Stereotomic BIM – a tool for designing low carbon architecture

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Abstract. This paper focuses on the development of a BIM (Building Information Modeling) tool for stereotomic design, aiming to create a bridge between academic research and practical implementation of stereotomy in the construction sector. The creation of a stereotomic BIM tool enhances the use of compressive materials within funicular shapes to minimize reliance on carbon-intensive steel-reinforced concrete slabs. The proposed BIM tool enables architects to design and visualize stereotomic systems, addressing challenges such as architectural specificity and technological expertise. Architects can work from initial shape concepts to the precise geometric definition of elements, benefiting from the interactive adjustment of subdivisions and considering materialization and assembly specifics. This approach aligns with the Industry 4.0 paradigm, contributing to both sustainable development goals and the evolution of construction practices.

Keywords: BIM adoption, Stereotomy, Generative design, Parametric design, Sustainability.

1   Introduction

1.1   The case for a low carbon architecture

Reinforced concrete is accepted as a major contributor to climate change (World Resources Institute, 2021). Research into construction technology is addressing this problem, targeting different vectors of approach such as using greener materials, lowering energy consumption of construction, or maintaining comfort conditions. The common goal of these different efforts is to reduce the number of resources needed, be them material or energetic. Looking into

construction materials, the main contributor in amount of CO_2 tones per year is reinforced concrete, whose ingredients cement and steel are major consumers of energy. Mining for these materials takes a big toll in the local environment, but it is the high temperatures necessary to transform limestone into cement, or iron and other metals into steel that are responsible for the greatest percentage in the carbon footprint.

Although many efforts have been made into creating greener versions of concrete, these researches approach on the dependency of a reinforced concrete approach to construction has been maintained, calling for alternative solutions based not only in different materials, but on different force demands which suggest different geometric shapes.

1.2 Compressive stereotomy as a viable solution

Inspired by architecture historic masonry techniques, Fallacara (2003) starts exploring stereotomic constructions in an updating effort of classic southern Italy stone construction, effectively introducing the digitalization of stereotomy. This idea of utilizing classic structural forms to overcome space by using geo based materials is also researched in the engineering side (Block, 2009), creating a renewed field of knowledge based in funicular structures, traditionally knows as vaults. Referencing innovators such as Gaudí, Guastavino or Isler, these structures are capable of spanning large spaces and withstand big weights using small amounts of expensive material; by expensive, we mean difficult to source, having a high energetic footprint, or featuring low circularity potential overall. A humble example of this potential is the ETH Zurich Pavilion in New Work by Hebel and Block (2014) where the voussoirs (structural blocks in a stereotomic construction) are made of waste cardboard.

Current stereotomic research has reached a development apex, as explained by Fallacara & Barberio (2018), and spectacular examples such as those by Pigram et al. (2012) or Clifford & McGee (2014) are exemplary to convince us of the feasibility of these structural systems as an alternative to carbon-heavy reinforced concrete slabs.

While understanding that expressive vaulted pavilions are not sufficient for the promotion of more compressive and low-carbon construction approaches, we follow the footprints of industrialized approaches for the replacement of concrete slabs by funicular designs (Costa et al., 2020; Rippmann et al., 2018) which implement updated stereotomic knowledge to fabrication and assembly strategies in the construction sector.

1.3 Hypothesis

This paper proposes digital tools that enable architects to narrow the gap between academic exploration and the construction sector. On one hand, digital tools have been instrumental in allowing researchers and innovators to design and build stereotomic shapes. Although Kilian (2003) developed specific C++

code to emulate hanging chains in CADenary, or Rippmann (2016) developed a Rhino plugin (RhinoVault) to create TNA stereotomic designs, these tools are too specialized, or out of reach for the average architect. This type of research works have already been successful in demonstrating the effectiveness and potential of using digital tools to power the introduction of stereotomic and other funicular constructions to the design lexicon of architects. However, this potential will not be leveraged while a culture of funicular building does not enter the architecture language. Starting with the Renaissance, architecture treatises were instrumental in disseminating new strategies, designs, or geometrical solutions to architecture challenges. Today, the computer software that the architect uses holds most of the geometric prowess he needs. The division of a segment in equal parts, or the drafting of an ellipse no longer pose difficulties, as CAD instantly provides the answer. However, CAD is no longer an innovation, but the technical basis for BIM, the current software paradigm used by architecture offices around the world. Building Information Modelling not only upgrades 2D (projections) drafting to full 3D models, but also provides these geometric entities with valuable semantic information about materials, finishes, structural function, and properties, among a plethora of other relevant construction related parameters. It is within this type of digital environment – currently dominated by Autodesk Revit and Graphisoft Archicad – that the average architect develops his designs, effectively replacing most of the previous work created in the drawing board or even with physical models. Although hand sketching or model making will hardly be totally replaced due to their intrinsic and irreplaceable qualities, an architect is usually dependent on the tools that his software provides, and most practitioners do not master programming languages. As such, this paper proposes the idea to integrate stereotomic arches or vaults into the BIM environment by creating specific tools and classes homologous to those such as Walls or Slabs.

