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ROBOTIC FABRICATION OF STONE ASSEMBLY DETAILS

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This research follows an important body of work from the past decade, which focuses on the design of global surface geometries for compression-only structural behaviour. For example, studies in thrust network analysis have made possible the design and computation of complex unreinforced freeform shell structures that work purely under compressive forces once they are completely assembled (Block, 2009). Recent built projects have shown that while it is possible to construct these structures with standard CNC fabrication tools and for them to demonstrate efficient structural behaviour with minimal bending as expected, a major challenge of building these structures is the development of effective assembly strategies during construction to handle tolerance (Rippmann et al., 2016). A second key challenge is the management of falsework, which is structurally necessary to hold individual voussoirs, or compression blocks, in place until the structure is stable, which is sometimes not until the final stone is placed.

These challenges are important to address in order for efficient, geometrically expressive masonry shell structures to play a larger role in the contemporary architectural fabrication landscape alongside conventional steel, concrete and timber structures. In response, the research presented here offers a new approach for the fabrication and assembly of freeform masonry shell structures that can be built with less error and less falsework. Made possible through a computational workflow that simulates structural behaviour during assembly instead of only after a structure is completed, the approach employs cast-metal joining details that bring ancient stonework techniques into the digital age with customised, mechanically responsive geometries.

New agendas for stone carving

Correlating forces (physics) and form (geometry) in 3D, thrust network analysis and accessible physics simulation environments based on dynamic relaxation have extended historical structural form-finding methods into new versatile digital design workflows (Block, 2009, Rippmann et al., 2011, Piker, 2013). One of the results of the availability of these new geometrical exploration approaches has been a renewed interest from designers

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in historical techniques such as stone carving (Lachauer et al., 2011, Rippmann et al., 2016, Clifford et al., 2015, Kaczynski et al., 2011).

Construction of discrete element structures

Most of the current research efforts in discrete element structures have focused on the production of geometrically challenging thin structures that perform efficiently once they are finally assembled. These efforts have not emphasised the forces arising during assembly, or have solved this problem through external means such as scaffolding, chains or ropes (as in Deuss et al., 2014). In contrast, this research approaches the problem of stability during assembly through integrated details.

Stone detail precedents and methods

Two types of detail precedent inform this research. The first is the historic process of carving a detail geometry into stone and direct casting metal into that geometry. This detail is often embedded inside the thickness of stone and is not visible. The motivation of this detail is to resist a possible future force, such as settling or an earthquake. These details are not constrained by the mass of stone, but rather by the properties of metal shaping or casting and the carving tools used (Leroy et al., 2015). The second detail precedent is a procedural one. For instance, Inca stonework carries vestigial details that hint at the sequence in which a wall was constructed. Each detail refers to a particular moment of assembly and its relation to previously placed stones. This concept can be seen not only in the way the stones notch into each other, but also in the nubs used to place the stones (Protzen, 1993). This research seeks to conflate these two detail concepts in order to incorporate procedural and sequential structural analysis to inform detail locations. These locations are responsive not only to the global conditions, but also to the discrete conditions of the in-progress assembly (Fig. 2).

This project examines the problem of assembling masonry structures through the integration of computation, analysis and simulation during the design phases. The motivation of the research is to develop a streamlined workflow which encompasses design, fabrication and assembly of discrete element structures by leveraging the possibilities of digital fabrication methods. Through a focus on historically inspired details, this paper seeks a new approach that can expand the possibilities for designing and building expressive, efficient structural forms.

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The assembly method in this research comprises six steps from design to assembly: base geometry, discretisation, physics analysis, detail design, fabrication and assembly. The method is exemplified by an eight-piece masonry structure case study shown in Fig. 5, manufactured at Quarra Stone in Madison, Wisconsin.

Base geometry

This research employs a method which serves to liberate geometry from the exclusive dedication to structural requirements. Though essential, structural forms rarely align with programmatic, ergonomic, thermal or formal concerns. In order to accommodate a confluence of differing concerns, the potentials of depth and volume are employed, resulting in an anti-isomorphic condition, as described previously (Clifford et al., 2015). This deep condition produces a zone of operation that Wolfgang Meisenheimer describes as the 'work body' (Meisenheimer, 1985) – a space between the visible architectural surfaces which is dedicated to the means and methods of making. This method begins with a base geometry informed by the above extra-structural concerns. This singular surface approaches a structural logic, but does not satisfy it. Through variable depth and detailing strategies, this non-idealised form transforms into a proposal which satisfies a thrust network within the middle third of the material depth (Fig. 3).

