Revising Stereotomy through Digital Technology

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Stereotomy is usually regarded as a classic discipline in the field of architecture which has lost its relevance to other construction methods. Recently we have witnessed approaches to the stereotomic way of building using modern digital technologies, bringing the discipline to the present. On the other hand, the complex shaped buildings being built in the present seem to lack some kind of structure visible in classic stone architectures. A shift in construction methods must be attended to, with its metallic beams and concrete massifs. For an understanding of what remains the same and what changes from the classic literature, this paper tries to create analogies between contemporary architecture surfaces and the discrete stone structures of the past. To achieve this, a concept of stereotomy semantics is introduced, creating a different posture towards the problem of division of surface in architecture.

Keywords: stereotomy, treatise, complex geometry, interpretation

ON STEREOTOMY
Stereotomy's meaning (from the greek, "stereo" - solid and "tomia" - section) gives us clues to its classical meaning. Cutting solids acknowledges the existence of a previous big mass of material which is to be separated into smaller blocks by a stonemason or a carpenter. This is a practice not so much concerned with the actual physical means to cut through stone, but with the intellectual means to find the correct shapes to be produced. This construction method has a strong tradition in architecture as it spawned bold structures, a large number of theoretical works and, possibly most importantly, Descriptive Geometry (1798), the synthesis of Gaspard Monge's stereotomy classes.

One of the most important research works on stereotomy in the architecture field came in 1567 with the first structured information on the subject contained in Philibert de l'Orme's "Le premier tome de l'Architecture". In this book, the author stresses the importance of control in design and construction, so that the architecture project may be undertaken according to the architect's vision until its final materialisation. This claim in favour of architects appeared in the Renaissance in a clear opposition to Gothic tradition. While in the late medieval cathedrals' ribbed vaults and buttresses were controlled by the stone masons, de l'Orme wants to affirm the architect as the incontestable decision maker. This is only possible if he possesses the technical means to project arches, vaults and its components in its three dimensional detail, and finally draft them accurately in paper, securing the design with a document.

De l'Orme inaugurated a tradition of research and publication on stereotomy, which encompasses more than 50 treatises published until the beginning
of the 20th century. Among the most relevant ones, the works of Girard Desargues on projective geometry (1640), de La Hire’s important notions on statics (1678), Frézier’s widely published and one the most used and referenced treatises in Europe (1737), and Monge’s work on developing the language with which most architects still project architecture today - Descriptive Geometry (1798).

The industrial revolution introduced cast-iron and later steel which replaced in many ways the use of stone in architecture, a construction technique strongly dependent in stereotomy knowledge. As new construction systems evolved, a loss of interest in individually cut stones gradually set in. To take advantage of the economical benefits of industrial mass production, materials were designed and employed following strict modular schemes, favouring designs based on symmetry and repetition. This new logic of modularity did not favor the exploration of unique architectural designs requiring customized building components.

THE INTEGRATION OF DIGITAL TECHNOLOGIES

Engineering, in the facets of CAD (design), CAE (engineering) and CAM (manufacturing) has been able to restore a much welcome enrichment in design possibilities of complexly shaped architectures. The availability of these technologies allows architects to design unique buildings with unique construction system and elements, as can be seen in the seminal project by Frank Gehry, the Guggenheim Museum in Bilbao. This project design process used parametric software which could handle a consistent 3D model, as well as report complete schedules of quantities and dimensions. Although some architects used mesh based modelling softwares in the turn of the century, NURBS (non-rational b-splines) is a type of geometry representation which has gaining traction in the latest years, together with visual programming tools. Architecture software has seen engineering tools embedded with FEM (finite element method) analysis, creating a more holistic view of design. Digital fabrication is becoming every time less bounded to a small number of axis, large robotic arms as well as more capable multi-material 3D printers can create complex and accurate shapes. These tools create a different point of departure when projecting architecture, expanding possibilities in all fields of architecture, including that of stereotomy.

Current research on stereotomy under the digital umbrella has produced very interesting results. A retake on classical stereotomy with contemporary technologies is the pioneering experiments of Giuseppe Fallacara of Politecnico di Bari on vaults made of digital fabricated stone voussoirs (Fallacara 2009), recently with the added component of post-tension. The BLOCK group of ETHZ has an ongoing research in digital stereotomy, which "develops a method for tessellating free-form masonry-like vaults" (Rippmann 2010). Justin Diles from Knowlton School researched in stereotomic hollow fiber blocks (Diles 2014). Other works like the ones from Matter Design (Kaczynski 2011) or Supermanouvre (Larsen 2012) only add to the clear notion that stereotomy as an architectonic theme is a continuing interesting approach, but now highly powered by current digital technologies. The understanding of stereotomy as a construction technique that depends on the unity of a multitude of small blocks of a single family finds a harmonious analogy in parametric strategies, in which a shape is computed a great number of times with subtle differences, accurately different to be part of a greater whole understood as a unified stereotomic project.

