Stereotomy, an Early Example of a Material System

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Stereotomy originated as a technique that accumulated theoretical and practical knowledge on stone material properties and construction. At its peak in the nineteenth century, by pushing the structure and construction limits, it gained the ability of using ``the weight of the stone against itself by making it hover in space through the very weight that should make it fall down'' (Perrault 1964, cited Etelin, 2012). The modern architectural tectonics, based on structural comprehension in architecture, found no value in stereotomy beyond its early, Gothic period. Similarly, digital architectural theory recognized in Gothic the early examples of a material systems. This paper reassesses stereotomy at its fundamental levels, as a material system based on generative processes that assimilate structure and construction through parameterization. In this way, a theoretical framework is established that exposes stereotomy's intrinsic potentials: the continuity of historic and contemporary examples, overlaps between current research endeavours, and its genuine relevance for contemporary digital architecture.

Keywords: *stereotomy, material system, Abeille vault, parametric design*

Introduction

Stereotomy is a technique that accumulated theoretical and practical knowledge on stone material properties and construction. It was primarily based on essential, complex geometric relationships embedded within stone masonry. In recent years, the advancement of digital design and fabrication tools that easily handled complex geometries had caused a renew interest in stereotomy (Fallacara, 2012; Fallacara, 2016; Rippmann, et al. 2011; Rippmann, et al. 2017; Burry, 2016; Varela, et al. 2016; Fernando, et al. 2015; Weir, et al. 2016; Clifford, et al. 2015). Historically, stereotomy was connected to certain structure and construction choices. Contemporary research initiatives, driven by various motivations and objectives, explored and questioned these choices at different levels.

Paper proposes a theoretical framework where the continuity of historic and contemporary stereotomy and overlaps between current research endeavours are exposed. Stereotomy is observed beyond its formal resolves and approached at its fundamental levels. More specifically, paper moves away from analysing stereotomy using traditional tectonic notions and approaches it as a generative material system.

Historic Overview

Stereotomy (Greek: στερεός (stereós) "solid" and τομή (tomē) "cut") originated in the Gothic period as a result of a reversal in construction thinking. Throughout Antiquity and the Middle Ages, buildings were thought of in the same way as they were made, from the ground up. For the Gothic builders, supported parts gave shape to the supporting parts, and imposed construction thinking from the top down (Sakarovich, 1998). Stereotomic form was seemingly based on a paradox: it used "the weight of the stone against itself by making it hover in space through the very weight that should make it fall down" (Perrault 1964, cited Etelin, 2012). It was actually derived from the underlying interdependencies that varied its constituent ashlars towards coping with the contextual forces.

Figure 1
Monastery of Notre-Dame de la Couture, Le Mans, 1720-39. (Photo: R. A. Etlin, from Etlin, 2012 page 23.)

As a technique, stereotomy explored the limits of spatial, structural and material principles through the application of current fabrication technologies and geometric knowledge. It offered immense novel possibilities that brought about an enthusiasm for amplifying the force flow complexity while providing solutions that purposely obscured structural comprehensions. By the nineteenth century, stereotomy became known as a 'bizarrely daring acrobatic architecture' (Etlin, 2012) (Figure 1). Concurrently, from the seventeenth century onward attitudes had developed that sought architectural "visual qualities capable of convincing a viewer about its solidity, and in this sense vraisemblance (plausibility) became important" (Sekler, 2009). "A structure should always look stable as well as be stable" (Evans, 2000). Stereotomy, an audacity bordering on foolhardiness (Evans, 2000) was shunned and abandoned.

Structural plausibility and legibility continued into twentieth century tectonics, and greatly remained a yardstick for architecture until today. In this context, any reassessment of stereotomy praised the early period, the Gothic, for its tectonic clarity, while the late 'acrobatic' (Etlin, 2012) variations were continuously found offensive and frivolous.