Discretisation

Next is the discretisation of the base geometry into voussoirs. Many different discretisation methods are possible – in this case, a Voronoi-based discretisation is created using a particle-spring system, which creates a random gradient distribution of 3D voussoirs that are larger toward the base of the structure (Fig. 4).

1. Six-piece mock-up, exterior.

2. (a) Cavities that were carved into stones and fitted with steel joints during the Angkorian era (Mitch Hendrickson, source: Cambodia Daily) and (b) Inca wall assembly detail (Brandon Clifford).

3. Section of assembly strategy.

4. A 3D diagram showing particles, springs and final voussoirs.

5. A 3D diagram showing the variable volume eight-piece mock-up and the results from the overall analysis showing reaction forces at the base.

Physics analysis

This method proposes an alternative assembly strategy for freeform stone shells that relies on a local understanding of forces at each step of the assembly sequence (Ariza, 2016). The structural analysis includes two steps: a global analysis that evaluates the equilibrium of the structure in its final state and a local analysis that evaluates all intermediate equilibrium states during assembly. The analyses are conducted with Karamba v.1.2.1, a finite element analysis plug-in for Grasshopper (Preisinger, 2013), and directly contribute to the design and distribution of cast tension details. Specifically, the analyses consider reactions generated at boundary conditions between elements and at the interface with the ground to determine the types and locations of necessary details.

Global equilibrium analysis

Because the base geometry is not generated to fulfil one single constraint (i.e. structural performance), global stability is not guaranteed. The results of the overall calculation of reaction forces at the base of the eight-piece section of the structure are shown in Fig. 5.

Local equilibrium analysis

The discrete analysis step comprises assigning an assembly sequence of voussoirs, determining the support location and condition of each voussoir according to the sequence and visualising the reaction forces at each support.

Assembly sequence

The sequence of assembling voussoirs does not affect the global stability of the final assembled structure. However, there is a big impact on stability during the assembly process. While this research does not rigorously address this question, the topic has been studied in Deuss (2014). This research establishes a reasonable assembly sequence using rings of voussoirs, and the most stable unit of each ring is assembled first. As each new voussoir is added, it is not possible to assume that the previous state of equilibrium is still valid. Ultimately, every previous interface between voussoirs needs to be checked, since each is affected by every new addition. As a proxy, in this case study the stability of the global intermediate, or the sum of all previously assembled voussoirs, is checked at the base (Fig. 5).

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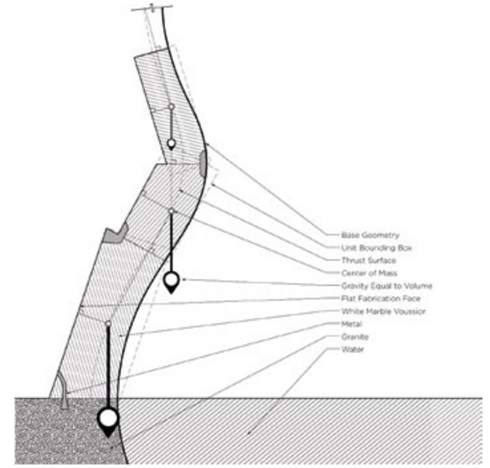

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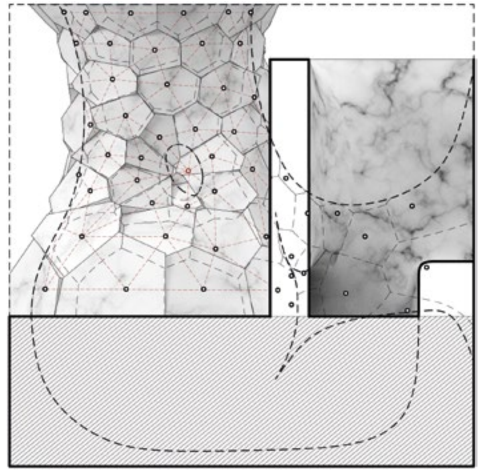