A brief analysis of the afore mentioned works shows us that the relation to classical stereotomy is being taken literally, on a direct relation to the works produced under the treatises of de l’Orme and Frézier. Although we can clearly detect differences to the pre 20th century approach, be it in the material employed, the much greater geometric freedom, or auxiliary forces other than simple compression, we propose a broadening of the field of stereotomy beyond compressive volumetric structures, so that a common line of thought can be traced between
structures built of smaller parts. We will define some notions of an on-going research in how classical stereotomy literature contains multiple hints and relations to contemporary projects so that the design of subdivided surfaces, as a natural descendent of stereotomic design, is ought to have a clear notion of the similarities and differences between the classical cutting of stone and the contemporary homonym.

**TOWARDS AN ENLARGED SEMANTICS**

A stereotomic project may be described by the verification of three invariants: pre-figurative, technical/-geometrical and compression statics (Fallacara 2003). If we develop these concepts, we may assert that the three fields present in a stereotomic architecture are those of drawing, projective-constructive technique and performance. The first enables us to preview the final appearance of the architectonic object, the second allows us to define it formally and performance validates the solution under a determined interest. This hypothesis allows us to observe stereotomy with one of its components expanded: performance. This performance may be tension statics instead of compression, or maybe surface curvature or even fabrication possibilities. By allowing us to broaden this concept, stereotomy can be taken into new fields not necessarily stone made. In classic stereotomy, statics is perceived as its performance determinant; in this context, we understand statics as a meaning within a semantic stereotomy.

By understanding stereotomy as a multi-semantic and methodical approach to subdividing surfaces, much of treatises' concepts can find a healthy echo in their digital counterpart of today’s high end architectonic complex structures. The need for the control of geometry is in great extent eased by the computer, which does not dispense mathematical and geometric principles for solving these kind of problems. A revision of stereotomy treatises can enlighten the design of subdivisions in various kind of architectonic surfaces, augmented by digital means in a similar fashion as mathematics empowered stereotomy. For the illustration of the idea of a semantic stereotomy, two different projects, Chartreuse de Valbonne (1770-1780) and Olympiastadion Munchen (1968-1972) we will be evaluated under these terms.

The vaults of Chartreuse de Valbonne show a very particular interest in creating decoration with the constructive stone blocks that support the church roof. Decorative religious themes seem to be a contrasting attitude towards military buildings' austere efficiency; Frézier is worried with the importance of Theory over Practice as to optimise the designs (Frézier 1738), an optimisation that should be understood in the context of a treatise of stereotomy written in the 18th century by a military man: structural stability and practical means of attaining the right geometry and transferring it to construction materials were the main drivers of his design. In Valbonne, the brothers France d'Avignon show a focused interest in the decorative curves, that lie above cutting simplification. Going beyond austere and economic constraints, decoration become this project’s stereotomic semantics.

On another hand, the tensile roof of Frei Otto’s Olympiastadion [1] is held by seemingly opposite forces than those that support the stone vaults of classical stereotomy; instead of compression, traction is what binds the whole structure together. The idea of traction related to stereotomy is not new. Although metal girders can be used to secure stones together, although a more striking example is that of the lighthouse known as Smeaton’s Tower (Rondelet 1868) in which the strong horizontal forces of the waves are held by a dovetail shaped interlocking system that does not allow blocks to separate from each other, creating a stereotomic traction system; this idea was recently used by Jeanne Gang in the Marble Curtain installation [4]. In Frei Otto's roof, the structure relies in a carefully crafted network of steel cables in tension, roughly following and generating the two main curvatures of the surface in an intrinsic orthogonal layout. The longest and radial cable direction becomes the guide for the continuous rows of repetitive acrylic panels. The resulting
grid of building elements is the stereotomy of this structure, materialised in the acrylic panels that, although not structural, are in a narrow relation with the underlying steel grid. The direct relation between force vectors and apparent division lines show its stereotomic semantics, producing a consistent grid consequential from the design intent and construction constraints down to its final appearance.

The Olympiastadion, together with other examples such as the Sydney Opera House, shows great efforts towards the optimisation of construction elements, producing a stereotomy that is bounded in its time by the design and production possibilities available. The advent of new technologies that enables new design approaches is embodied by the Valbonne vaults; the brothers Franque d’Avignon turned their attentions to a more elaborate decorative scheme in 1770 because structural stability and fabrication drawings knowledge was mastered enough and did not pose an obstacle to other design intents. In a similar fashion, the introduction of the computer in such processes means a gain in production and accuracy, quantity and quality. This simple fact, powered by algorithmic design and digital fabrication, broadens the gamut of possibilities as one is not restrained to use repetitive modules in a complex construction. A digital and contemporary interpretation of classic stereotomy is considered, providing positive arguments in building a contemporary stereotomic approach.