Stereotomy in Contemporary Architectural Theory

Similarly, the Gothic found relevance within digital architectural theory. It was recognized as an organizational system that defined the form from the convergence of forces (gravity, perception, and social organization) resolved through the elements' mutual relationships. Form was an amalgam of variations driven by operational and procedural rules (Spuybroek, 2011). In short, the Gothic provided digital design processes with historic case studies on topological form conceptions instigated by active space of interactions.

Moussavi interpreted Gothic as a system of bays acting as base units. Each base unit was versatile, not fixed and could vary as it repeated, or even mutate, when hybridized with other base units. The novel and unpredictable forms were temporarily and spatially specific, yet capable of responding to external concerns (Moussavi, 2009). Likewise, Spuybroek interpreted the Gothic as a system that changed through ever-shifting combinations of variable and flexible subelements: the ribs. The system's relationships were fixed, but not the resulting forms (Spuybroek, 2011). In conclusion, the Gothic was understood as an early example of a material system, where fairly simple behaviour by individual elements resulted in complex and irreducible collective behaviour (Spuybroek, 2011).

Although relevant, the interpretation remained limited. Its analytical processes, derived from traditional tectonics, observed solely the expressive potential of construction techniques (Frampton, 1995) through the parts-to-whole relationship logic. Stereotomy, on the other hand, required analysis beyond the visual legibility offered by Semper and Frampton, that recognised "classicism was as much parametric and generative" as the Gothic (Carpo, 2011). The understanding of stereotomy could not be divorced from a procedural analysis of its formation processes.

Material System Based on Generative Rules

Sekler recognized architectural formation processes in his definition of tectonics, the expressive result of a structure realized through construction. Structure, an abstract concept, was an arrangement system or principle destined to cope with the contextual force flow, and construction was its concrete realization (Sekler, 2009). Construction encompassed material properties, tools, technology and procedures, fabrication constraints, and design, geometric, and instrumental knowledge (Witt, 2010). Tectonic was not a result of mechanistic notions as form reproduction tools, but machinic notions that determined elements' variations, interrelation, multiplication, and complex organizations (Moussavi, 2009). It was inseparable from the architectural form in general, stereotomic in particular, albeit varied visual comprehensions that were unintentionally clear in the Gothic period, and intentionally ambiguous during the stereotomic peak.

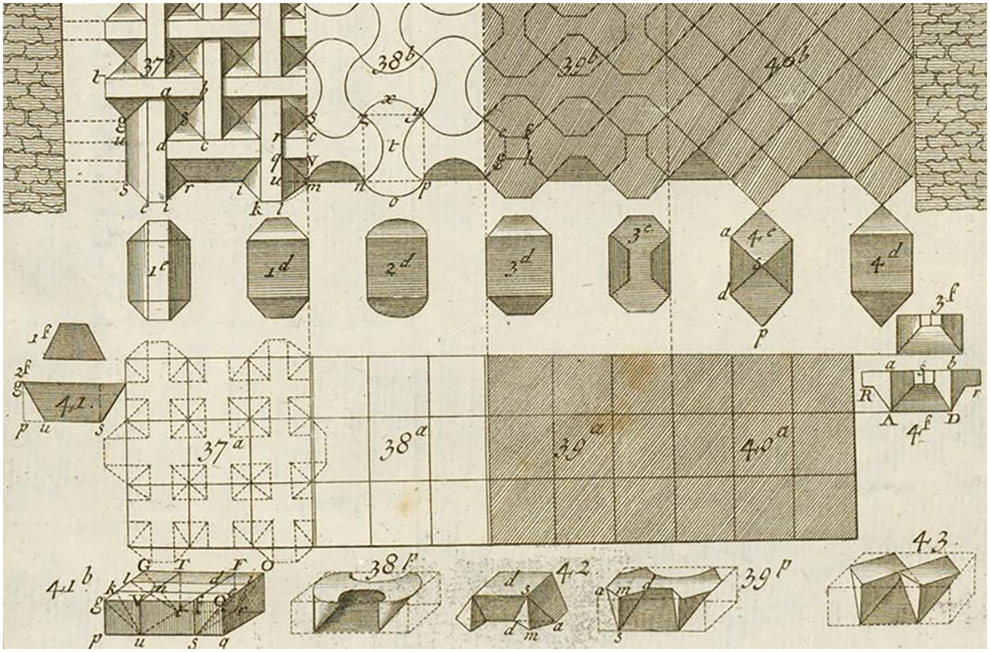

Figure 2
Flat Vaults 37&41 - Abeille Vault 38 - Truchet Vault 39, 40, 42 & 43 - Frézier (Adapted from La théorie de la pratique de la coupe des pierres et des bois, by Amédée François Frézier, Planche 31, http://www.e-rara.ch/zut/content/pageview/8691852)