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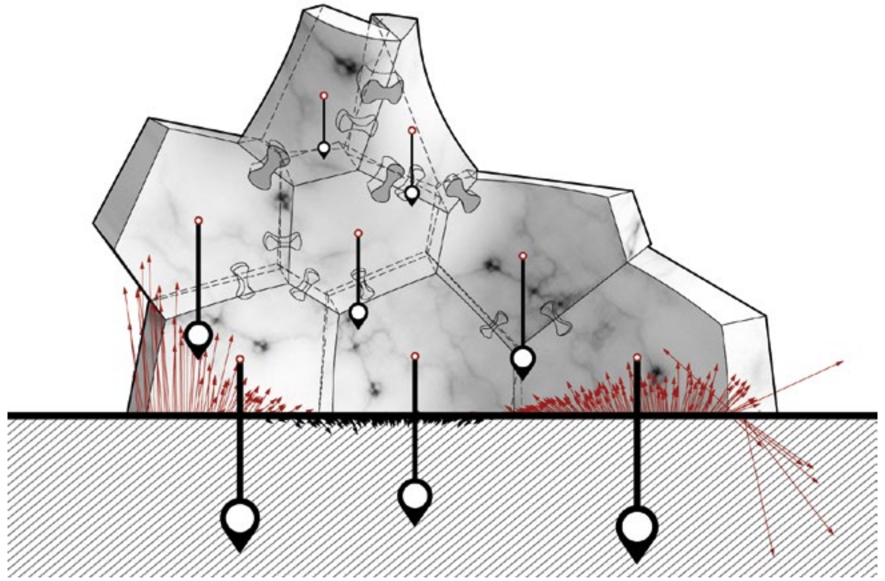


Detail design

Details can be inspired by different motivations. In this project, the role of the details is to coordinate different type of constraints: structural (type, direction and magnitude of reaction forces), fabrication (properties of the carving and casting tools and machines) and assembly (direction and fixing steps of units). This approach takes advantage of the ability of robots to perform custom non-repetitive stone carving and match it with cast metal's ability to be formed with geometric flexibility.

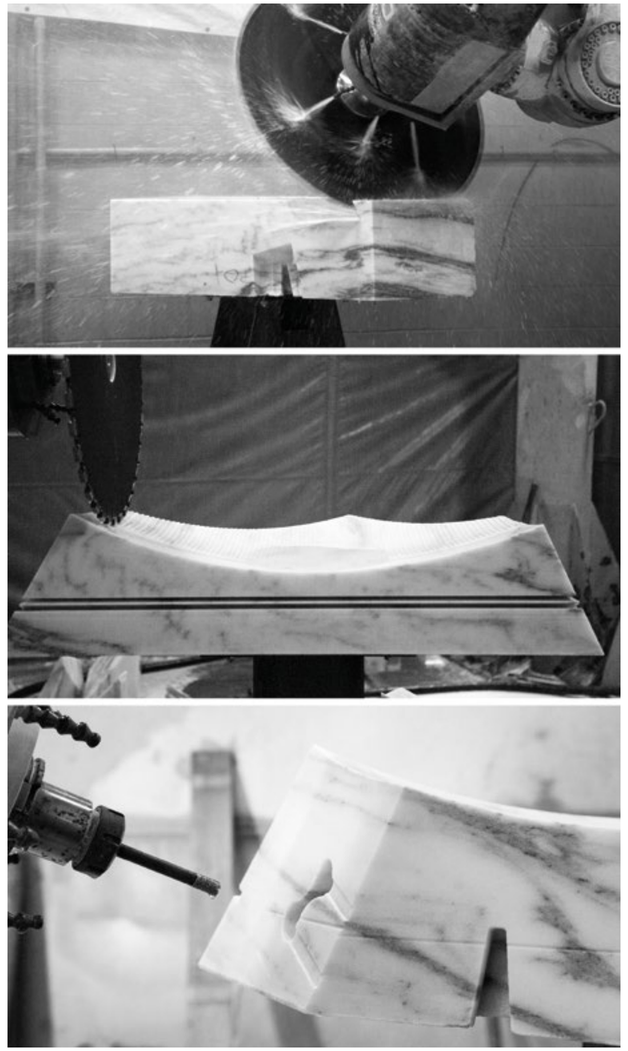
Structural constraints

The reaction forces of the discrete analysis are interpreted one by one, matching type, direction and magnitude with specific geometric detail strategies. Compression forces require surface area, so the planar edges of the voussoirs are left unmodified. Tension forces in the plane require a locking geometry in plane and in the direction of the tension vector to avoid units pulling apart. Out-of-plane tension forces and bending moments are counteracted with couples on opposing faces. In-plane shear forces require a locking geometry perpendicular to the plane of action of the force.

