Digital Inca: An Assembly Method for Free-Form Geometries

Chapter · November 2015

DOI: 10.1007/978-3-319-24208-8_15

2 authors:

Brandon Clifford
Massachusetts Institute of Technology

Wes Mcgee
University of Michigan

Digital Inca: An Assembly Method for Free-Form Geometries

Brandon Clifford and Wes McGee

Abstract

Inca masons mastered a unique procedure of stone construction resulting in complex and precise configurations of visually zero-tolerance alignment. Each stone is nibbled away by a gradual transition of hammerstones from course to fine as the carving approaches a precise alignment on each edge at the visible face. Beyond this shared front edge, a gap opens to allow mortar to be packed in from behind for structural and setting purposes. These formations are limited to vertical walls as a result of the use of plumb technology. With so much current attention being focused on free-form geometries and procedural methods for masonry vaulting (Andriaenssens et al. 2014), this paper proposes a translation of the Inca wedge method into a digital process whereby stones align with each other to produce a global figure without the use of templating, falsework, or formwork. This differs from most conventional masonry processes whereby mortar is applied to units before positioning, allowing alignment to templates through the malleability of the mortar. Instead, units are dry fit to each other and then set in place. This inversion of the alignment procedure relies on precision carving of voussoirs to align with each other at specific moments in order to ensure proper self-assembly while simultaneously accepting mortar for setting. The resulting prototype shell structure is composed of uniquely carved voussoirs of autoclave-aerated concrete set with plaster in a similar manner to the Catalan and Guastavino methods. Previous research (Ramage 2006) has demonstrated the advantage of this lightweight material for vaulting purposes. The combination of this material property with the Inca assembly method

B. Clifford (✉)
Massachusetts Institute of Technology (MIT)/Matter Design, Boston, USA
e-mail: bcliffor@mit.edu

W. McGee
University of Michigan/Matter Design, Ann Arbor, USA

M.R. Thomsen et al. (eds.), *Modelling Behaviour*, DOI 10.1007/978-3-319-24208-8_15

results in an expedient assembly of complex shell structures. The potentials of this proof-of-concept suggests through results that future research can advance the intelligence of error aggregation through the aid of measuring, correcting, and carving throughout the assembly process just as the Incas constructed.

Introduction

Inca stonemasons held tremendous knowledge in a particular method of making resulting in timeless stone constructions. This architecture emerged from procedural logics that are sequential, rule-based, and adaptable; therefore aligning with contemporary topics in the integration of computation with fabrication. In recent years, significant attention is being paid to the capacity of computation to aid in the production of free-form shell structures, both virtually and physically. In translating the conceptual principles of compression-only structures into physicality, a series of hurdles commonly emerge. These include determining how to intelligently carve volumetric material into unique geometries that precisely align with each other in space, how to determine the sequence of assembly to maintain structural integrity, and as a result, how to reduce the waste of falsework and formwork. These hurdles are not new. They have existed throughout the history of spatial masonry construction. A paper (Rippmann and Block 2011) demonstrates the advantages of re-learning ancient knowledge—in that case it was the sixteenth century technique stereotomy. This influential text contributes to a consortium of research that is attempting to re-engage the topic of volume, not only for the vacuum of current knowledge in the topic, but for the potentials it serves to define space structurally. Other contributions include 'Stereotomy' (Fallacara 2012), 'Volumetric Robotics' (Clifford 2014), as well as papers like Feringa and Sondergaard (2014) and McGee et al. (2012). This paper seeks to mine the potentials of Inca masonry construction and identify which knowledge is capable of contributing to the hurdles listed above. In doing so, it explains an Inca method and prototypes this procedure with contemporary tools and materials. It proposes a translated method that employs ancient knowledge into a process to precisely carve Autoclave Aerated Concrete (AAC) with self-inscribed information to assemble free-form geometry shell structures without the aid of templating, falsework, or formwork, while ensuring structural stability.

Inca Architecture

There is a great deal of speculation surrounding Inca stonework. How did such a primitive civilization produce these precise mortar-less alignments as shown in Fig. 1 at a time prior to mechanization? A paper (Protzen and Nair 1997) examines this conundrum. These voluptuous assemblies are indicative of Inca architecture; however, similar examples can be found in other cultures that employed hammerstones instead of metal tools such as Egypt and Rapa Nui (Easter Island). The most archetypal works of the Incas exhibit a number of inventions as a result of their own technology. From the unique process of quarrying, to the fitting, dressing, and assembly of stone, the Inca rarify their technology to produce incredible works of architecture. Significant research in the field of archaeology has contributed to a better understanding of how the Inca constructed, most notably 'Inca Architecture and Construction at Ollantaytambo' (Protzen 1993) and 'Inca Architecture' (Gasparini and Margolies 1980).

Fig. 1 Inca wall construction in Cusco Peru

Hammerstones

Perhaps the central technology that defines the works of the Incas is the hammerstone. Outwater stated in 1959 that "[v]ery few tools are in evidence at the site [Kechiqhata]. There were some hammerstones of diorite but very few picks or wedges." (Outwater 1959, p. 28) Protzen later suggests these picks and wedges must have been from a later era, as there is "only scant evidence that the Incas split rocks with the aid of wedges." (Protzen 1985, p. 166) Instead, the Incas were carving stones with other stones, requiring a paradigm shift in our conception of stone carving. As Dean explains, "the In[c]a referred to the working of finely joined masonry as *canincakuchini*, which is derived from the verb *kanini* (*canini*), meaning to bite or nibble." (Dean 2010) Hammerstones are employed in two manners—drafting and dressing. Drafting is a technique whereby the hammerstone strikes close to the edge and around the perimeter of a stone in order to remove large portions of the stone as they blow out from the side. The other technique of dressing involves hammerstone striking relatively perpendicular to the face of the stone to nibble away at a rounded figure. This technique removes less material, but allows for greater precision and is typically employed in a progressive manner from course to fine where greater definition is required. There is a further technique of polishing, though not employed in the prototypes of this paper.