2   Methodology

Looking at the general objective of implementing a fully working (Archicad or Revit) tool for designing stereotomic structures, we propose a methodology to subdivide this larger effort. A survey of digital tools for the creation of stereotomic designs will provide insight into digital helpers such as advantages and disadvantages within this; the careful proposal of stereotomic macro-shapes such as arches, flat vaults, or catenary vaults; the interactive adjustment of the subdivision; options targeted to specificities of materialization and assembly. All these options are evaluated under the Stereotomy Semantic Classification, SSC (Azambuja Varela, 2020) to cater to a unified and consistent development and implementation of stereotomic construction.

3   Initial planning of a Stereotomic BIM tool

3.1   Digital tools for stereotomy

There is a variety of tools to assist in creating funicular structures in CAD, starting with the aforementioned CADenary, Kangaroo, RhinoVAULT or Smartform. Following the inverted logic used by Kangaroo to simulate equilibrium in structures under compression only (also known as Gaudi's inverted chain models, hanging sheets by Isler, all within Hooke's springs law), other simulation tools may also recreate these shapes for visualization purposes such as Blender, Cinema4D or 3ds Max. Although these tools have proven to be efficient in the design of funicular structures, they fail to cater other important vectors within this research objectives: user accessibility, stereotomic specificity and fabrication documentation.

The average architect does not have access to the mentioned specialized tools because they demand months or years of training for efficient usage; to combat this shortcoming, we propose the integration of funicular functionality directly in BIM packages for easy and direct accessibility, which should also be integrated in new IFC classes. Generic funicular shells are only the starting point for a design, and unless the final built work is made of a paste like material, a detailed design is needed; in the case of prefabricated building components, stereotomic concepts come into play and they should be accessible for the architect to make design decisions to inform the final building proposal. Finally, a streamlined communication between the design team and the contractor should be powered by automatic fabrication documents in the form of quantities sheets or 3D models of each bespoke building component / block / voussoir.

3.2   Macro-shapes

Stereotomic design is classically bounded by categorizations observable in treatises, and more recently in contemporary classifications. Although this type of design is fertile in the advancement and proposal of innovative solutions, a BIM environment benefits from automation, which is proportionally more feasible as the amount of pre-knowledge of that system For example: although a window can be designed in infinite ways, we can assume the vast majority of opening types to fall under a little number of categories, such as side, top or bottom hanging – by offering these possibilities in the design tool, we are already catering to the vast majority of the market. Or even the design tool for a wall: by assuming that the opposite faces of a wall are parallel, most wall design needs are covered, while specific geometries might be manually modelled with other non-automatic tools. Having this is mind, an initial version of this tool would allow for the design of a set stereotomic shapes (arch, vault, stair flight) with a pre-defined subset of parametric options.

Depending on the BIM software, some of these architectural elements might be understood as belonging to other parent elements, or as independent elements. For example, a vaulted ceiling may be designed similarly as a slab, typically as an independent object in the floor plan. On the other hand, an arch might be planned as an independent element, like a beam, or as the head of a window or door; in the latter case, its location, span and depth will directly be derived from the window or door.

3.3   Stereotomic parameters

The design of stereotomic structures is inherently connected with the idea of parameters. In order to refer to a clear reference of these parameters, we may use the SSC. As such, besides general dimensions and shapes – such as floor plan boundary, height, thickness, or others – options such as the macro-shape generation method (BAA), surface subdivision (BC), or voussoir surface and perimeter design (CB and CC) can be directly correlated with the SSC. Other kinds of information, usually present in BIM Building Materials, can also be derived from the SSC, such as material sustainability (CAA), structural performance (CAB), or fabrication typology (CAC).