**CASE STUDIES**

The relation between digital technologies and an expanded concept of stereotomy shall be explored in three case studies. Curvature as a performance factor is explored in the EMP Museum sheet metal façade; the second example shows that decoration, or the architectural language, drives the construction of the concrete surface of Casa da Música; the last example shows how history revision can play a decisive role in a contemporary stereotomy that is driven by different drivers only possible due to today’s technologies.

**Casa da Música**

OMA’s project (1999-2005) for a concert hall in Porto [2] is a concrete polyhedron which sits in the ground with no immediate out a clear direction. This lack or orientation is also found in the exterior enclosure where there is hardly a vertical wall or horizontal direction, except for the main windows. An important role in the definition of the strange balance of this building is played by stereotomy, helping create an architecture expression by imprinting formwork lines in its surface, simulating its own reality. This dialogue between form and function in architecture can be traced back to the old Egypt where capitals evoked lotus, papyrus and palm trees, or Greeks who were responsible for creating the classical vocabulary and system. By Vitruvius’ account, the logics of wood construction were petrified; although some could condemn the misrepresentation of the constructive system, classic language has been ever since one of the main references in architecture design. The design intent becomes as important than the constructive system itself, lending to an expression system in itself.
Casa da Música's exterior walls are all built of concrete cast in place [3]. The construction of the walls was phased, because concrete has a limit on its height for proper setting. Because concrete is a ductile material while it is setting, horizontal lines appear naturally in the top height of the concrete layers, regardless of formwork. The architects seem to have had a different purpose for the appearance of the building, denying its relationship to gravity and its horizontal and vertical related vectors. Standard formwork panels were chosen, creating a rectangular array. This array of panels is aligned with a roof edge and from there, it develops around the facets of the building creating oblique directions which are aligned in an intrinsic surface analysis but completely unaligned as seen from the outside. A conflict is generated between the construction lines and the falsework (Figure 1), in a tension that clearly marks a stand from the architect's point of view: the division lines apparent in the surface ought to be oblique. The intention of organising a prefabricated, mass produced false work, much like in the architecture of Tadao Ando, is an expression of stereotomy for a subjacent idea of organisation is implied by the apparent junctions. These false work imprinted junctions are key to express the design intent in the architecture, gaining prominence above the construction lines, for its expressive and intentional aesthetics, making the polyhedral nature of the project (Figure 2) change its own stereotomy semantics.

**EMP Museum**

Gehry's EMP Museum (1995-2000) is covered in sheet metal in a double curvature configuration. Sheet metal does not admit double curvature, so the design had to be rationalised into developable strips. Breaking down a curved surface to smaller parts which bear a smaller curvature is an approach that can be traced back to the earliest records on stereotomy practices. The first forms of stereotomy relied in shapes easily projectable to a plane, featuring variation in only one dimension, such as arches and barrel vaults. The method for materialising this kind of designs was mainly "par équarissement"; this process relies in having two or more projections drawn in a block of stone and then having the mason carve, progressively from both sides until these meet. As the discipline created more complex shapes such as the skewed arch or arrière-voussure the transferring "par équarissement" revealed its shortcomings as the bounding box would be too big or the orthogonal projections not sufficient to describe the complexity of the angled shape.
Philibert de l’Orme introduced another method in his "Le premier tome de l’Architecture" which allowed for much more complex shapes to be worked out of stone. The method, called "par panneaux", relies in a different projection for each face of the voussoir by rebating, which were complex geometric operations for the 16th century. This achievement allows for true size drawings in sheets to be put directly in the block of stone as to carve progressively until these sheets meet. The projection of each of the individual faces (Figure 3) of a construction block - be it planar or not - implies a target plane that should conform to a possibly curved surface. Depending on the ability of the draftsman and stonemason, a high curved surface might produce inaccurate results for its inaptness of true size in direct projection into a plane.

The direct relation between division design and materialisation possibilities creates a two way play, in which the feasibility of imprinting a "panneau" is influenced by the design and the design is constrained by the afore mentioned feasibility. This symbiosis is also present in the EMP Museum sheet metal cover.