Quarrying and Configuring

Because the Inca were using hammerstones instead of metal picks or wooden wedges, the process of quarrying in the proper sense was rare. The majority of stone acquisition was done through a process of selection from loose rockfalls. The approximate stone is then dressed "only minimally before it was sent on its way to the construction site." (Protzen 1985, p. 165) The configuration of these stones is not pre-determined, but the result of a sequential assembly from the bottom up of irregular forms that are scribed and minimally carved to align with their neighbors.

Fitting

Stones can be site-dressed to fit by either carving the existing assembly to accommodate the quarried stone, or vice versa. Occasionally both methods are applied to a single fit. Two common theories exist that explain how the Inca determined the geometries needed to carve these unique units of construction. The first theory employs templates and the second requires dry-fitting. This is not to suggest that the Inca only used one of these methods. Instead it is highly likely the Incas employed both.

Templating

This common theory suggests that a wooden template is constructed to scribe the existing condition of either the assembled wall or the quarried stone. This template is then translated onto the stone that will be dressed to fit and used as a guide to approach the desired profile geometry. This process is ideal for stones that are too large to maneuver over and over again, but does not produce the same precision of the dry fitting approach.

Dry Fitting

One byproduct of the carving method of nibbling with hammerstones is a great deal of stonedust. In the dry fitting theory, as described by Protzen (1985) this stonedust coats the set stones while the loose stone is set into place. This stone is then removed and where the stone is touching the existing condition, the dust is compacted and visualizes where material needs to be removed. This is a tedious process and limits the size of the stones to something easily maneuverable. While this fit is more precise than the templating approach, it is also more laborious.

Finishing and Dressing: The Wedge Method

The use of hammerstones to draft and dress the stones results in three geometric conditions—face, edge, and wedge (Figure 2). As previously described, the sides of the stone are drafted to produce the approximate profile of the stone. This act of drafting removes cleft chunks of stone from the sides at obtuse angles to the cut. When precision is required, the stone is flipped over and dressed from the fact, progressively moving closer and closer to the desired geometry. This face dressing explains the most characteristic geometry of the Inca stonework—the rounded face. This rounding is not just a result of the carving method, but also preforms an important task of providing the distinctive chiaroscuro that disguise subtle misalignments that invariably happen upon assembly. The drafting and dressing produce the geometries of the cleft sides and the rounded face. The condition between these two is the most important—the edge. The edge is rather well defined, but is always produced at an

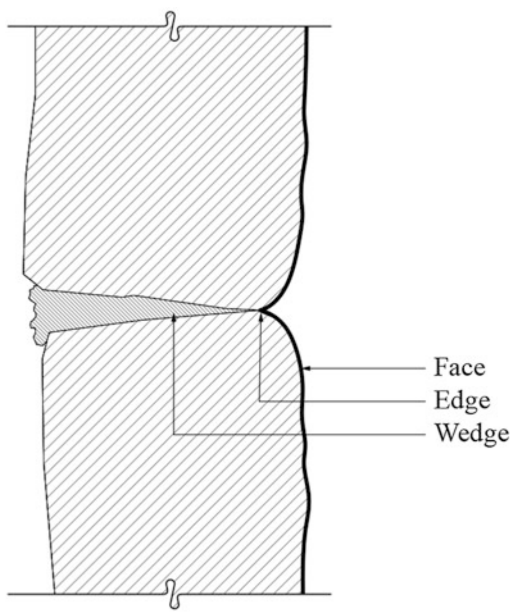


Fig. 2 Section through an Inca assembly revealing the three geometries

Fig. 3 A series of Inca constructions that reveal the voided wedge between stones

oblique angle. This edge is the only alignment between stones. The sides of the stone have been roughly drafted in order to not collide with their neighbors. This opening produces a negative wedge between stones that can be filled in with rubble from behind as shown in Fig. 3. Harth-terré introduces this *piedra-cuña* (wedge-stone) as the technique that allows the Inca masons to produce this illusion of apparently mortarless assembly (Harth-terré 1964).

Occasionally, the Inca did fit their stones with complete continuity from front to back, but these moments are rare. They are reserved for temple construction as well as the occasional corner condition. The rarity of these full-contact fits speaks to the difficulty of such an alignment. The wedge-method on the other hand takes less carving and fitting, but produces a similar visual result. It has one further advantage of privileging one side for visibility. In the case of the wedge construction, the back face of any stone is hidden inside the rubble, and therefore is not required to align to anything. It can be deep or shallow, depending n the needs of the visible face; a variable this paper employs.

Mortar Bed Versus Dry Fit

While it is commonly assumed that there is no mortar between the joints of these Inca walls, this is not true. This wedge simply disguises the mortar to the visible face. Even though the Inca constructions do contain mortar; the logic differs greatly from the conventional mortar bed approach. In conventional masonry, standard units are set into a mortar bed that employs viscosity in order to align the stone to a global goal—typically a horizontal string. This method uses the variability of the mortar joint to adjust for the imprecision of the unit. The Inca process shifts alignment from the process of setting to the process of fitting. Precision carving allows the stones to dry align with each other before setting.

