 17).

Type 1 parts are made from solid EPS foam, digitally carved with a 5-axis milling machine, and wrapped in layers of GFRP stiffened with epoxy resin. (This part type is used for the base of the prototype.) A Type 2 part has a hollow, closed cross-section and is made only from GFRP. Four foam molds are required to make a Type 2 part—a mold for the front face, a mold for the back face and mold for each interior flange. The individually molded faces are glued together with high-strength epoxy. A Type 3 part is similar to a Type 2 part but has a “C”-shaped cross-section with internal stiffeners to keep the cross-section from collapsing.

Fig. 14 The schematic design of the *Plasticity Pavilion*

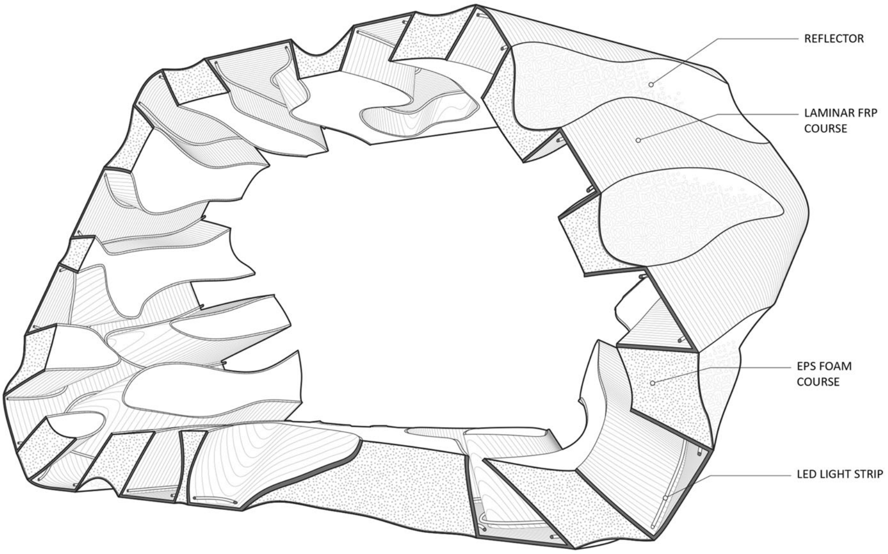

Fig. 15 Cross-section of the *Plasticity Pavilion* schematic design

Fig. 16 Sectional proof-of-concept prototype for the schematic design of the *Plasticity Pavilion*

Since the entire form cantilevers, the parts are bolted together to accommodate bending forces. Gluing the parts together would have been preferable for stiffness; however, bolted connections made it possible for the prototype to be disassembled, shipped and reassembled for the final round of competition judging.