Defined in this realm, stereotomy was a material system that assimilated structure and construction negotiations as a set of generative rules that were themselves subject to evolutionary change, and once fixed could be fleshed out in a wide variety of [tectonic] forms (Heyman, 1998).

Stereotomic Analysis Methodology

New Structuralism theory argued for digital architecture based on spatial, structural, and material principles synthesis in lieu of the traditional form-structure-material sequence. (Oxman, et al. 2010). Due to their intrinsic overlaps, New Structuralism offered relevant analysis procedures for assessing stereotomy as a material system. A set of historic stereotomic assemblies was analyzed (corbel, circular and flat arches, corbel and circular domes, barrel, groin, helicoidal, trompe and shallow vaults, and Abeille, Truchet and Frézier flat vaults (Figure 2)) through New Structuralism's processes (structuring, digital tectonics, and digital morphogenesis).

In the first step, the structuring process, the mathematical/geometric, syntactic and formal stereotomic logic was analysed and recognized. Specifically, structural patterns, geometric attributes, and configurative transformations were discretised into generative rules. In the next step, the digital tectonics, generative rules were formulated into parameters and their interdependencies to establish the digital parametric model design substance. In the last step, the digital morphogenesis was enabled within the parametric models and provided diverse topological outputs, design explorations and prototype fabrication information. The analysis actualized novel forms that explored adaptive, configurational, and transformability potentials beyond their original design intents (Oxman, et al. 2010). Finally, the analysis exposed common underlying stereotomic parameters.

Stereotomic Parametrization

The four common underlying parameters that activate a stereotomic material system were: base surface geometry, distribution grid, and two relating to the single unit configuration: perimeter faces rotation and thickness.

The base surface geometry was determined by the force flow, the line of thrust, and directly reflected

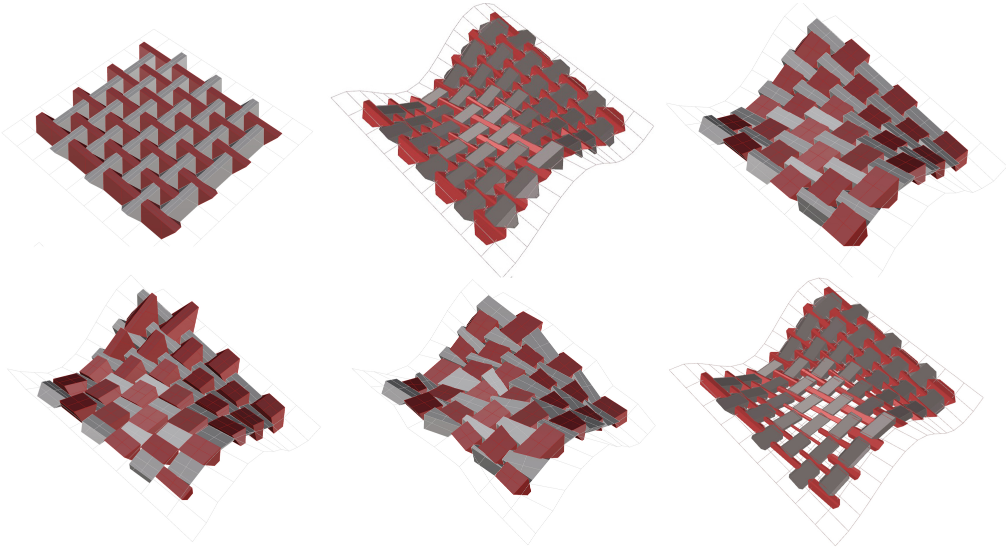

Figure 3
Configurational variations of the Abeille stereotomic material system

structure. Structure varied during the construction process due to varied force flow. It also had varied final intents, from pursuits in the force flow optimization to specific aesthetics. The base surface geometry was interdependent with the single unit geometry, since an assembly was concurrently a whole subdivided into single units and a propagation of single units creating a whole.

