

Digital stereotomy

The rejuvenation of stone masonry

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Abstract. This paper explores four factors contributing to the revival of stone masonry; aesthetics, externalities, representational tools and cutting technologies. The ongoing desirability of stone for architects and designers for aesthetic reasons; sustainability benefits of stone due to its potentially reducing hidden externalities of production and transportation; the development of representational tools in terms of advances in computer aided design, simulation, analysis and manufacturing; and advances in production technologies. This paper focuses on how digital technologies are making stone a viable material for architects and designers.

Keywords: Stereotomy, Stone, Voussoir Geometry, Arches, Robotics

1 Introduction

Product of nature, stone has been a building and sculpting material throughout human history. Michelangelo Buonarroti completed the colossal figure of David from a block of Carrara marble hewn from a quarry that had produced stone for two thousand years. Carrara marble is currently highly regarded as a classical natural stone. In fact current researchers in the region such as Carrara Robotics¹ group developed robotic wire cutting based on prosthetic systems to carve into the stone. Wesley McGee director at the FABLAB in Taubman College University of Michigan wrote,

'Several researchers have tested applications for robotic wire sawing, but the capabilities of a robotically guided wire cutting operation to yield complex units in a finishes/semi finished state has not been studied extensively.' [1]

The integration of visualisation systems with the flexibility and portability of industrial robotic manipulators could produce unparalleled efficiencies in stone masonry.

This paper explores the four main factors of the revival in stereotomy frequently referring to current designers who are developing stereotomic methods, principally,

¹ Carrara Robotics based on Prosthetic systems: <http://carrara-robotics.com/>
<http://vimeo.com/94076571>

Giuseppe Fallacara, and also Philippe Block from the Block research group; the Hyperbody Research Group; and Professor Mark Burry work in the restoration and extension of the Basilica i Temple Expiatori de la Sagrada Família in Barcelona, Spain. Digital technologies are making stone an increasingly viable material for architects, this paper explores some advantages and limitations of working with stone.

2 The Aesthetics of Stone Cutting

The architectural preference for stone inevitably arose from stone's ubiquitous existence; it is symbolic, elemental. Attached to this are the streams of cultural, psychological and ecological associations. It is durable, low maintenance, many are visually pleasing, it's tactile and thermal qualities make it an enduringly desirable material. To an architect or sculptor's eye, some visually attractive features of stone blocks are flaws, leaving them structurally fragile. Small pieces of stone, which will not be used structurally, can be flawed and therefore beautiful; large blocks that will carry heavy loads must be free from flaws. The vital task of identifying flawed and flawless stone begins in the quarry.

At the time of the Renaissance it was common for architects and sculptors to travel long distances to visit quarries, select the stone blocks, and make arrangements for their transport. Michelangelo always visited the quarries. For a facade project in Florence, after sketching the design, he selected a team of quarrymen, and travelled into the mountains, cut the immense slabs he chose, then delicately and slowly slide them many miles to the building site. The marble had to be of "*good quality, white and beautiful, and without faults,*" [2]

The statue of David, carved by Michelangelo from 1501-1504, from a large block of Carrara marble quarried forty years earlier in the Apuan Alps of northern Tuscany. Agostino di Duccio received the commission in the 1460s, roughed out the figure in the quarry to reduce the weight before transportation into Florence. Duccio abandoned this half cut stone and it remained in Florence until Michelangelo inherited it. Therefore the task that Michelangelo had in front of him was to find a figure sculpture inside a rough and irregular chunk of stone. Making the choices about how to cut back the stone is the art of stereotomy.

2.1 Stereotomy Defined

Stereotomy can be simply defined as the art of cutting solids. In relation to architectural construction, it is a set of geometric instructions and techniques of drawing and cutting blocks of stone for their assembly into complex structures. It has its origins as a French term combining two Greek words meaning 'stereos'(solid) and 'tomy'(cut).²

The earliest and most influential texts on cutting geometrical solids is Euclid's 3rd Century BC texts³. Although there is no unambiguous literary evidence for

² Greek: στερεός (*stereós*) "solid" and τομή (*tomē*) "cut "

³ Euclid: Greek (Εὐκλείδης) (Four Books of Conics by Euclid 300 BC)

theorizations of stereotomy between the Classical eras and seventeenth century France, Euclid's works were likely to have been the core texts for the practice of stone masonry.