Translation Prototypes

With this foundational understanding of how the Incas constructed, this paper seeks to find a viable translation of this technique into contemporary practice. It is not immediately feasible, or practical to directly carve stone with hammerstones and manual labor. The following two prototypes test a hypothesis that via subtractive machining of Autoclave Aerated Concrete (AAC) one can assemble a free-form geometry shell structure. Previous research by Ramage (2006) explored these unique material capacities toward the ability to erect compressive vault structures using the Guastavino method (Ochsendorf 2010), as the lower density of AAC allowed larger panels and thus a faster installation rate.

Fig. 4 Images of the units and assembly of prototype #2

Prototype 01

The first prototype distilled the Inca condition down to the wedge, neglecting the rounding of the face. This was intended to test that it could be possible to employ the edge as a spatial alignment from unit to unit. A free-form dome geometry serves as the global figure with three units applied to this figure. The front edges align precisely with an acute angle, and opens in the back to produce the wedge. The machining process revealed that this sharp front edge becomes fragile in such a brittle material, suggesting that the rounded pillowing has some material advantages. Upon assembly, two more issues emerge. The first being that with only one edge of alignment between parts, it is difficult to locate a unit because the edge acts as a hinge. Given there is adequate curvature to the figure, three parts better align in space. The second issue is that the assembly is difficult to get precise alignment and the sharp edge reveals the inaccuracies in the manual assembly process. Aside from these two concerns, the assembly process is rapid and stable.

Prototype 02

In order to combat the previous prototypes concerns, a second prototype produces a rounded geometry on the front face to protect the brittle edge of the material, as well as help disguise the mis-alignments upon assembly. This rounding is not done as a nostalgic replication of the Inca construction, but the result of understanding the role this rounding performs. It is important to round the front face geometry while maintaining a clear edge with an obtuse angle to aid in the alignment. The second advancement in this prototype is the nub that appears in the center of each side. This nub aligns between units as a stop that resists the hinging index issue. In the event this nub needs to be removed, it is minimal enough that it won't require the caving away of an entire face. The assembly of this ten-unit prototype emerged successfully and rapidly as seen in Fig. 4, serving as a proof-of-concept to move forward and test the proposed method against a larger assembly.

Method

A larger installation, titled 'Round Room' is produced in order to test these principles on a larger assembly. This production requires the use of complex geometry, structural calculations, fabrication limitations, and assembly procedures—each entangled with the rest. The following describes the process and techniques, many of which expand upon previous research by the authors (Clifford and McGee 2014) that manifest in the project 'La Voûte de LeFevre'.

Geometry

A free-form geometry is first composed to approximate a possible structural condition. A particle-spring system evenly distributes points across this surface with a dimensional variable set at 45 cm establishing the size of the resulting parts. A three-dimensional voronoi calculation breaks the single figure into discrete polygonal units of approximately 45 cm in diameter. Each central point then generates a vector normal to the figure and defines a plane on the back face for fabrication purposes. This plane moves backwards until it ensures all edges of the face geometry are at least one inch positive of the fabrication plane. The perimeter of the intersection between this plane and the voronoi calculation is offset inward to begin the wedge and nub geometry. Each edge is checked for length to make sure they are long enough to add a registration point, and if so, the offset polygon is pulled out to align with the initial intersection polygon precisely at the mid-point of the edge length as demonstrated in Fig. 5. A ruled surface geometry is generated between the front edge and the back offset, nub. This geometry is ruled in order to allow the parts to be swarf machined in a similar manner to the previous application. (Clifford and McGee 2014)

Structural Computation

After the geometric calculation is generated, a closed unit can define its own volume. This volume is used to inform another particle-spring system that ensures a thrust-network may fall within the thickness of the material. As opposed to a typical hanging chain model where the mass of each node is uniform producing a catenary geometry, this Thick-Funicular calculation (Clifford 2013) checks the volume of each unit and re-defines the particle of the unit with this number as the vertical thrust (Figs. 6, 7 and 8). This volumetric version of the Thick-Funicular calculation is identical to the one described in 'La Voûte de LeFevre' (Clifford and McGee 2014); however, the variable that allows the unit to be heavier or lighter relative to its neighbors is the depth dimension of the back face. While the calculation is running, if a particular node is higher than it should be, that back face is brought closer to the original one-inch offset thus reducing the volume and mass.

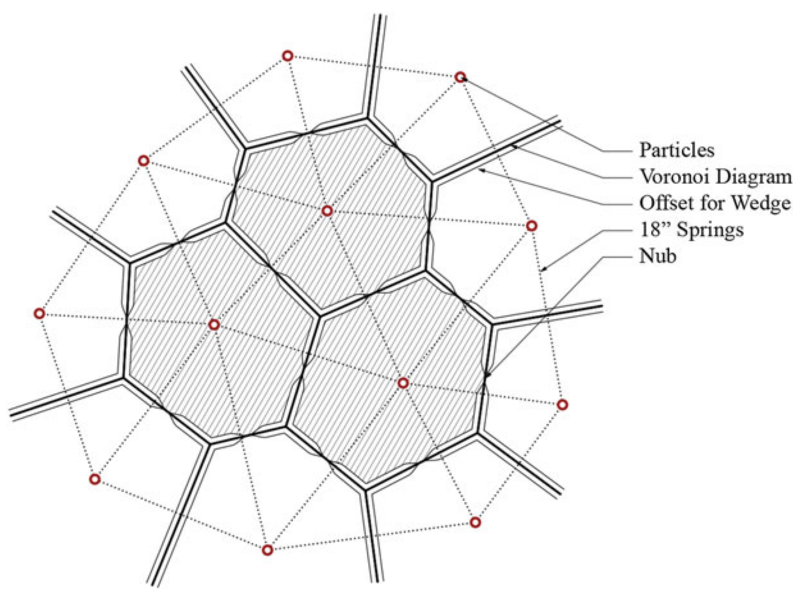


Fig. 5 A 2d diagram of the unit discretization, wedge offset, and indexing nub geometries