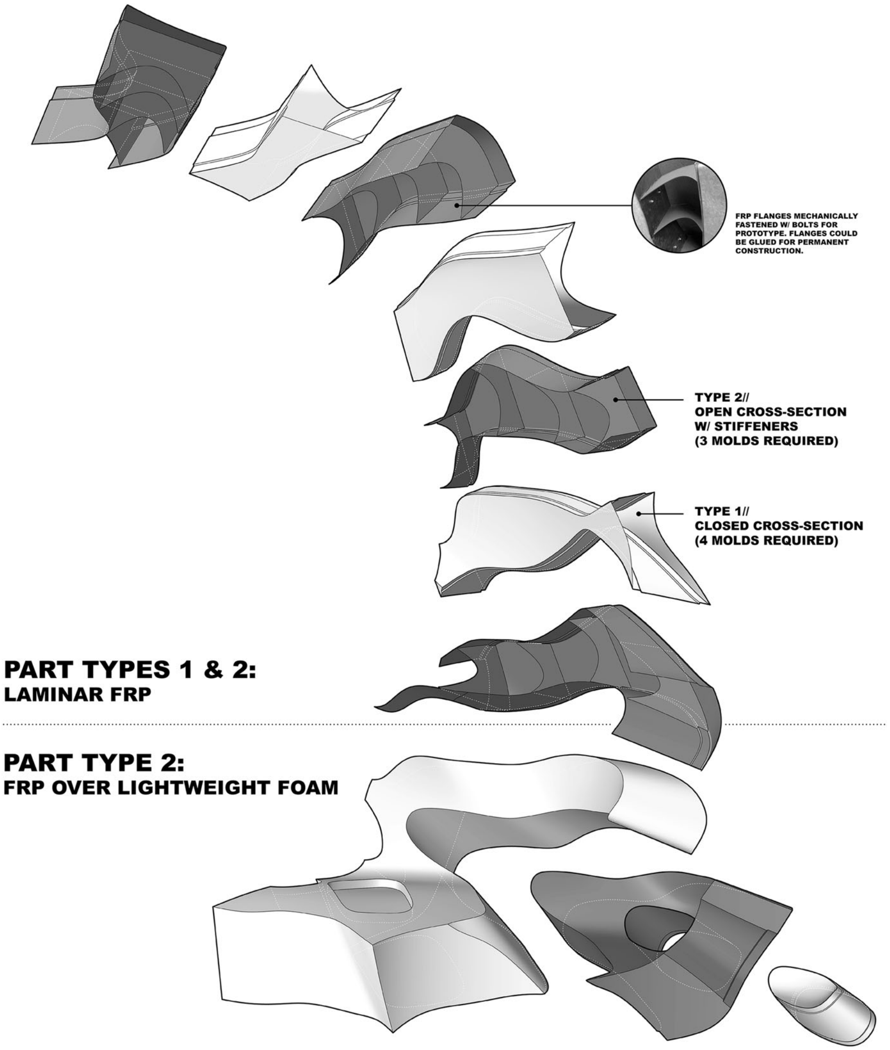

Fig. 17 The prototype tests three related part types

Final Design and Construction

The prototype was well-received by the competition jury, and the design was selected for further development and full-scale fabrication at the Kreysler and Associates factory in American Canyon, California. The fabricator had very large CNC cutting machines—a KUKA robot and a 5-axis gantry milling machine—each capable of cutting extremely large foam parts (Fig. 18). To take advantage of these machines, the pavilion was redesigned with a less dense tessellation pattern; the final proposal had only 10 large parts (Figs. 18, 19, 20). Ultimately, for reasons of time and budget, only five of these large parts were fabricated for the final pavilion;

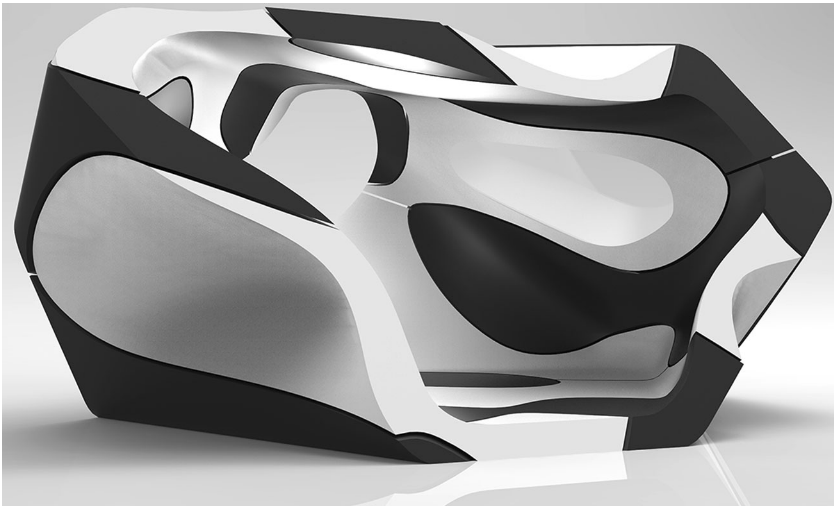

Fig. 18 The final design of the *Plasticity Pavilion* features fewer and much larger parts

a single steel column carries the load for the missing parts. To speed up and reduce the complexity of construction, only Type 1 parts were used for the final *Plasticity Pavilion*: solid EPS foam parts encased in a 2 mm thick shell of GFRP. To provide an attractive finish, each part was covered in a lightweight plaster and “faired”—made smooth—by hand with large blocks of sandpaper before being sprayed with two coats of paint.

The large parts used for the final *Plasticity Pavilion* can be classified as Cyclopean masonry: each part is larger in size than a person. But unlike the stone elements used for historic Cyclopean construction, the *Plasticity Pavilion*’s parts are extremely lightweight. Each part can be lifted into place by approximately four to five people (Fig. 21). For example, the part shown in Fig. 21 has an overall volume of 1.2 cubic meters but an approximate weight of only 55 kg.