The French term has its origin in Philibert de L'Orme's 1567 treatise on architecture.⁴ Although Fallacara does not suggest "*a direct geometrical connection between Euclid and de L'Orme*", rather, that L'Orme had an interest in "*Euclid's work, considering it a very high digest of methodological rigor.*" [3] This conception of stereotomy is far more abstract than Michelangelo's direct engagement with the stone and leads us into the problem of representation.

Sakarovitch in his paper, 'Stereotomy, a multifaceted technique' describes stereotomy as "*the art of drawing the shapes to be given to stones (and bricks) for future assembly*" [4] which also includes aspects of structural analysis.

3 Externalities

In economics an unpriced externality is any cost associated with the production of material that doesn't have a direct financial impact for example the pollution of the environment. One of the key drives towards making the economy and the physical environment more sustainable is to turn unpriced externalities into priced externalities for example making manufacturers pay for their pollution. Considering the vast interconnectedness of manufacturing processes calculating all the externalities is exceedingly complex.

Professor Geoff Hammond and Craig Jones of the Sustainable Energy Research team (SERT) at the Department of Mechanical Engineering, University of Bath, UK created an inventory of the carbon and embodied energy found in common construction materials. They define embodied energy as the "*total primary energy consumed(carbon released) over its life cycle...known as 'Cradle- to-Grave'.*" [5]

Table 1: Comparison of embodied Energy of various building materials [5]

Materials	Embodied Energy Co-efficient EE-MJ/Kg
<i>Stone</i>	<i>1.00</i>
<i>Concrete</i>	<i>1.39</i>
<i>Clay Bricks</i>	<i>3.00</i>
<i>Autoclaved aerated concrete blocks</i>	<i>3.50</i>
<i>Plasterboard</i>	<i>6.75</i>
<i>Timber</i>	<i>8.5</i>
<i>Glass</i>	<i>15.0</i>
<i>Steel</i>	<i>35.3</i>
<i>Plastic</i>	<i>80.50</i>
<i>Aluminum</i>	<i>218.00</i>

⁴ Philibert de L'Orme is attributed with the origin of the stereotomic discipline. [3] Original text: The First Volume on Architecture of Philibert De L'Orme, Paris, 1567

Table 1 reveals the low embodied energy of stone compared to other building materials which is an advantage in construction appeal. Sustainable building practice must include the costs of these negative externalities and produce an architecture that is truly cheaper, not just temporarily cheaper given the regulatory conditions.

Giuseppe Fallacara, also describes the current situation and renewed interest in stone in terms of its ecological and sustainable values:

'The ecological qualities of stone are compelling: unparalleled durability, natural cooling, lack of pollution by toxic waste. The use of stone can reinforce the genius of the place by providing new buildings, however modern in form, that blend with the colour, texture, and materiality of the past'. [6]

4 Representational Tools

Stereotomy as a discipline of study is inherently, and increasingly, abstract. Through the nineteenth and twentieth centuries, it became largely an exercise in descriptive mathematics, with decreasing relevance to the material process of masonry. It is logical that the vast majority of highly skilled masons across the centuries were, or could have been, functionally illiterate and ignorant of mathematics. Their training was practical and physical. They gained their skills through intensive four-dimensional engagement, not through the study of two dimensional representations.

The usefulness of a book on stereotomy is inherently limited. A linear sequence of two dimensional representations is an inadequate manner of communicating wholly four dimensional problems. Perhaps responding to the limiting costs associated with printed illustrations, and an academic interest in mathematics, many stereotomy texts are works of applied mathematics. S. Edward Warren's 1875 book, 'Stereotomy - Problems in Stone Cutting', contains a little over one hundred pages and only twenty six illustrations; the book no doubt would be more useful if these numbers were reversed. A.W. French and H.C. Ives' 1913 'Stereotomy', a similar book of similar length, certainly improved the situation by including forty five illustrations, but the fundamental problem remained.

While the field of stereotomy languished in this half practical, half geometrical condition, the field of descriptive geometry, which academic stereometers pursued, ultimately contributed to the mathematical operations underlying digital modelling tools available today. These advances in mathematical representation have made stereotomic study available to people who do not have extensive knowledge of advanced geometry.