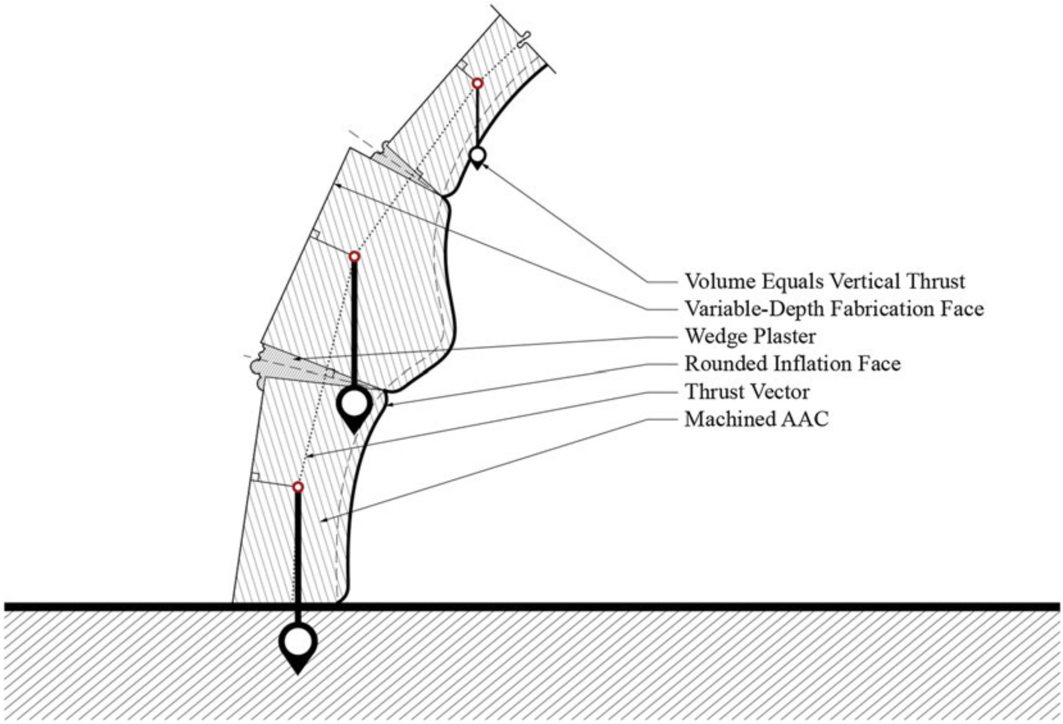
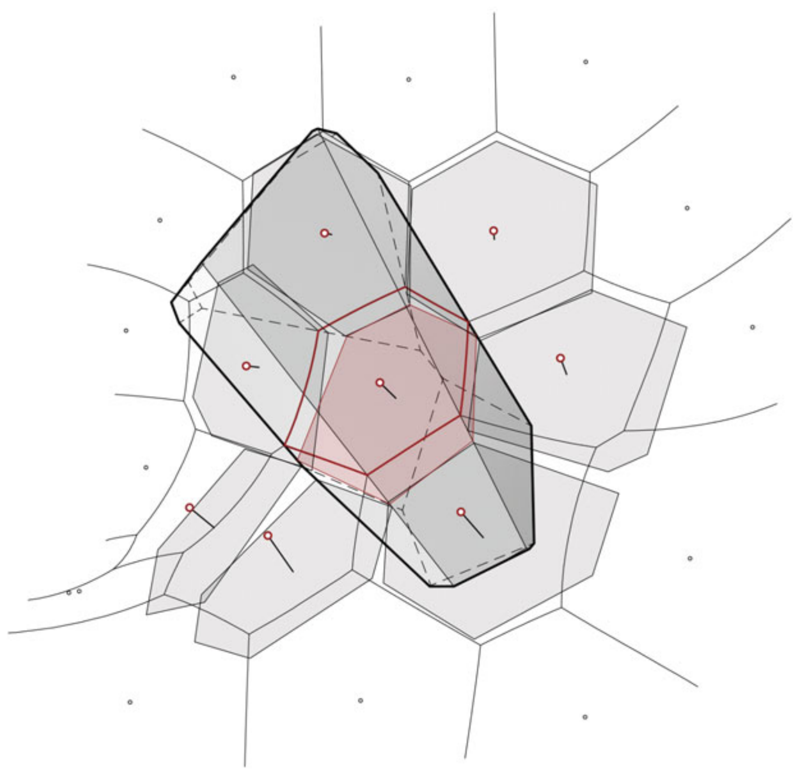


Fig. 6 A section revealing the wedge method as well as the geometries of the variable depth back face that redefined the volume in order to ensure the thrust network falls within the depth of material