A	TOMOTECHNY	B	EQUILIBRIUM	C	VOUSSOIRS
AA	MATERIALIZATION PROCESSES	BA	MACRO-SHAPE	CA	MATERIAL
AAA	Subtractive	BAA	Generation method	CAA	Sustainability
AAAA	- 2D cut	BAAA	- Top down	CAAA	- Extraction
AAAAA	- Milling	BAAAA	- Constant Profile	CAAB	- Transportation
AAAAB	- Laser / Blade	BAAAB	- Varying Profile	CAAC	- Processing
AAAB	- 3D cut	BAAB	- Bottom up	CAAD	- Fabrication
AAABA	- Milling	BAABA	- Hanging model	CAB	Structural performance
AAABB	- Saw	BAABB	- Graphic statics	CABA	- Compression
AAABC	- Wirecutter	BAB	Continuity	CABB	- Tension
AAABD	- Water jet	BABA	- Segmented	CABC	- Weight
AAAC	- 3D carve	BABB	- Continuous	CAC	Material typology
AAACA	- Chisel and Mallet	BB	STRUCTURAL FUNCTIONING	CACA	- Subtractable materials
AAACB	- Milling	BBA	Compression only	CACB	- Formable materials
AAACC	- Saw	BBB	Compression and tension	CACC	- Addable materials
AAB	Additive	BBBA	- Tension resistant voussoirs	CB	INTRADOS AND EXTRADOS
AABA	- Material Extrusion	BBBB	- External reinforcement	CBA	Surface
AABB	- Binder Jetting	BBC	Tension only	CBAA	- Double Curvature
AAC	Formative	BC	SURFACE SUBDIVISION	CBAB	- Single Curvature
AACA	- One-off Mould	BCA	One level subdivision	CBAC	- Planar
AACB	- Reconfigurable Mould	BCAA	- Pattern	CBAD	- Textured
AB	CENTERING	BCAAA	- Periodic	CBB	Perimeter
ABA	Temporary	BCAAB	- Non-periodic	CBBA	- Concavity
ABAA	- Support structure below	BCAB	- Performative subdivision	CBBAA	- Convex
ABAAA	- Extruded grid	BCABA	- Curvature	CBBAB	- Concave
ABAAB	- Per-Voussoir	BCABB	- Aesthetics	CBBB	- Correspondence
ABAAC	- Along lines	BCABC	- Voussoir dimensions	CBBBA	- Analogous
ABAB	- Tensioned voussoirs above	BCB	Multiple level subdivision	CBBBB	- Differentiated
ABB	Permanent	BCBA	- Courses and voussoirs	CC	CONTACT SURFACE
ABBA	- Composite	BCBB	- Micro voussoirs within macro	CCA	Geometry
ABC	Inexistent	BD	FOUNDATION	CCAA	- Ruled
ABCA	- Self supported	BDA	Site fixation	CCAB	- Planar
ABCB	- Externally supported	BDAA	- Pre-existing static base	CCAC	- Composite
AC	TECHNICAL DRAWING METHOD	BDAB	- Purposed static base	CCB	Friction
ACA	2D	BDAC	- Tensioned springers	CCBA	- Smooth
ACAA	- Trait	BDAD	- Wall or lintel supports	CCBB	- Rough
ACAB	- Descriptive geometry	BDB	Springer	CCC	Mortar
ACB	3D	BDBA	- Materiality	CCCA	- Gap filling
ACBA	- Computerized model	BDBAA	- Same as voussoir	CCCB	- Binding
ACBB	- Computational model	BDBAB	- Different material	CCD	Interlock
		BDBB	- Geometry	CCDA	- Alignment
		BDBBA	- Subdivision conituinty	CCDB	- Sliding prevention
		BDBBB	- Specific design	CCDC	- Cantilevering

Figure 1. Stereotomic Semantic Classification showing the highlighted concepts transported to the Stereotomic BIM tool.

4   Tool prototype

A full stereotomic tool must allow for the design of various types of structures, as clarified in 3.2. For brevity reasons, this paper will detail the interaction scheme for the Vault tool. The flow of user input events is laid out in figure:
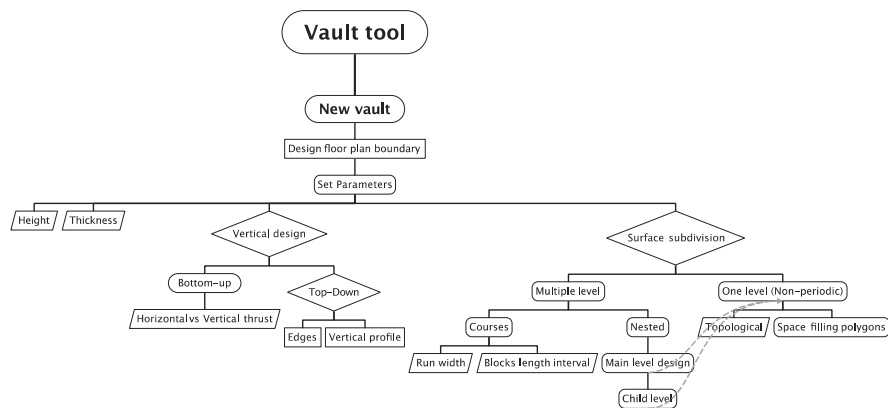

Figure 2. Flow chart of user interaction events in the usage of the Vault tool for element creation.

