Stereotomic vaults

Using digital tools to customize artificial stone blocks

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Il mondo sta affrontando sfide ambientali complesse: si stima che, solo nel settore delle costruzioni, il cemento e l'acciaio siano responsabili di oltre il 10% delle emissioni globali. Guardando indietro ai modelli costruttivi tradizionali, troviamo che la pietra è un materiale affidabile fin dai tempi antichi. Il ripensamento generale dei materiali e dei sistemi costruttivi conduce il paper verso l'ipotesi di una nuova architettura stereotomica in pietra.
A partire dalla tecnica digitale per la produzione di conci a ridotto sfrido di materiale si descrivono, infine, gli esiti della ricerca sperimentale che ha portato alla produzione di uno stampo a geometria variabile utilizzabile per la pietra artificiale.

Stereotomia, Fabbricazione digitale, Progettazione computazionale, Cambiamento climatico, Stampo

The world is facing extreme environmental challenges and, within the construction sector only, predominant materials such as cement and steel account for more than 10% of global emissions, catering for a need to change. By looking backwards in time, to practices before these materials were introduced, we find in stone a reliable material since antiquity. To avoid unnecessary embodied carbon materials in spans, such as roofs and slabs, stereotomic vaults are proposed in this paper, introducing techniques to create voussoirs while reducing resources and waste. A set of experiments illustrate the concept of a variable geometry mould usable for artificial stone, breathing new life into centuries old concepts of structural stone.

Stereotomy, Digital fabrication, Computational design, Climate change, Mould

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Introduction – Problem

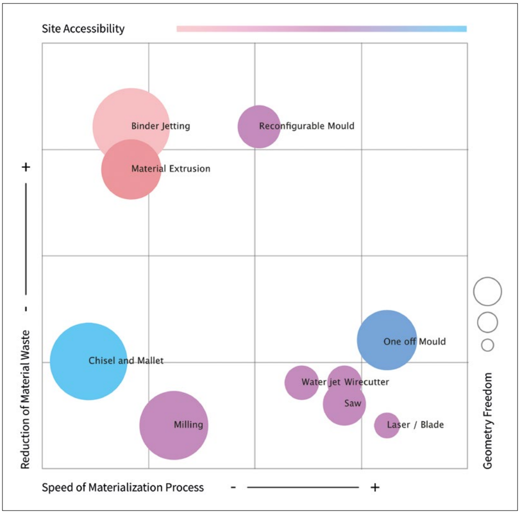
Climate change is one of the most important challenges of mankind, and the construction industry accounts for 6% of the total CO2e emissions ("Climate Watch" n.d.) inciting research on the mitigation this environmental impact. Special attention is taken by the heavy energy and carbon embodied materials widely used in reinforced concrete: steel and cement (Van Ruijven et al., 2016, p. 15). Although instrumental in the advancement of architecture and building technology in the recent past, these materials are also responsible for enormous quantities of energy spent in their production. An environmentally feasible material, when locally sourced, able to span large spaces is wood. However, the fire and rotting resistance of stone comparing to wood, the perceived nobility of stone as a material, and the architectonic expression of a construction whose time span of existence surpasses the ephemeral human presence in the mortal world in a clear eloquent reference towards Vitruvius' firmitas, has given stone structures a special place in construction history.

Stone's neutral environmental impact is joined by a longevity well attested through the observation of the architraves in Egyptian or Greek architecture, the arches of Roman aqueducts and bridges, or the stone vaults which evolved from the late Romans into medieval cathedrals complex vaults.

Classical Stereotomy

The technique to use carefully cut stone to realize ever more complex vaulting structures came to be known as stereotomy. The geometry of each of these stones, called voussoirs, carefully shaped in flat and curved surfaces, allows them to fit with other voussoirs and correctly drive the weight forces through the structure into walls, columns and eventually to the ground. The development of this art, had a symbiotic relationship with the development of geometry itself, and it can be said that Descriptive Geometry is a product of stereotomic development (Sakarovitch, 1998, p. 241). The refined development of stereotomic geometry allowed for complex realisations, of which the orthogonal semi-circular arch was an old memory. However the introduction of new materials with a strong flexural strength, such as steel and reinforced concrete, allowed for less structurally optimized shapes, or to solve a span with one elements which would otherwise require multiple smaller voussoirs in the case of stone construction. These changes in design and construction approach reduced the need for a highly refined, particular geometry for each building block, thus contributing to the growing scarcity of stereotomic design and cutting knowledge.