Fig. 7 A 3d diagram explaining the geometries that discretize the units, determine the back face plane



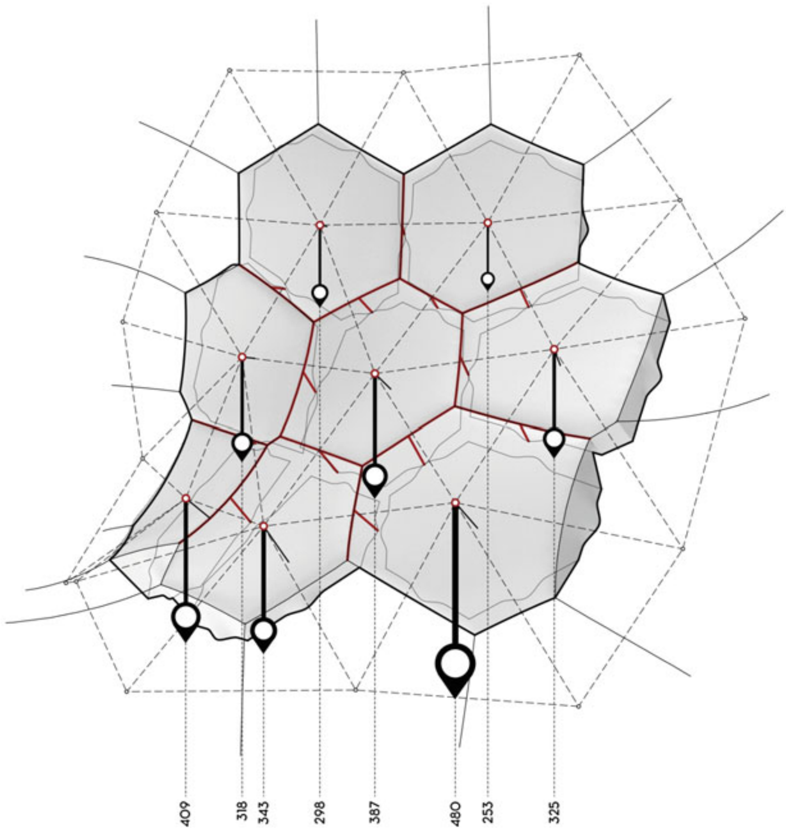


Fig. 8 A 3d diagram explaining the variable-volume particle-spring structural calculation. The *vertical pendants* represent the volume of each unit thus re-defining the vertical thrust of the particle in the system. The *red lines* represent the only coincidental geometries between units—the *front edge* as well as the *nub* defines a 'T' shaped intersection

Machining

The initial prototypes were machined on a typical five axis router, but the final installation components were wet machined with a Kuka KR500 at Quarra Stone, inc. AAC blanks were pre-sized using a slab sawing process, which allowed the final machining process to proceed as quickly as possible. The surface machining process used on the pillowed face of each unit is the primary time constraint, with the swarf or flank machining process used on the sides proceeding relatively quickly. An ongoing collaboration with Quarra Stone is investigating the development of new workflows, which translate directly from the generative model to machine code using the SuperMatterTools script library (McGee and Pigram 2011).

Assembly

The first course of units that align to the ground are wedge plastered from unit to unit, but glued to the base in order to act as a foundation and resist any horizontal thrust as seen in Fig. 9. In a manner similar to the Incas, each unit is dry fit to its neighbors prior to being mortared in place. The edges and nubs align the unit in space with the previous units as guides. Once fit, a batch of plaster is mixed and transferred into a piping bag in order to squeeze the plaster in from behind. A rather liquid mix is used in order to obtain the correct viscosity. Throughout this process, one installer is holding the unit in place while another is piping the plaster as demonstrated in Fig. 10. A single bead of plaster is applied to the backside of each wedge, drying in a time between one and