In the above chart, we can see different type of events, symbolized by different elements. The rectangle stands for drafting (geometry) input, the parallelogram asks for numerical input, and the capsule and the diamond present multiple options. Although the parameters scheme shown in Figure 2 could be easily implemented in a visual algorithm authoring tool like Grasshopper (visual programming tool present in Rhinoceros 3D, developed by Robert McNeel & Associates.), it is understood that a tool whose main objective is the promotion of stereotomy through its easification should be readily available in the most used architecture design software packages. As such, the visual prototyping of the tool interaction is illustrated in the case of Archicad, one of the mainstream BIM applications.
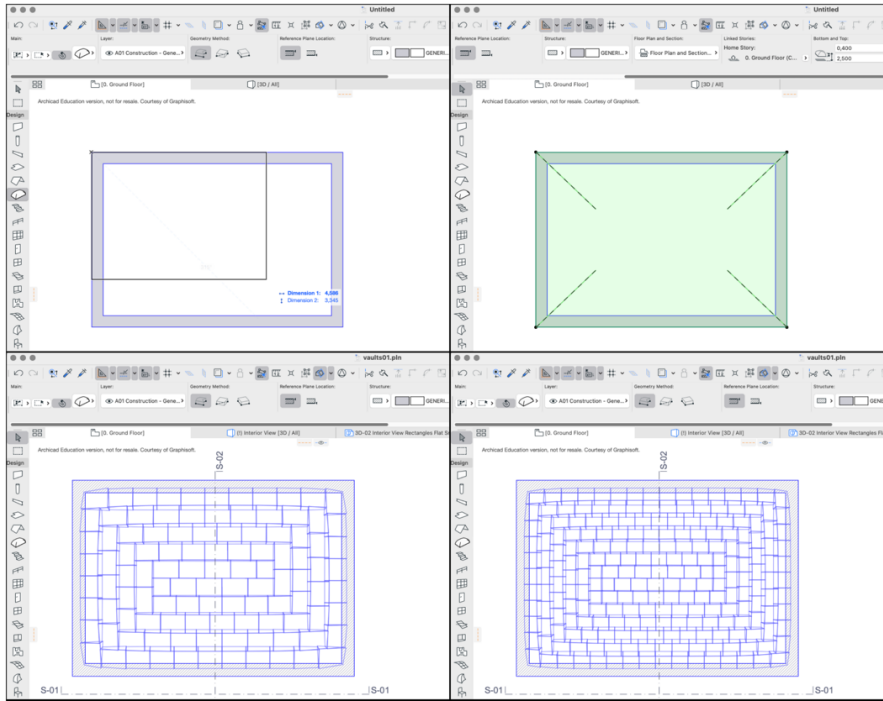
1258

Figure 3. Creation process in Archicad's plan view. a) A new vault is created using the rectangle option; b) The new vault is created, and still misses subdivision; c) A courses and voussoir subdivision is tested; d) A finer subdivision is created by changing the courses width and run length parameters.