Fabrication constraints

The type of stone, the geometric properties and the performance of tools define the carving constraints. This paper's case study uses Vermont Marble and a blunt electroplated tool. The tool diameter defines the minimum radius of possible carved curvature, and the tool shaft height defines the maximum carving depth. This last parameter is key to specifying possible locations of tension details.

Casting constraints are dictated by the way in which the metal flows through and freezes in the mould when poured. Sharp external corners result in more rapid cooling, leading to increased grain size and brittleness. Sharp internal corners often result in cracking during freezing. Drastic changes in cross-sectional area and volume result in uneven cooling and grain structure. Since traditional clips and butterfly joints in wood or wrought metal do not suffer from such constraints, cross-sectional areas can be varied as much as needed. The translation of this geometry to cast metal requires modification to maintain a constant cross-sectional area throughout the joint.



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Assembly constraints

The assembly strategy is composed of two steps: registration and fixing. In order to register the pieces that are in place, a precast metal drift-pin is inserted, followed by the cast in-situ final fixing of the unit. This two-step assembly strategy determines the drafted geometry and the material selection of the drift-pins.

Robot control and constraints

Industrial robots are designed to be highly flexible manipulators, but this flexibility results in compromises with respect to overall volumetric accuracy. One technique for minimising positioning error is to utilise an external synchronous positioning axis (rotary table). By allowing the robot pose to be restricted to a smaller range of motion and a reduced range of joint configurations, accuracy can be improved; in addition, the overall work volume of the robot increases significantly. Both of these techniques are employed in the fabrication of the case study. In order to maximise part accuracy, individual voussoirs are processed from a solid blank to the finished part using a single fixturing set-up on a flat back face.

6. Cutting operations: (a) edge saw cutting, (b) face side-cutting and (c) detail milling.

7. (a) Casting of specimens, (b) casting of joints in-situ and (c) sample specimen of tension joint.

Cutting operations

The production of individual voussoirs benefits from an automatic tool changer set-up and comprises four robotic carving operations (Fig. 6). The majority of the stock is removed with a thick diamond composite blade. The first operation, a saw slab-cutting strategy, is used for cutting the flat-bearing surfaces of the voussoir. This proved to be the most efficient operation, with a higher material removal rate (material removed per minute). Then the internal face is accomplished with a parallel kerf-roughing and a side-cutting finishing, the latter in a motion perpendicular to the previous direction of the blade. Finally, an electroplated diamond tool is used for a pocketing milling operation that produces the joint voids.

Automation of geometry for toolpathing

While the implemented algorithmic design approach generates highly unique geometries with relative ease, it was important to identify production bottlenecks early in the project. While fully automated design-to-machine code strategies have been implemented in certain projects, it was determined that a hybrid approach would integrate better with the fabrication workflow at Quarra Stone. This involved the automated generation and organisation of 3D part files with the needed 'helper' geometry to work smoothly with the production CAM package used by the fabrication team.

Assembly

Several challenges arise in the placement of the individual voussoirs. First, the stones are never set upon a level surface and the centre of mass of the piece is often not directly over the bearing surface, resulting in temporary instability during assembly. Second, while the meeting faces of the voussoirs are drafted in all directions, which facilitates positioning, there are still several degrees of freedom in the movement of the stones as they are individually placed. To counteract this temporary instability, a two-step assembly method is implemented.

Fitting and registration

Using minimal, adjustable tension and compression falsework, each voussoir is fitted in place by hand and registered to its correct location by a precast tapered drift-pin applying tension normal to the adjacent faces of the two stones. This registering operation facilitates the minute adjustment of the voussoirs after placement and temporarily holds them in place during the completion of the ring. The malleable drift-pins also have the capacity to be adjusted to fit in case of fabrication inaccuracies.