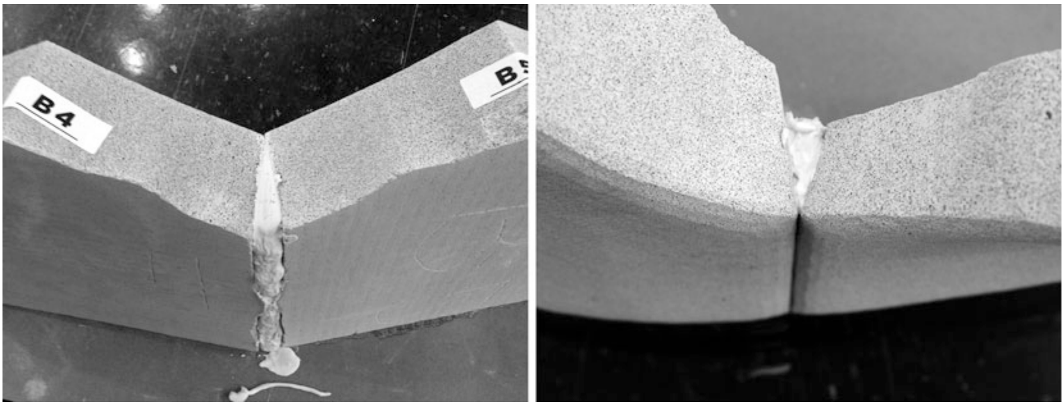


Fig. 9 Detail images of the wedge method from the non and visible sides

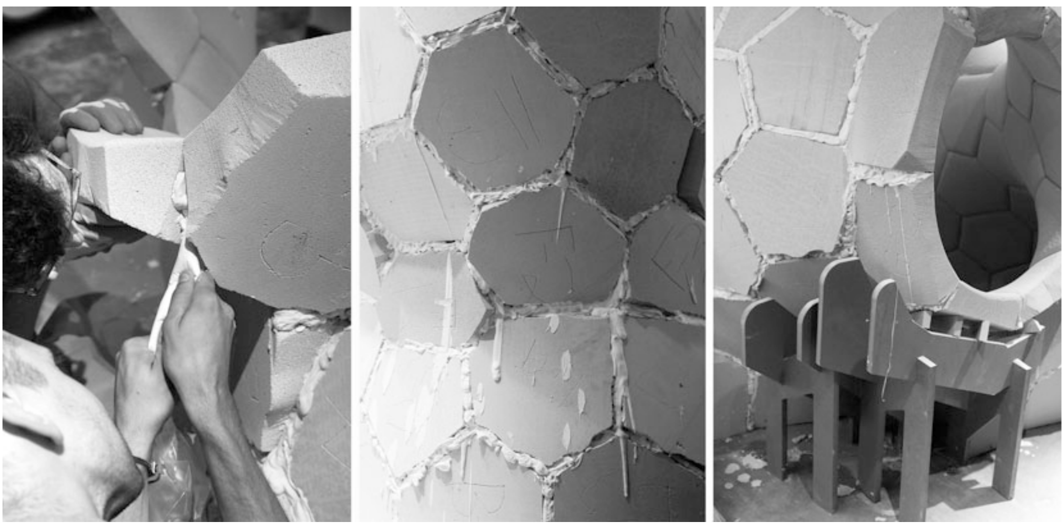


Fig. 10 Images of the assembly process as well as the undercarriage supports

three minutes. At that moment, the first installer is able to let go of the unit while the second installer continues to fill the voided wedge with plaster. The tolerance of misalignment from unit to unit was around 0.8 mm for the first few courses, shown in Fig. 11. This could be the result of tolerance issues in the machining process or assembly, but fell well within visible tolerance. During this period, no carving or fitting is employed. As predicted, this error aggregated as the assembly continued. When the errors became closer to 3 mm, they became more visible and a new process of the Inca dry fitting was employed. The first installer would set the stone where it was intended to be placed and immediately remove it. The collision between the geometries becomes visible as the AAC is compressed slightly producing a white powder on the surface. This white powder represents geometry that needs to be removed. The installer then shaves away at these moments in the collision and re-fits the parts until an entire edge is aligned and the assembly process can continue. The advantage of this shaving process is a precise fit