Distribution grid was determined by structure and construction choices. Historically, typical distribution grids used were: running bond, rectangular grid, hexagonal grid, radial grid, and irregular grid.

The rotation of the single unit faces that were neither intrados nor extrados, the perimeter faces, defined the structural action of the whole, or parts of, the assembly. Faces perpendicular to the force flow determined arches for linear assemblies and shells structures for surface-based assemblies. Alternating inward outward perimeter faces rotation established either a topological interlocking or reciprocal frames type structure.

The single unit thickness was the distance between intrados and extrados faces. For statically determinate assemblies it was dependent on structure, as the force flow had to be accommodated within the material thickness. In statically indeterminate assemblies it was dependent on construction.

The four formulated parameters and their interdependencies defined the stereotomic material system. Specific structure and construction choices were assimilated within the material system by providing specific parameter values. In conclusion, structure and construction choices were not necessarily predetermined, as they informed the stereotomic material system, but did not activate it.

Abeille Flat Vault Material System

The stereotomic parametrization process was illustrated through the Abeille flat vault example. Firstly, the Abeille vault was defined as a material system, followed by formal explorations through parametric variations. Further, nontraditional, non-masonry structure and construction assimilations within the material system were explored through the design and construction of a stereotomic plate pavilion, technically an oxymoron.

Visually, the Abeille vault was based on identical ashlar truncated tetrahedral configurations: a poly-

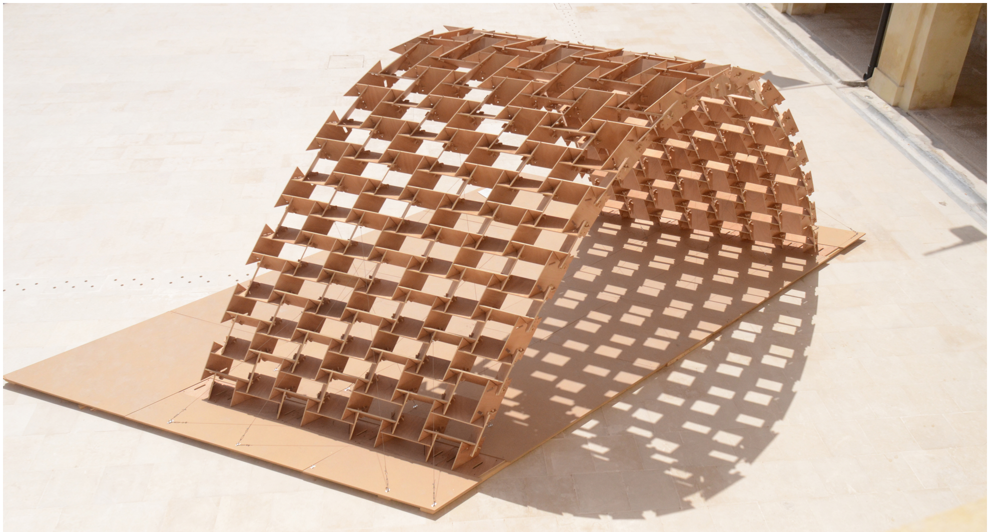

Figure 4
Stereotomic Plate Pavilion, Malta 2014, Irina Miodraogic Vella (University of Malta), Steve DeMicoli (DeMicoli & Associates, dfab.studio) Dr Professor Toni Kotnik (Aalto University)

hedron with axial sections in the shape of an isosceles trapezium. The ashlar geometry and the rotation of neighbouring ashlars by ninety degrees established their mutual arrangement: each ashlar was carried on two neighbouring ones through its protruding cuts, and at the same time provided support for two others on its sloped cuts resembling reciprocal frames structures (Miodragovic Vella, et al. 2016).