Lightweight parts enable the *Plasticity Pavilion* to be a portable structure; however, portability also means that the pieces cannot be permanently joined. This creates structural complications. Since the shape of the pavilion is not a compressive vault, bending occurs in the parts and “masonry hinges” can form at the joints of the structure (Heyman 1995). In permanent GFRP construction, parts can be glued together along matching faces with a high-strength adhesive; however, to maintain portability, metal connection plates joining the parts together are hidden between the joints of the structure (Fig. 22). Each plate is first glued to the EPS foam during an early phase of construction and then laminated into the GFRP shell encasing each part during composite lay-up.

The finished *Plasticity Pavilion* was first exhibited at the University of Houston in the spring of 2015 (Fig. 23). The pavilion later traveled to the 2015 National Convention of the American Institute of Architects (AIA) in Atlanta, Georgia, where it was exhibited by the American Composites Manufacturers Association (ACMA). Articles about the pavilion were featured in both the print and web

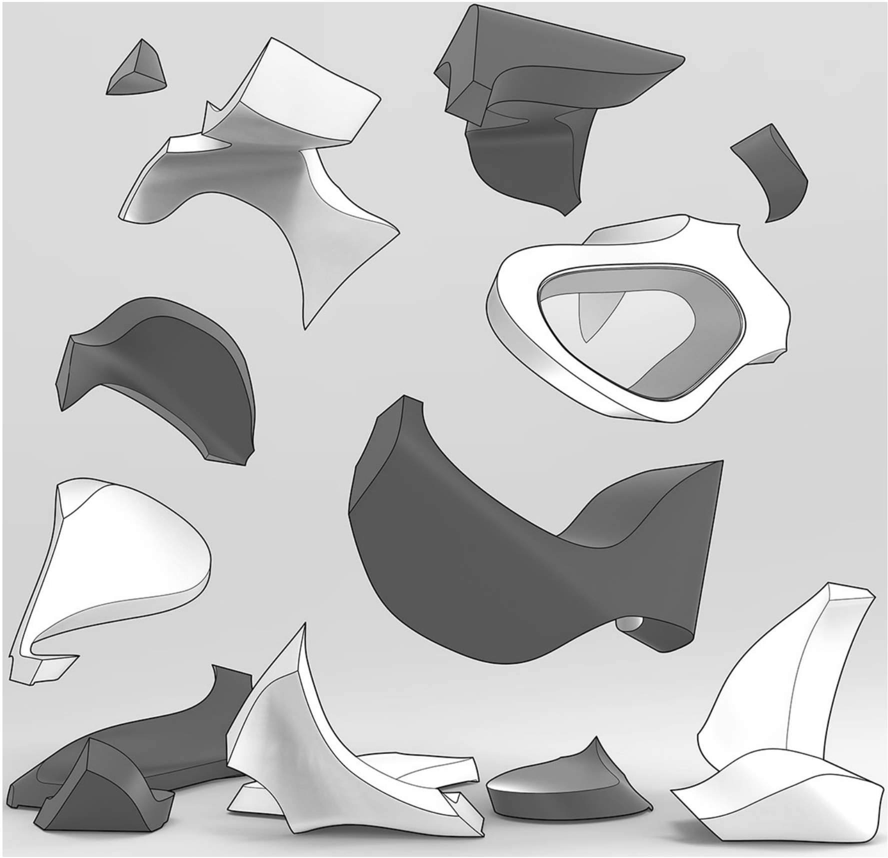

Fig. 19 Exploded view of the Plasticity Pavilion showing the ten Cyclopean parts

editions of *Architect* magazine, the professional journal of the AIA, to coincide with the convention (Brownell 2015a, b). These articles, aimed at wide audience of architects, reveal the growing interest in stereotomy as a construction technique and plastic as an architectural material.