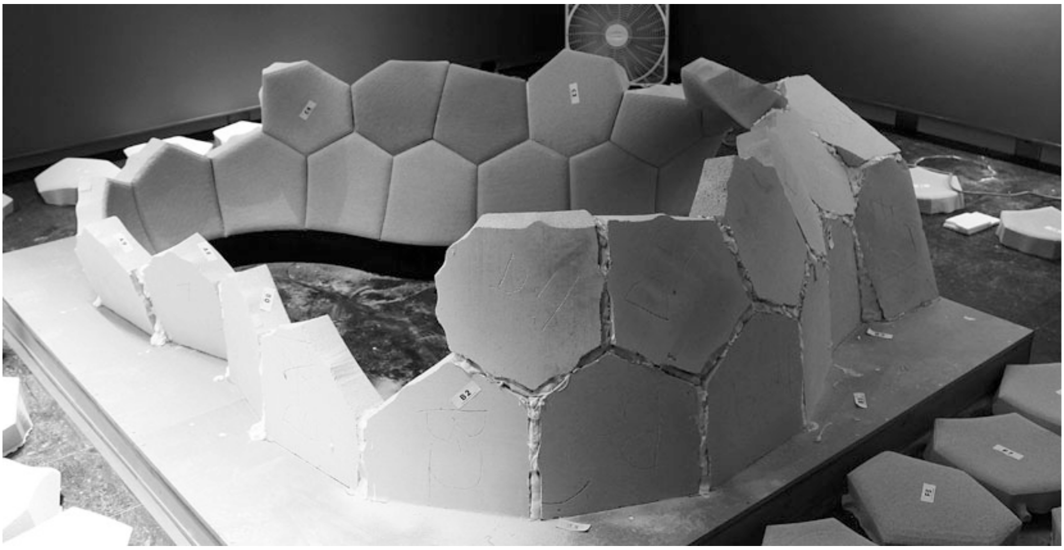


Fig. 11 The first couple courses of the ‘round room’ assembly process

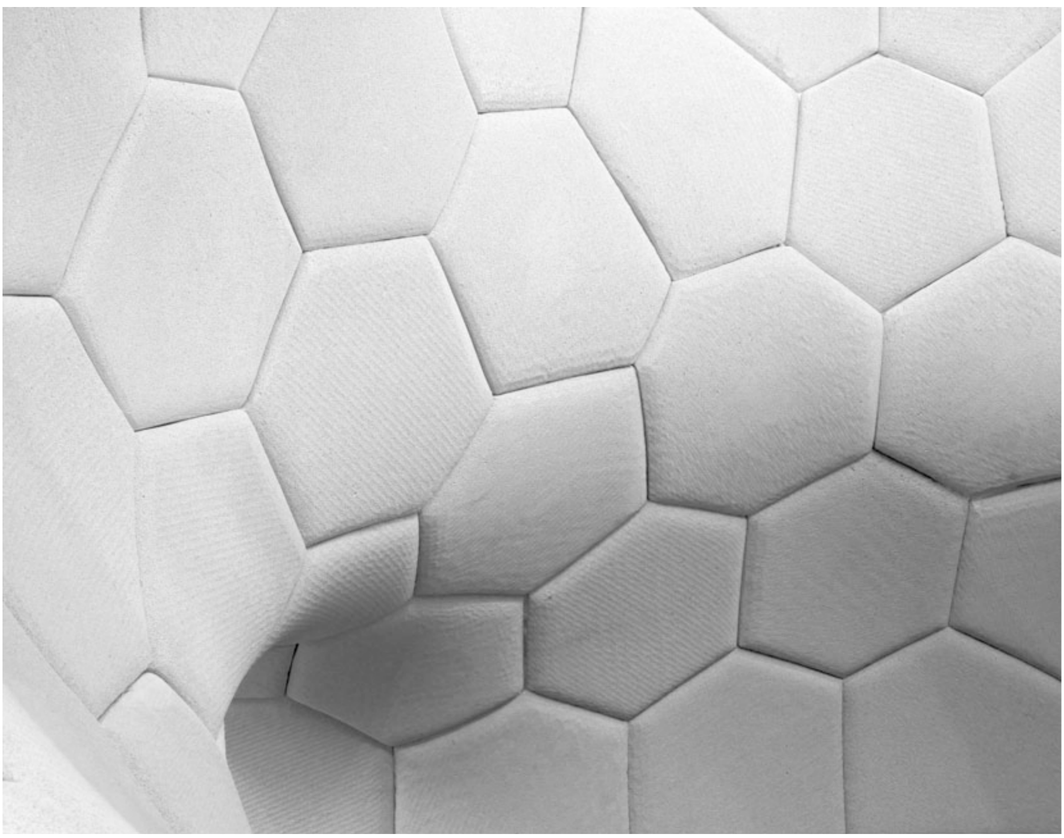


Fig. 12 Image of the final visible assembly of the ‘round room’