Defined parametrically, as a stereotomic material system, the Abeille vault was based on a planar, horizontal base surface and a square distribution grid. Each parameter face was rotated 54.7 degrees from the base surface, in the direction opposite to the rotation direction of the adjacent faces, instigating topological interlocking structure. Thickness was determined by two trimming planes, differently positioned base surface tangent planes, one at the surface level, and the other at some distance below. Finally, the parameters interdependencies were established (Miodragovic Vella, et al. 2016).

The Abeille stereotomic material system's configurational variations were explored. Initially, the focus was on parameter values, assigned arbitrarily, often extremly to amplify possible inconstancies and limits in the validity of the digital tectonics formulation and corresponding digital morphogenesis. The resulting outputs remained virtual, without any pursuits for their physical resolve (Figure 3). Next, the Abeille stereotomic material system was further complexified by increasing the number of polygon sides that made the distribution grid and/or increasing the number of rotation alternations per ashlar face. In this way, other established stereotomic elements were derived confirming the parameters' validity (Miodragovic Vella, et al. 2016).

Finally, the Abeille stereotomic material system structure and construction assimilation was tested through a full scale prototype, a pavilion built for Malta Design Week 2014, held at Fort St Elmo, Valletta (Figure 4). It was a collaboration between the authors and Steve DeMicoli (DeMicoli & Associates, dfab.studio). Due to site sensitivity and budgetary concerns the material used was not stone masonry, but a sheet material, marine plywood. This allowed for "in-house" prototyping and fabrication, fast, manual on-site mounting/demounting and total reversibility requested by the organizers.

The design process started with the translation of the structure and construction choices into values to inform the stereotomic parametric model. The solid blocks assembly logic was discretized into an assembly of plates. The plate configuration was derived by 'merging' the touching single unit perimeter rotated faces of adjacent elements: the two faces that shared the same rotated plane became a six-pointed plate (Figure 5). The resulting structure remained topological interlocking, of single unit perimeter faces, rather than the volumes they enveloped.

The base surface geometry was a linear extrusion of a catenary curve defined by the force flow and fabrication optimizations. The result was a five meter span, four meters long, parabolic vault. Although the plate configurations varied along the changing cur-

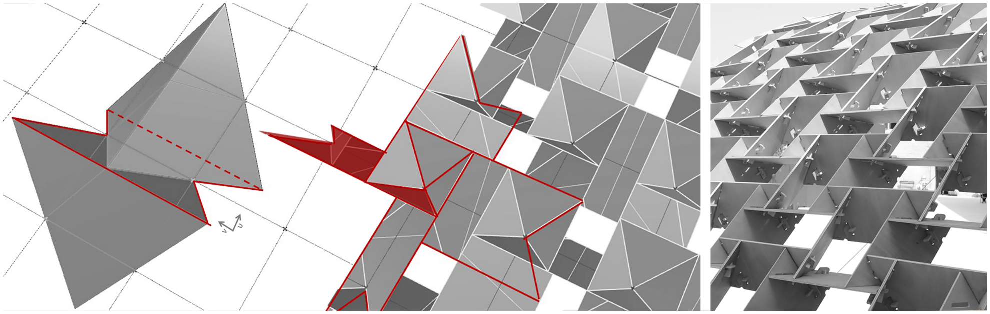

Figure 5
Discretization of the solid blocks assembly logic into an assembly of plates

vature of the catenary profile, the linear extrusion allowed for repetitive plate types, and thus, faster fabrication.

The structure also determined the plate rotation angle. Through full scale prototype testing, a sixty degree rotation angle from the base surface was determined as the optimum to avoid deviation in the vertical plates that formed the arches. The limited CNC bed size defined the irregular rectangular grid field sizes, maximum plate lengths and widths.