Conclusion

The projects described in this paper successfully demonstrate that stereotomy need not be limited to heavy materials, solid parts or compression-only shapes. The research presents a process for generating novel tessellations from free-form geometries with simulation tools. It shows how volumetric parts with complex silhouettes and double curvature can be derived from these tessellations and employed for stereotomic constructions. The research also presents methods for building parts from lightweight GFRP and tests structural forms that work in both tension and compression. Laminar poché is proposed as a term to describe

Fig. 20 The pavilion is made from foam parts cut by robots and other large CNC cutting tools. The parts are wrapped in a 2 mm thick layer of glass-fiber reinforced plastic

Fig. 21 The Cyclopean parts of the pavilion are light enough to be manually lifted into place

Fig. 22 Corresponding steel connections are laminated onto the matching faces of the parts, allowing them to be joined and carry load in bending

Fig. 23 The *Plasticity Pavilion* was exhibited at the Tex-Fab Plasticity Symposium at the University of Houston and the National Convention of the American Institute of Architects in 2015

stereotomic architecture that uses parts made from GFRP shells that are either completely hollow or encase lightweight materials like foam. Finally, the research tested a new form of Cyclopean masonry. Applied to the *Plasticity Pavilion*, the research successfully tested a contemporary version of this ancient technique with large parts—each significantly bigger than a person—that are so lightweight that they can be lifted into place by a just few people.

While the projects described in this paper employ volumetric parts derived from sinusoidal tessellations, the ideas and methods explored in the research are not restricted to these shapes. Future exploration into lightweight stereotomy made from plastic is rich with potential and can proceed simultaneously along technical and design trajectories. For example, a more systematic exploration of how GFRP parts work in bending would be of immediate value. Such a study would likely analyze the parts themselves and the structural connections used to link them, whether mechanical or adhesive. Additionally, the research opens the door for myriad possible constructions employing laminar poché. This concept could be applied to the development of Cyclopean parts with cavities that are partially or completely inhabitable. On the other hand, hollow parts developed at almost scale could be filled with materials that passively regulate ambient conditions like temperature or incorporate technologies that actively enhance architectural performance. This paper presents just a few of the vast innovations that open up when stereotomy is pursued with expressive parts made from lightweight plastics.

References

Brownell, B. 2015. One Word. *Architect* (2015) 5: 26.

Brownell, B. 2015. The Future of Plastics in Architecture. *Architect* Magazine. http://www.architectmagazine.com/technology/the-future-of-plastics-in-architecture_o (accessed 1 November 2017).

Block P., M. DeJong, D. Escobedo, M. Escobedo, J. Ochsendorf, M. Rippmann, and T. Van Mele. 2016. Armadillo Vault: A Complex Shell Structure Consisting of 399 Stone Blocks. *Detail* (2016) 10: 940-944.

Carpo, M. 2011. *The Alphabet and the Algorithm (Writing Architecture series).* Cambridge: MIT Press.

Clifford, B. 2017. The Cannibal's Cookbook: Mining Myths of Cyclopean Constructions. (1st ed.). (n.p.): Author.

Dean, C. 2010. *A Culture of Stone: Inka Perspectives on Rock.* Duke University Press.

Feringa J. and Søndergaard A. 2014. Fabricating architectural volume: Stereotomic investigations in Robotic Craft. In: *Fabricate: Negotiating Design & Making*, eds. Fabio Gramazio, Matthias Kohler and Silke Langenberg, 76–83. London: UCL Press.

Höweler E. and J. Yoon. 2016. Zero Tolerance: Design and Delivery of the MIT Collier Memorial. A/R/P/A: Issue 04, Instruments of Service. http://www.arpajournal.net/zero-tolerance/ (accessed 1 November 2017).

Heyman, J. 1995. *The Stone Skeleton: Structural Engineering of Masonry Architecture.* Cambridge: Cambridge University Press.

Naboni R. and Paoletti I. 2015. *Advanced Customization in Architectural Design and Construction.* Heidelberg: Springer.

Potié, P. 1996. *Philibert de L'Orme : figures de la pensée constructive*. Marseille: Editions Parenthèses.

Rajabzadeh S. and M. Sassone. 2016. Brick Patterning on Free-Form Surfaces. *Nexus Network Journal* (2017) 19: 5–25.

Warren, E. 1875. *Stereotomy: Problems in Stone Cutting. In Four Classes.* New York: John Wiley and Son.

Justin Diles is an Assistant Professor at the Knowlton School of Architecture at The Ohio State University.