01

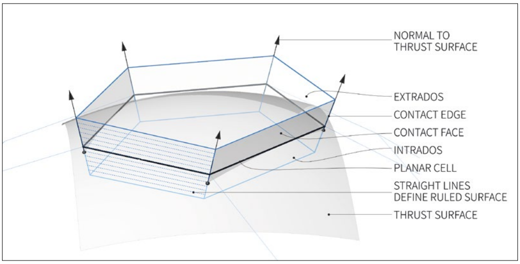


01
Various materialisation processes compared according to four factors

02
Constituent parts of a typical voussoir

Digital Age

The Second Industrial Revolution allowed for the production of mass standardised steel elements, catering for an Architecture of standard measures and angles itself. However, The third Industrial Revolution allowed for the development of computers and computer driven machines. Instead of relying in repetition and modularization, architects such as Lars Spuybroek or Frank O. Gehry used innovative digital technologies to design and materialize buildings which depend in bespoke construction elements, much akin to the stereotomic approach before mass standardization.
These possibilities sparked the imagination of researchers interested in the history of construction and architecture who, whether through computation (Trevisan, 1996, p. 1) or declarative modelling and digital fabrication (Fallacara, 2003, p. 213), revived ideas of stereotomy in contemporary times. The possibility of having a digitally controlled ma-



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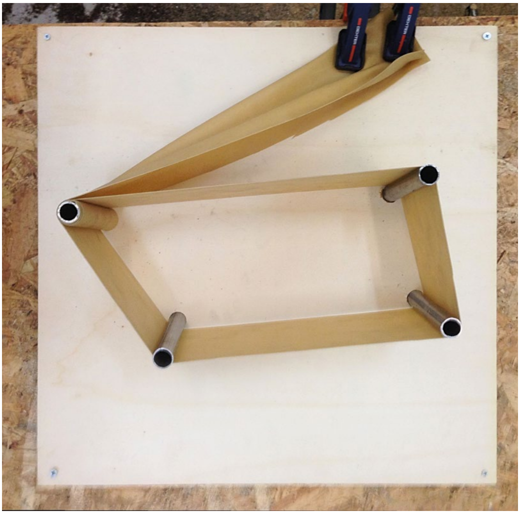
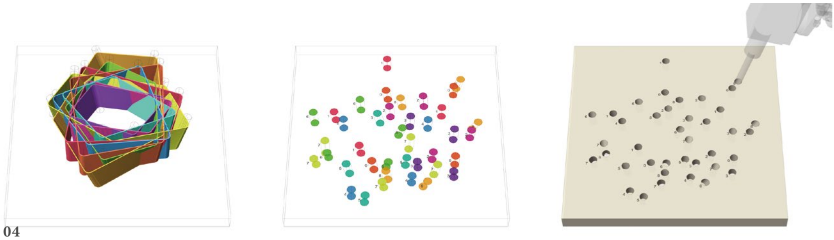


03
Proof of concept model to test the adaptation of the rubber band to the desired contact face geometry

chine cutting a block of stone also potentially widens the spectrum of geometries a voussoir may exhibit, in contrast to the lesser geometries able to be reproduced by hand labour. Since these seminal experiments, an augmentation of stereotomic related possibilities have been explored in the design and materialization fields. Algorithmic models are able to tackle the specific geometry of hundreds of voussoirs under a specific design, aided by the usage of CNC machines equipped with different tools and materials, as pointed by Fallacara and Barberio (2018, p. 9). This set of changes have allowed architects to introduce challenging designs and rethink stereotomy beyond its classical definitions, while keeping its principles and advantages.
In the pursuit of making stereotomic construction an updated feasible alternative to current steel and concrete approaches, its applicability must be maximized. For this research, four vectors were analysed: technology accessibility, material waste, speed and geometric freedom. Having environmental issues as a staple, the chart in fig. 01 shows additive fabrication or reconfigurable moulds' strength as an efficient technology to produce voussoirs. This research illustrates one of these methods, reconfigurable moulds, from its inception until a matured stage of prototypical production.

Cast stone as a solution

The purpose of this research is to explore the concept of a mould which reduces cast material waste and time/energy in the production of multiple moulds. As such, the inclu-



04

sion of capability of adaptation to different variable geometries is important to allow for the efficient reuse of a mould for multiple customised blocks.

A brief survey of variable mould technology shows three different strategies: pin-type tooling controlled surface (Pedersen et al., 2010, p. 6), reusable formed sand (Oesterle et al., 2012, p. 263), and elastically controlled ruled surfaces (Loh et al., 2018, p. 738). In all of these examples, the variable part of the mould corresponds to a large surface, identifiable in a voussoir as the intrados.

Although the intrados is part of the visible vault surface [fig. 02], stereotomic construction efficiency is dependent on the correct transfer of loads between voussoirs, through juxtaposed contact faces. As such, a controlled geometric accuracy in the contact faces is the focus of the researched mould system.