Seattle’s music scene, embodied by Jimmy Hendrix, was perceived by Frank Gehry’s design as an explosion of shapes and colours - these were embodied in seven different volumes. The initial design foresaw the facade built in shiny terrazzo as an analogy to the lacquered finish of electric guitars. The possibility of this volumetric stereotomy was discarded due to cost issues, and it was replaced by a skin cover made of sheet metal. Constraints in material dimensions and curvature, as well as fixation technology were key influences in the division design. The departing point was a grid of four-sided panels bounded by flow lines (curves of constant U or V), with maximum dimensions of 10’ x 15’ and maximum square area of 100 square feet (Shelden 2002). The first action was to identify panel planarity through its mean gaussian curvature: regions which fell under a pre-determined tolerance were considered planar; others were subdivided in smaller region so that fitness was acquired. Once the surface was divided in regions whose curvature was similar to planes - to a specified extend - a grammar was applied to further divide (Figure 4) these according to maximum sheet dimensions (48” x 96”).

The stereotomy design methodology of the surface of the EMP Museum has two main moments: the division into macro regions and the division within these regions to create the final building blocks - micro stereotomy. This final design could only be achieved once the macro stereotomy could be unrolled so that its design could be somewhat "imprinted", just as de L’Orme’s "panneaux". But instead of being bounded by stonemasons capabilities and compression only statics, Gehry was directed by the sheet metal properties and industry capabilities in deforming it to attain curvature.
**Ponte Truchet**

The Ponte Truchet (2007) by Giuseppe Fallacara has in its design a clear idea: to transform the interlocking blocks flat vault seen in Frézier's work into a ribbed vault by means of a topological transformation. The main source of inspiration for this vault is Jean Truchet, (1657-1729), a Carmelite man of science, namely mathematics. One of his interests was in tilings, and he registered a patent on a vault construction system (Figure 5) which uses only one kind of voussoir to attain doubly flat faces, perfecting the previous Abeille design. A report published by the French Royal Academy of Sciences praised the design but argued that its construction would be too difficult for the varying curvature of the surfaces and the need for a perfect fit.

Fallacara saw this as an opportunity to put to test contemporary technologies. Computer driven multi-axis machines make no distinction between straight lines or highly varied curves. Not only a vault was fabricated with this curved voussoir, but a deformation was also applied to the initially flat vault, making it into a barrel vault, a skewed barrel vault (Figure 6). This is a subversive move, because the vault that was composed of only one template that repeated itself in all its extension was transformed into a structure that is composed of unique voussoirs in half of it. Although this could be understood as a drawback toward the original Truchet design, it ought to be perceived in its context: stone voussoirs are cheaper to be produced by machines than by human labour. Because the design is parametric, and voussoirs were not designed individually by hand, but automatically through a set of rules; and stone working machines do not work with templates or moulds but individually at each block, this design is utterly contemporary although it links directly with the theoretical tradition and finds in this historic design an opportunity to create a vault that is decorative and structurally more effective than a simple barrel vault.

**REVISING STEREOTOMY THROUGH DIGITAL TECHNOLOGY**

These examples provide an insight on how stereotomy can have an alternative, yet in continuum understanding to the classic theory. Despite the elaborate and accurate nature of many stereotomic designs produced in the 18th and 19th century, there is a constant throttle in the complexity of these designs, be it in the geometrical design, or the ability to reproduce it physically with the necessary accuracy. This throttle is deeply connected with the technology available at the time which, although capable of intricate designs, comes at a high human labour cost.

With the possibility of using the computer to automate drafting tasks under specific rules, the stereotomic design can achieve levels of perfection not possible before; on the other hand, CNC machines allow us to fabricate the exact geometrical
shape needed, instead of falling to La Gournerie's arguments (Rabasa 2011).

Be it in structural elements, formwork, cladding or even decoration purposes, a new kind of stereotomy that depends on theory and reason as much as it did three centuries ago is taking shape, as the emergence of an expanded architectural morphological freedom has not only taken place, but it is already in its course. This new shapes have their closest relative in stereotomy treatises, where clear options are taken to its subdivision or regulation. An analogy is not only possible but necessary, in order to provide elements to evaluate and push forward today's morphological possibilities.

Semantic factors such as the nature of materials, the type of connections between parts, the forces that connect them, planarity of surface, thickness of the structure, density of subdivisions, all of these factors may somehow replace or augment classic needs of stone stereotomy in a productive digital environment.

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FIGURE CREDITS
Figure 1 - Photo from https://commons.wikimedia.org/wiki/File:A_Casa_da_M%C3%BAsica.jpg and drawings by the author.
Figure 2 - Drawing by the author.
Figure 3 - Delorme, P 1567, Le premier tome de l'Architecture, F. Morel (Paris), p. 100.
Figure 4 - Original image changed by author. https://commons.wikimedia.org/wiki/File:Razvan_-_Orendovici_-_EMP_SFM_Building_(4170362500).jpg
Figure 5 - Recueil des machines et inventions approuvées par l'Académie Royale des Sciences, 1699, p. 163.
Figure 6 - Original image changed by author. http://www.lithicdesign.it/portfolio/ponte-truchet/

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