4.1 Gaudi and CAD

Antoni Gaudi based his geometry on hyperboloids, paraboloids, and hyperbolic paraboloids which closely resembles catenary curvature tracing the arch's line of thrust. The geometrical problems of working with hyperboloids, paraboloids, and hyperbolic paraboloids are not covered in Euclid's work. This means that most

masons were likely to have been unprepared to produce these shapes and that the graphical technique for the layout drawings was insufficient for the task. This may explain why Gaudi worked with models. As the work undertaken today⁵ is the effective reverse engineering of Gaudi's models, a graphic technique was developed by his successors. Burry states,

'Such graphic techniques were the tools of the stereotomers of the past but the graphic technique for the intersection, for example between a sphere and cone, could not be adapted for the intersection between a circular and elliptical hyperboloid inclined differently with respect to the datum plane.' [7]

Burry further explains that the benefits of computational models are the ready application of such tools to diverse aspects of the construction process: automated manufacture, calculation of volume and mass of the irregular shaped pieces, and the calculation of the centre of gravity to facilitate the correctly orientated hoisting of the heavy masonry pieces. It is a combination of a surface and solid modelling facility which is now making a significant impact on the working method. Solid modelling Computer Aided Design(CAD) tools can replicate the plaster model-makers methodology almost exactly, making them more likely to be used by architects investigating the potential for modern stereotomic practices. Computational modelling also enables an opportunity to work in a 'parametric' rather than 'explicit' environment. This is where the object can be described as a series of relationships to which dimensional values can be given later and changed at will. *"This facility elevates the tool from working slavishly to a known intention to working more intuitively with the designer's considerations."* [7] The models produced on the screen from these software programs can then be used to drive saws or mills directly and fashion either a model, a prototype, mould or finally the finished article.

5 Cutting Technologies

The return of stereotomy is largely due to the improvement of representational tools, with the application of these representational tools the material problems of the stone mason will become the pathway to revive the stalled tradition of stone architecture. As Fallacara states:

'Once a slow and painstaking process of cutting each stone by hand, now stone masonry can proceed rapidly with computer-guided cutters that can fashion more complex shapes than a person working manually with hand-held tools. And computer graphics enable architects to explore sophisticated forms, while subjecting them to static analysis for safety' [6].

⁵ Work undertaken today of the Sagrada Familia began in 1979: <http://mcburry.net/overview/>

5.1 Stone Cutting

As far as we can see, the segmented arch and the tunnel vault also known as a barrel vault first appear as brick constructions in the 3rd millennium BC in regions where there was a shortage of wood, such as Mesopotamia and the valley of the Nile. Stereotomic stone cutting developed with the introduction of the *vousoir*. A *vousoir* is defined as a “wedge shaped stone with two oblique faces by means of which it rests on the adjacent *vousoirs*, laterally transferring the vertical forces due to its own weight and any other loads.” [8] Figure 1 illustrates a segmented arch composed of four *vousoirs* either side of a central key stone.

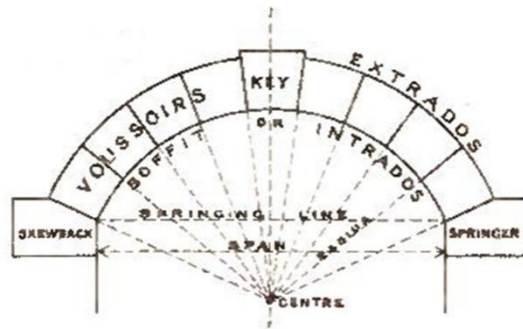


Figure 1: Segmented Arch with defined terms: [9]

The problem faced by medieval builders in the realization of vaults was how to cut the *vousoirs* constituting a structure. Aita implies that the medieval builders answered the structural questions, coincidentally by solving the geometrical problems: symmetry, stability, material resistance and equilibrium of forces. Jacques Heymen, in ‘The Stone Skeleton’ describing the design requirements for masonry arches, “failure of a masonry structure will occur when the line of thrust can no longer be contained within the stonework.” [10] He then describes in terms of design principles certain assumptions which can be made about the material. These include:

- (1) Stone has no tensile strength (assuming that the arch *vousoirs* are laid dry or with very little mortar).
- (2) The compressive strength of stone is effectively infinite.
- (3) Sliding of one stone upon another cannot occur. It implies that wherever there is a weak plane, for example between *vousoirs*, the line of thrust should not depart too far from normality to that plane.