In order to avoid inaccuracies in the reconfigurable mold, the geometric idea line as shortest path between two points is used. Looking at fig. 02, the linear nature of the planar cell may be transposed to a surface by moving it in space along the contact edges, assumed to be normal to the thrust surface itself (Rippmann, 2016, p. 190).

The validity of the proposed new mould system is attested by the accuracy of the fabricated voussoirs, in this case be-

04
a) All bands in same board generate hole overlapping
b) solution found with a genetic algorithm for non-overlapping holes
c) milling preview

05
Assembled vault:
a) general perspective
b) top view
c) detail of edge, exposing the cylindrical voids;
d) bottom view of centre vertex

05

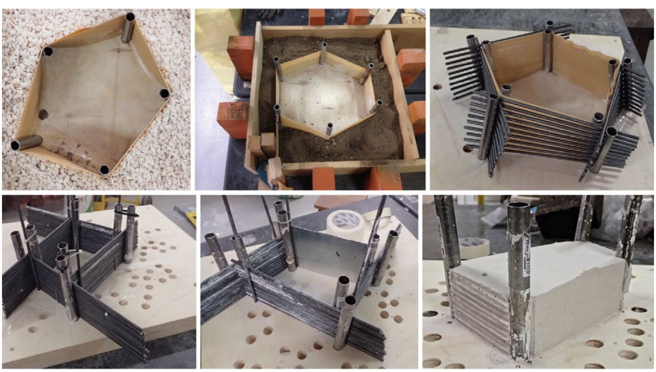
longing to an asymmetrical three legged vault composed of nine voussoirs.

Flexible Conoid Contact Faces

The first experiment draws on a simple idea: to stretch a membrane around contact edges, thus recreating the necessary voussoir geometry. This simple idea was materialize For the materialization of the contact edges, steel tubes are inserted in specially angled holes, drilled in a base plate with a mill mounted in a 6-axis robot. For the assembly of each mould, a group of as many holes as contact edges is needed, allowing for an optimization of the base plate area by placing as many holes as possible in the same plate. A genetic algorithm is used for the calculation of a layout that encompasses all necessary drills in the same wood board. In fig. 04 we can see different moulding stages represented with different colors, as well as its corresponding holes.

The drilling of the holes by a robotic arm is the last stage of a continuous digital flow encapsulated in one singular algorithm. This code starts by the design of the vault with the help of computational simulation of a stereo funicular network, continues by transforming the network into a solid representation of the vault with its various voussoirs and inherent angles, uses each group of contact edges as inputs for the genetic algorithm that calculates the layout of the drilling stage, and finally creates specific CAM instructions for the digital fabrication of these holes.

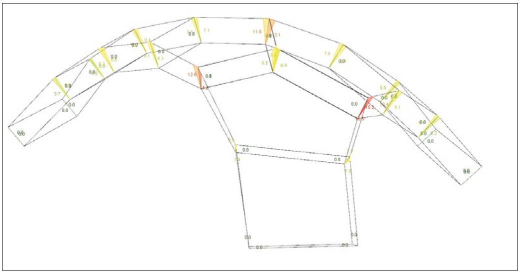
After the drilling of the holes, the mould assembly takes place. The tubes are inserted in the corresponding holes, the rubber membrane is wrapped around them and the system is sealed. After the casting and curing, the apparatus is disassembled, showing the finished voussoir and its characterising holed edges, tectonic signifiers of its materialisation



06

06
Experiments on reducing deformities in the mould surface:
a) gravel
b) earth
c) rods and membrane
d) only rods
e,f) rods and sheet metal

07



07
Calculation of angles between contact edge and normal to adjacent intrados edge

process. Some imperfections and undulations in the contact surfaces do not prevent the nine voussoirs, all different in shape and size, to be assembled in a stable vault [fig. 05].