Following the rationale behind the main construction components in Archicad – such as the wall, slab or beam – the first interaction prompts the user to graphically design the plan location of the element. In the case of the vault, the geometrical method is homologous to that of the slab: first, the horizontal projection is designed (Figure 3), and afterwards most vertical dimensions and characteristics are defined parametrically as see in Figure 4. This is where the semantics of stereotomy come into play, allowing for concepts such as Bottom-up vs Top-down design to be chosen, as well as allowing the user to choose the angle of the thrust discharge (Figure 5) which will eventually impact in the horizontal resistance demands of the support structure.
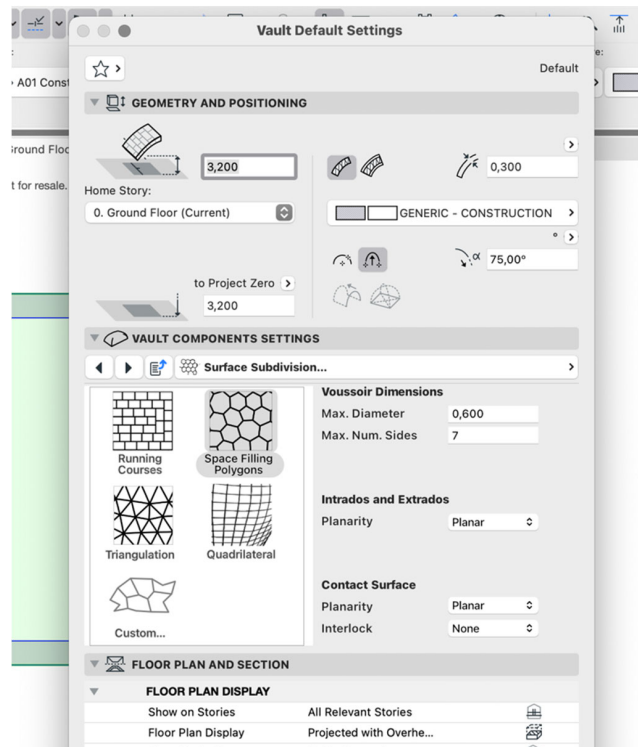
Figure 4. Settings window where the user can set the Vault object parameters such as Elevation, Thickness, or Vertical design. In the realm of Surface Subdivision, the right panel changes according to the type of subdivision chosen in the thumbnail area. The button above reading "Surface Subdivision" allows the iteration of other settings such as Springers, or Connection with Above Slab, for example.
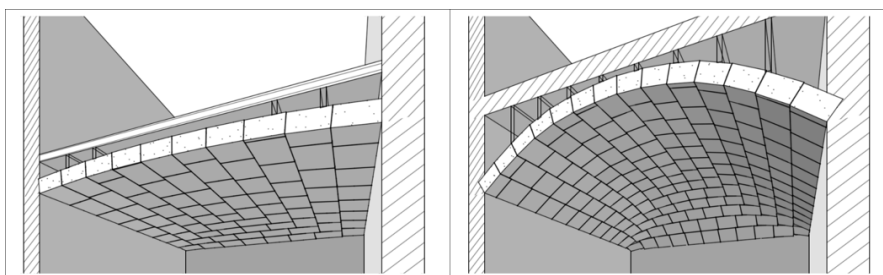

Figure 5. Perspective view with Cutting Plane activated of a course subdivided vault with variations in the parameters Thrust angle and Voussoir dimensions. Left: A flatter vault solution with larger voussoirs, where the horizontal thrusts require stronger walls or other kind of horizontal lock; Right: A vault with steeper thrust angle and smaller voussoirs.

The tool also allows the architect to choose an existing subdivision according to predefined strategies or specify his own. For example, Figure 6 shows a space filling polygons strategy which is generatively created upon a few parameters such as voussoir maximum diameter or intrados planarity.
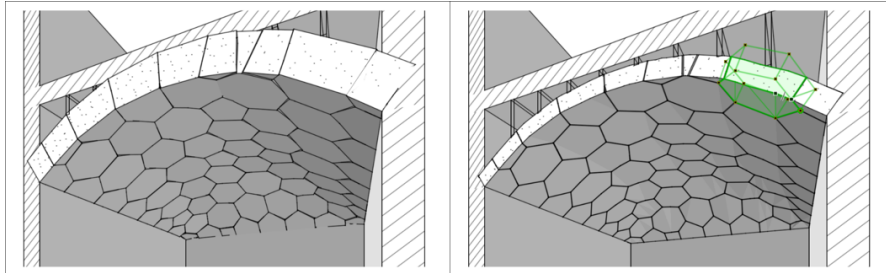

Figure 6. Perspective view with Cutting Plane activated of a Space filling polygons vault with variations in the parameters Thickness and Intrados Surface planarity. Left: A thicker vault featuring planar intrados voussoirs; Right: The same vault with thinner thickness and curved surface intrados, where an individual voussoir is highlighted.

5   Discussion

The design of a stereotomy BIM tool which serves as an interactive, modern version of classic treatises will aid architects in designing stereotomic systems from general shape to their subdivision and geometric definition of elements. Future avenues of research contemplate the detailing of options in a more complete Stereotomic tool, fabrication documents generation, or specification draft for IFC integration. Overall, the empowering of architects with tools that facilitate the integration of more sustainable building techniques will drive construction into the Industry 4.0 paradigm while contributing to many UN Sustainable Development Goals.

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