5.2 Digital Stereotomy

The development of custom hardware for digital stereotomy is being explored by the Block research group in an experimental setup for automated fabrication of voussoir geometry for freeform masonry-like vaults. Through a combination of form finding techniques such as Thrust Network Analysis (TNA) and a four-axes computer numerical controlled (CNC) hot wire cutting technology, stereotomic methods driven directly by digital technology are being investigated. Specifically the geometrical interdependencies between the generation of the voussoirs and the physical limitations of the fabrication on the basis of structural information. *“The principle is tested physically by cutting individual foam blocks, simulating the rapid and efficient cutting of natural stone with a diamond wire saw.”* [11]

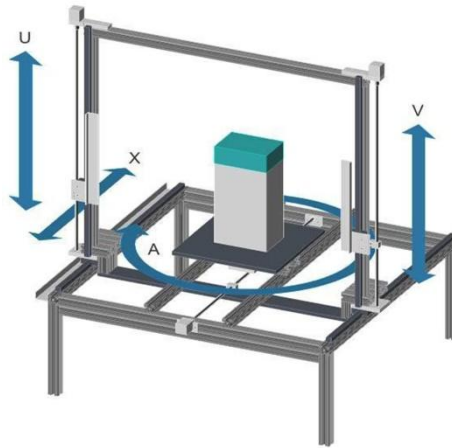


Figure 2: Customized 4 axes CNC wire cutter [11]

McGee et al. (2012) discusses several architectural processes, conceptual motivations, tools and techniques for the production of architectural volume. Using an inexpensive material Expanded Polystyrene (EPS) foam, which can be cut with a hotwire, *“provides a method whose historical precedent can be associated with stereotomy and the developed surface of traditional stone masonry.”* [1] Robotic hotwire cutting (RHWC) was explored as an efficient method as opposed to dedicated CNC machining. This has many advantages over traditional CNC milling at an architectural scale including reduced machining time, and a better surface finish. Whilst limitations may include higher production times, the limiting of available geometries to ruled surfaces and inaccuracies caused when dealing with the material variability.

The RDM Vault as shown in Figure 3, a collaborative project between Hyperbody and ROK- Rippmann Oesterle Knausse/ ETH Zurich, makes use of RHWC and explores a joint approach to the design and fabrication of vaulting

structures. This is where the components are nested completely within a volumetric block of material. Although this technique is limited to ruled geometries, the entire exterior of the component is shaped, and thus the aggregation can more accurately approximate a freeform surface. In this case the use of a robotic arm “*typically costs less than half the price of a typically capable dedicated CNC machine.*” [1]



Figure 3: RDM Vault [1]

Comparing the above approaches of Burry, Block and McGee et al raises the question of whether the same result can be set up with an industrial robot arm. In the case of Block “*A customised machine setup was developed in respect to the technological, economical, and ecological relevant fabrication constraints.*” [11] Burry states in regards to the stereotomic opportunities for the stone masons to sculpt and cut straight lines on corresponding 2D templates or “*to automate this cutting process using contemporary robot stone cutting equipment.*” [12]

McGee et al used a 6-axes robot arm and states that, ‘*Dedicated CNC approaches are likely to always possess an advantage in terms of accuracy and overall capacity, but there are potential applications where the flexibility and portability offered by industrial robotic manipulators can fill a unique role in fabrication. Several researchers have tested applications for robotic wire sawing, but the capabilities of a robotically guided wire cutting operation to yield complex units in a finishes/semi finished state has not been studied extensively.*’ [1]

In addition to the advantages outlined by McGee et al, the use of robot arms for fabrication has lowered the barrier to entry for architectural researchers and practitioners alike, as demonstrated by the establishment of the Robots in Architecture Association and international conference in 2012. The standard hardware platform, combined with integration layers for common CAD software, creates new opportunities for architects to experiment with novel stereotomic approaches.

6 Conclusion

The revival of stereotomy in the architectural discipline is due to four main factors. The aesthetic value; hidden externalities in production and transport influenced by sustainability; advancement of representational tools and developments in cutting technologies based on the industrial robot arm.

The change in the aesthetic value of stone is difficult to trace across the centuries. However it has always been a part of architectural construction, and we can speculate that it is inevitable that it will continue to be so in the future.

If we anticipate the actual cost of the production of goods will be reflected in their market pricing, that unpriced externalities will become priced, the very low embodied energy of stone will lead to its relative price decrease compared to other building materials.

The recent rapid rise of 3D modelling software and sophisticated digitally controlled tooling and cutting technologies adopted from the automation industry, allows for more complex structural investigation and form finding techniques. The instructional properties of software combined with a robotic arm can perhaps be compared to the methods in creating custom hardware in the development of stereotomic techniques cutting techniques.

The developments in computational tools have enabled the study of stereotomy to be more readily accessible to those who do not necessarily have the knowledge of advanced geometry. This consequently makes stereotomic information more widely appreciated and potentially used in the construction industry to create more varied, cost effective and sustainable solutions.

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