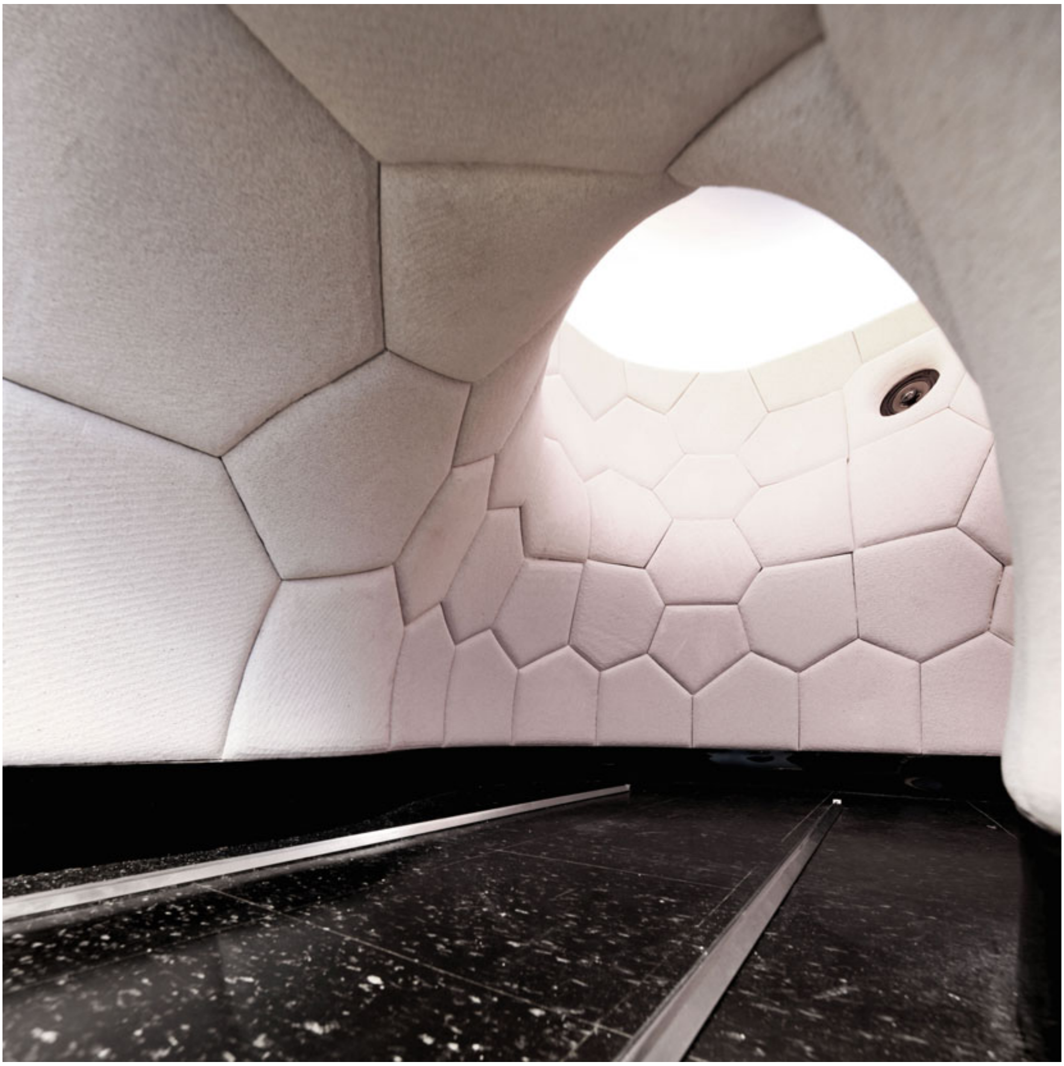


Fig. 13 The ‘round room’ by matter design and quarra stone

can be achieved without an ideal pre-existing condition. The dis-advantage being that is it ensures the following units will be further out of spec as the lower cells are now shorter on some edges. At a certain point, these errors aggregated so much that yet another process of Inca templating is employed. When a cell is too large to fit in a location, the surrounding cells are arched over the location leaving a void that is templated with a piece of paper and transferred onto the original unit. The unit is then manually cut to align with the template and face-placed into position. This manual process may be similar to the Inca method; however, undermines the computation and digital fabrication process. As the assembly continues and errors aggregate, the efficiency of the process progressively slows down to accommodate these manual fits, ultimately approaching the original manual process (Figs. 12 and 13).

Conclusions

This paper demonstrates the possibility of learning from the Inca in order to inform contemporary shell structure production. By employing this past knowledge of the wedge method into a way of carving AAC and assembling via the Guastavino approach, it is viable to construct a free-form shell structure without the aid of templating, falsework, or formwork. This method proves viable; however, will require future research to resolve a number of concerns—the primary being the aggregation of errors upon assembly. A number of techniques—such as the wedge and pillowing—carry over from the Inca method into this translation; however, there are a number that do not. One process that does not carry over and speaks to the difficulty of this prototype is the sequential carving of units with bed-joints to align a stone to an existing condition. In the Inca process, the stones are carved simultaneously to the assembly process in a sequential manner. This paper proposes a method whereby all the units are carved prior to the assembly in the hope that errors only aggregate within a tolerance. While the prototypes in this paper do employ the dry-fit and templating methods, these are employed in a manner that does not re-inform the initial calculations, or the subsequent units, but rather as a way to ensure pre-fabricated units may assemble together. In order to more intelligently respond to the shortcomings of this approach, future research can extend the computation into the process of assembly, carving and adjusting future units to account for assembly aggregation errors.

Acknowledgments The 'Round Room' is the result of a partnership between the authors (www.matterdesignstudio.com) and *Quarra Stone* (www.quarrastone.com) as fabricators with structural engineering by *Simpson Gumpertz and Heger* (www.sgh.com). Prototypes were produced at the *University of Michigan FABLab* and the installation was installed at the *MIT Keller Gallery*. This project is funded in part by the *Council for the Arts at MIT* and the *Belluschi Lectureship*. The thick-funicular calculation employs Kangaroo (www.grasshopper3d.com/group/kangaroo) as the physics engine solver for the particle-spring system developed by Daniel Piker to work inside Grasshopper (www.grasshopper3d.com), a plugin developed by David Rutten for Rhinoceros (www.rhino3d.com), a program developed by Robert McNeil.

References

Andriaenssens S, Block P, Veenendaal D, Williams C (eds) (2014) Shell structures for architecture: form finding and optimization. Routledge, London

Clifford B (2013) Thicker funicular: particle-spring systems for variable-depth form-responding compression-only structures. Struct Archit Concepts Appl Challenges 2:205–206

Clifford B (ed) (2014) Volumetric robotics: MIT architectural design workshop. Matter Design Press, Boston

Clifford B, McGee W (2014) La Voûte de LeFevre: a variable-volume compression-only vault. Fabricate: negotiating design & making, vol 2, pp 146–153

Dean C (2010) A culture of stone: inka perspectives on rock. Duke University Press, Durham

Fallacara G (2012) Stereotomy: stone architecture and new research. Presses des Ponts, Paris

Feringa J, Sondergaard A (2014) Fabricating architectural volume: stereotomic investigations in robotic craft. Fabricate: negotiating design & making. vol 2, pp 76–83

Gasparini G, Margolies L (1980) Inca architecture. Indiana University Press, Indiana

Harth-terré E (1964) Técnica y Arte de la Cantería Incaica. Garcilaso

McGee W, Ferringa J, Sondergaard A (2012) Processes for an architecture of volume: robotic wire cutting. Rob|Arch robotic fabrication in architecture, art, and design, pp 62–71

McGee W, Pigram D (2011) Formation embedded design: a methodology for the integration of fabrication constraints into architectural design. ACADIA 2011, pp 122–131

Ochsendorf J (2010) Guastavino vaulting: the art of structural tile. Princeton Architectural Press, Princeton

Outwater J (1959) Building the fortress of Olantaytambo. Archaeology. pp 12–28

Piker D (2014) Dynamic remeshing. www.grasshopper3d.com/profiles/blogs/dynamic-remeshing-now-with-feature-preservation-curvature. Accessed 19 May 2015

Protzen JP (1993) Inca architecture and construction at ollantaytambo. Oxford University Press, Oxford

Protzen JP (1985) Inca quarrying and stonecutting. J Soc Architectural Historians XLIV(2):161–182

Protzen JP, Nair S (1997) Who taught the inca stonemasons their skills?: a comparison of tiahuanaco and inca cut-stone masonry. J Soc Architectrual Historians LVI (2):146–167

Ramage M (2006) Structural vaulting built with aercrete masonry. Masonry Int 20:29–35

Rippmann M, Block P (2011) Digital stereotomy: voussoir geometry for freeform masonry-like vaults informed by structural and fabrication constraints. In: Proceedings of the IABSE-IASS symposium, London, UK