Due to site, budget and mounting constraints, elaborate falsework had to be avoided. To deal with the varying force flow during construction a self-stabilizing structure was achieved thorough plate rotation and plate configurations. Through topological interlocking, corbelling and nominal propping various stable configurations were achieved prior to the vault sides being connected and the arch mechanism activated. By following a diagonal, weave-like mounting sequence the assembly stiffness was continuously increased (Figure 6).

In the final outcome, the traditionally solid stereotomic appearance was transformed into a lightweight lattice assembly (Figure 7). Still the generative rules that activated the material system remained apparent showcasing that it was driven by underlying parameters informed by the structure and construction choices.

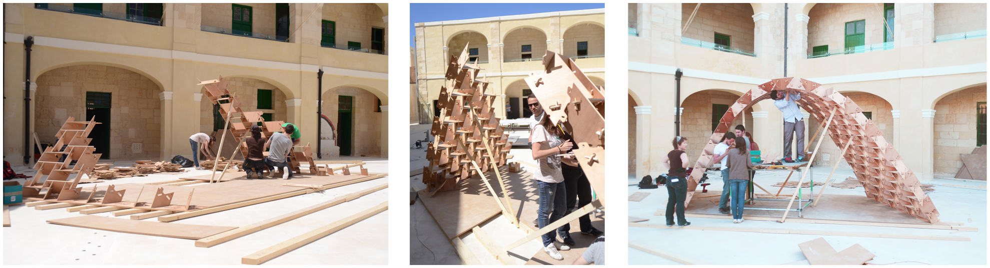

Figure 6
Various
self-stabilizing
configurations
during construction

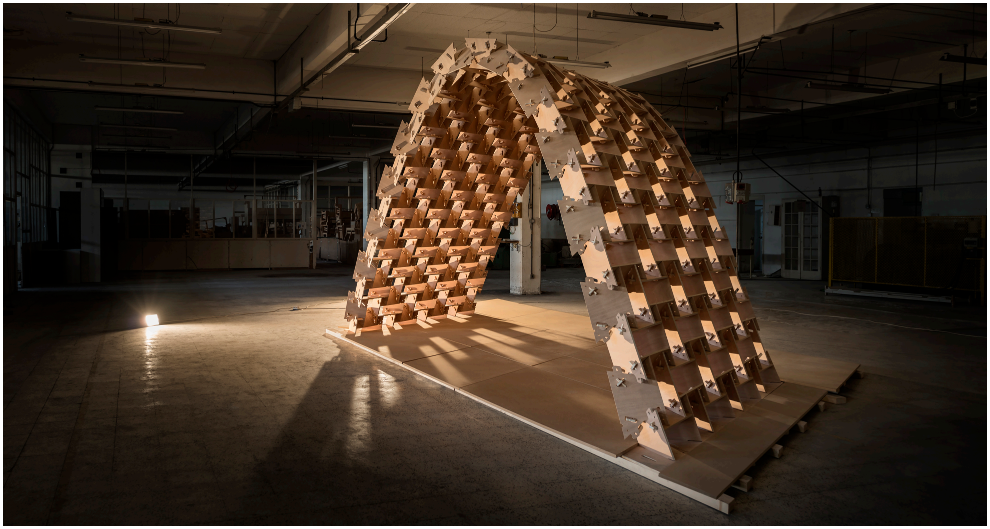

Figure 7
Stereotomic plate
pavilion (Photo by
Alex Attard)

Conclusion

"Similar processes do not necessarily beget similar shapes. Understanding these processes, on contrary, will help us shape better things" (Carpo, 2011).

The main objective of the presented assessment, and resulting theoretical framework was to view stereotomy beyond its formal visual comprehension of traditional tectonics to include generative processes that assimilate structure and construction through parameterization. Any stereotomic assembly, historic or contemporary, could be referenced, defined, and described to establish a productive relationship between stereotomy's past and future. In this way, stereotomy's intrinsic potentials were exposed and its genuine relevance for contemporary digital architecture could be traced and recognized.

Finally, the proposed theoretical framework is neither final nor conclusive, but open to further contributions and revisions.

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