Exploration of Mould Surfaces

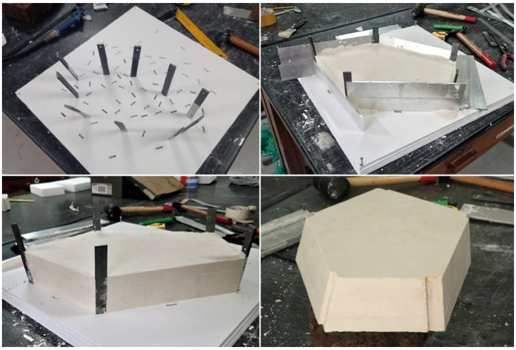
The accuracy shortcomings in the above experience called for a revision of the system which could cater for a more reliable materialisation of the contact surfaces.
Various experiments illustrated in fig. 06 called to counter effect the bulging out effect caused by difference in pressure between the inner and outer side of the membrane.
A final experiment, composed of a mould sealed in three sides with a rod system and in one of the sides with a tentative sheet metal system produced a finish near perfect and suitable for the fitting of stereotomic blocks against each other, as an efficient flow of forces would be transferred through the totality of the contact surface.
The observations made to this final experiment gave clues to the creation of a system based in rigid metallic bars. This rigidity potentially negates the possibility of torsion fo the mould surface and, thus, of using a skew ruled surface in favour of a planar surface. Although using planar surfaces as contacts faces could slightly reduce the freedom of design of a stereotomic structure, this is mitigated by the usage of planarizing algorithms. The adoption of such strategies allows for the adoption of rigid planar bars as reinforcements, which also allow for thinner and planar contact edges guides.

Rigid Planar Contact Faces

Following the successful application of rigid elements, a new mould system was designed. The number of holes was multiplied by 1.5x, but their footprint was reduced dramatically. These changes called for a revision of the algorithm that finds a solution for the layout of multiple holes in the same base plate. A more efficient system was designed with particle physic as a driving engine, using repulsion forces to keep set of holes apart from each other; this strategy revealed to produce much quicker and efficient results. After the drilling of the new types of holes, the process followed the same principles as the ones described in the chapter Flexible Conoid Contact Faces. However, this moulding system did not require the stretching of rubber, tape, or the wrapping by a ratchet strap. In this case, after inserting the parallelepipedic bars, the rigid planar contact surface bars are simply fit between the support bars, ensuring a tight fit. While the flexible mould adapts easily to any angle, the rigid planar bars feature an orthogonal end and their adaptation to angles is compromised with the width of the support bars. As such, the model contemplated this constraint, and the maximum angles between contact edges and adjacent contact face normal to intrados was calculated to ensure feasibility and avoid spillages, as seen in fig. 07. Additionally, these gaps were filled with was to avoid dents in the mould. Following the same mould disassemble procedure, the fabricated voussoirs exhibited perfectly finished planar surfaces, which naturally resulted in a zero compromise fit between contact faces, as seen in Fig. 8. The vault was assembled, verifying the accuracy of the mould system which created voussoirs with nearly zero waste.

Conclusions

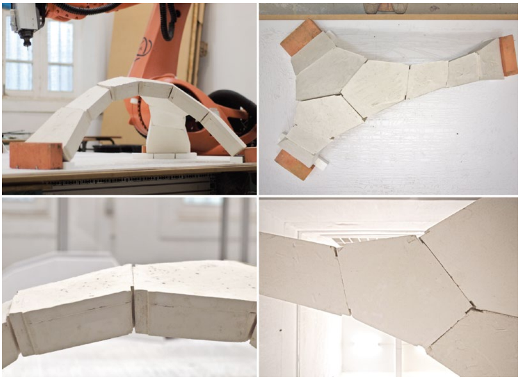
Stone has long been the material synonym of perenniality. However, this notion of indifference towards time belongs to the material itself, and not to the human relationship with it. Carving stone to build is an act eventually as old as architecture itself, lending these fabricated stone across millennia to serve as testimonies to the human development in both technological and artistic approaches. The set of experiments here described show but one more chapter in the relation of man with stone. Instead of subtracting material from a large rock, this research suggests that stone voussoirs



08

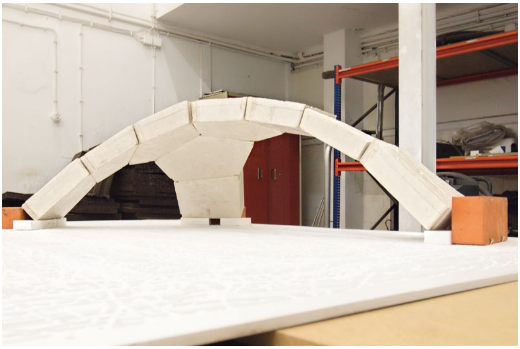
08
a) Steel bars in base plate
b) planar aluminium bars, with voussoir already cast
c) aluminium bars removed
d) finished voussoir

09



09
Assembled vault test. Notice the detail of the flush contact faces and the small footprint left by the vertical supports

10
Planar TriArch built with plaster voussoirs



10

may be obtained by moulding crushed stone with processes such as artificial stone, or geopolymer based materials. This change of attitude is directly related to a more environmental conscious where high embodied energy materials such as steel or cement are avoided, much as unnecessary mining or waste of stone in subtractive fabrication methods. This research contributes to solving current environmental problems by presenting methods inspired in the history of stone construction, and updating it to today's possibilities showing the continuously evolving relation between man and stone through time.

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