Casting and fixing

After the placement of an entire ring of voussoirs, the pre-machined drafted voids of the shear details located between the most vertical faces of the stones are filled with metal in-situ, permanently fixing the ring together. Finally, the precast adjustable pins holding the course in place are cast over in-situ, permanently locking the drift-pin in place. Additionally, any gaps between voussoirs resulting from the tolerances in fabrication are filled during the pouring of the in-situ joints. This series of operations is then repeated for each consecutive ring.

Research evaluation

The validity of the structural analysis and assembly method was assessed through a series of structural tests of specific cast details and prototypes. The former evaluated the material strength and efficiency of the joint geometry throughout a series of controlled specimens. Different mock-ups explored the possibilities and performance of the various available machining methods, the casting and assembly processes and the materials to be used in the precast and in-situ details. The final eight-piece case study served as a final evaluation of the overall detailing and assembly method.

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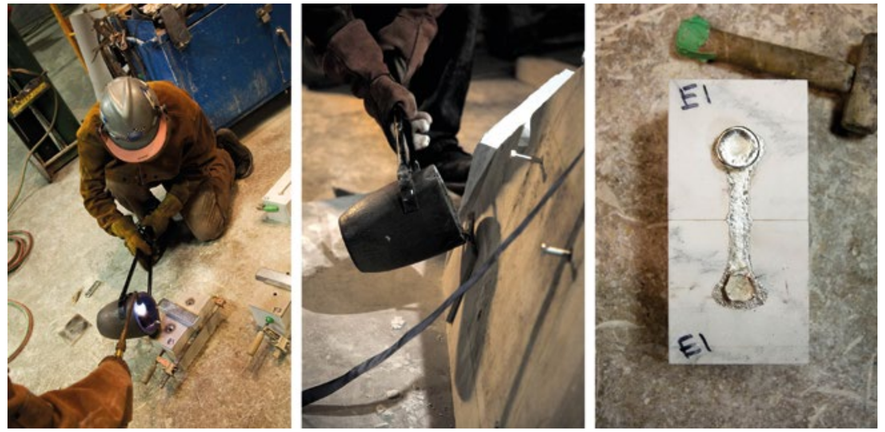

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Material tests

Structural tests were performed on details with two different casting alloys: pewter (AC or Brittania), an alloy of tin, copper and antimony; and zamak 3, an industrial die-casting alloy of mostly zinc, copper and magnesium. Despite having a much lower ultimate tensile strength (51.7 MPa) than zamak (284.8 MPa), pewter was selected due to its lower melting point, shrinkage and brittleness, its resistance to work hardening and its higher flow rate (Fig. 7).

Ten geometric variations of tension joint were tested. Controlling variables included the length, depth and thickness of the joint. Three specimens of each geometry were tested to failure under tension. The most successful specimens transferred between 9 and 12.5kN under tension (Fig. 8).

Eight-piece case study

The eight-piece case study made from Vermont Marble served to evaluate the various aspects of the research. In terms of fabrication, inaccuracies (up to 3mm) related to the location of joints were handled with the specific assembly strategies described above. The most critical inaccuracy location was found to be the intrados of the voussoir, for which further fabrication and assembly strategies need to be studied. In terms of assembly, ratchet straps attached to the fixtures of the flat back face were found to be a useful temporary falsework method to support pieces in place until the final fixing of the ring was achieved. Regarding structural performance, units with larger instability were successfully supported by drift-pins in cases of no larger than 3mm inaccuracies. This last test proved the importance of the geometry of the drift-pin as a tolerance-handling method.

Conclusion

This research successfully demonstrates a new method to design, analyse and construct complex geometry shell structures which satisfy a confluence of architectural concerns, without the need for extensive falsework, formwork or templating. Through computation, digital fabrication and the adaptation of ancient detailing strategies, this method points to a possible application of design in synchronous feedback with the constraints of assembly. While the potentials of such a method accommodate an endless number of possible geometries, the analysis points to a series of constraints. These constraints exist primarily in the structural and material properties of stone and metal, the geometric constraints of fabrication and the problematics of compounding errors during assembly.

Future research seeks to further evaluate the capabilities of assembly simulation and sequential fixing in the construction of a full-scale marble caldarium.

8. Geometric variations of joints (from upper left, A to J) and tension testing of specimen F1.

9. Six-piece mock-up, detail showing units 3 and 5 locked with the in-situ casting technique, and unit 6 supported by two drift-pins.

10. Six-piece mock-up, interior.

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