WATERJET AND WIRE-CUTTING WORKFLOWS IN 
STEREOTOMIC PRACTICE

Material Cutting of Wave Jointed Blocks

SHAYANI FERNANDO, DAGMAR REINHARDT and 
SIMON WEIR
1,2,3 University of Sydney, Australia
1,2,3 {shayani.fernando|dagmar.reinhardt|simon.weir}@sydney.edu.au

Abstract. In the context of stereotomic practice, advanced fabrication with waterjet and wire-cutting of interlocking wave geometry has opened up new possibilities for crafting stone modules with precision and efficiency. This paper discusses the utilization of machined cutting techniques, the processes and workflows of fabricating joint systems for arched and vaulted surface geometries. It presents a comparative study with multiple criteria; such as geometry, method, material, machine and workflow. Furthermore, this paper presents research into the comparison between abrasive waterjet cutting and wire cutting of modules in stone and foam.

Keywords. Stereotomy; Wire Cutting; WaterJet; Wave Blocks; Workflow.

1. Introduction

The use of cutting methods in stereotomic practice has significantly changed due to advances in computational design and manufacturing workflows. Developments in abrasive wire and waterjet methods have further advanced cutting capabilities for complex curvilinear geometry. This paper extends previous research into the development of fabrication options using ruled surface geometry for interlocking wave joints, “Stereotomy of Wave Jointed Blocks” (Weir et al. 2016). Here, EPS foam prototypes were produced using a robotic hot wire end effector on a 6 axis Kuka Robot arm (figure 1). All the faces of the polygonal shape were split up into non-repeating edge loops. An appropriate interpolation level was set for any curves, and the edges within the edge loop were used to find coordinates and angles for the robot to move through.

The research explored hot wire cutting as a representational process since it is cost effective and efficient for prototyping iterations of the wave blocks at various
scales. Even with this consistent method, there were numerous outcome errors explained in section 4. In comparison, the research continued with a test wave block in stone (figure 2) cut using an 11 axis abrasive wire-saw with 10mm diamond wire at 50mm per second.

Figure 1. Two pass cutting sequence of EPS Foam blocks (Image source: Weir et al. 2016).

Figure 2. Left: T&D 11 Axis abrasive wire-saw cutting (Gosford Quarries). Middle: Base wave block Mt White sandstone Right: Sandstone cut blocks (Image source: Fernando 2016).

Building up from this, the present paper first discusses current precedents for manufacturing and material performance of different joint systems with waterjet and wire cutting machine methods. Then reports on ongoing research into wave joints that were produced with different methods, machine applications and materials.

2. Current Stereotomic Practice

Advanced computation and manufacturing has redefined stereotomic practices’ scope and complexity. Burry argues that the once ancient craft of cutting stone by hand to the architect’s precise measurement was a ‘highly laborious undertaking’ (Burry 2016). Fallacara, notes that a renewed interest in stereotomy stems from the fact that ‘stone masonry can proceed rapidly with computer-guided cutters that can fashion more complex shapes’ (Etlin et al. 2008).

2.1. PRECEDENT WORKFLOWS

Whilst the industrialisation of serial articulated robots for automated tasks was important, now multi-functionality is key, for it ‘allows a robot to change from a milling machine to a 3D-scanner, just by switching its end effector’ (Braumann & Bell-Cokcan 2012). Enabling better efficiency for multiple tool changes in the
WATERJET AND WIRE-CUTTING WORKFLOWS IN STEREOTOMIC PRACTICE

workflow of abrasive wire cutting. For example, a wiresaw end effector can be replaced with the finishing spindle tool without having to re-calibrate the position of the cut object.

Yet the main challenge of using industrial robots is to program their movements efficiently. The developments of plugins such as ‘KUKA|PRC’, ‘SuperKUKA’ and ‘HAL’ that are integrated into software used for architectural design have provided architects with the potential to plan, simulate and analyse a robot’s movement from within a familiar CAD/CAM environment (Braumann & Bell-Cokcan 2012).

A direct workflow between design and robotic tool path for subtractive cutting is demonstrated by recent projects for hotwire applications, such as work by Schwartz (Schwartz and Mondardini 2014), McGee & Pigram (Braumann & Bell-Cokcan 2012), and Søndergaard (McGee et al. 2014). Schwartz and Mondardini (2014) employed the HAL plugin to support the integrated design and prototyping of Abeille’s vaults by using the plugin to ‘compute the inverse kinematics of the machine, to detect eventual collisions, and solve the orientation of the hot wire in a specified domain of rotation around the wire’. This is significant as robot control data files are generated to work the robot, which allows for a repeated and fast interactive workflow.

2.2. PRECEDENT SUBTRACTION METHODS

A number of projects can be traced that explore challenges for stereotomic practice, particularly joint methodologies. For example, McGee et al (2012) and Feringa and Søndergaard (2014), (Carrara Robotics) have demonstrated novel approaches to cutting sandstone and marble with custom developed abrasive diamond saws.

Subtractive methods in processing stone range from CNC milling, sawing, wire cutting to abrasive waterjet cutting techniques. Saw blades in the initial roughing stages, produce an efficient cut per unit cost of tooling. Milling machines, usually more expensive, subtract material requiring detailed finishes. Abrasive waterjet cutters use high pressure streams of water mixed with abrasive garnet to erode material producing a thinner kerf. These methods are utilised in projects such as the ‘Armadillo Vault’ by the Block Research Group, consisting of self-supporting, compression only, mortar-less structural sandstone (figure 3). Employing primarily a saw blade for the cutting sequence of each module for both machine efficiency
and cost implications (Rippmann 2016). The saw blade allows for unique surface textures shown on the inner face of all the panels.

2.3. PRECEDENT IN MATERIALS AND MACHINES

Expanded polystyrene (EPS) foam as a representational technique for complex stereotomic practice is often applied in current robotic stereotomic research. Cutting this inexpensive material with a hotwire, closely links contemporary methods to historical precedent and the ‘developed surface of traditional stone masonry’ (McGee et al. 2012). Similarly, in the RDM Vault (Ibid 2012), robotic hotwire cutting was explored as an efficient method opposed to dedicated CNC machining; with advantages over traditional CNC milling at an architectural scale including reduced machining time and better surface finish. Whilst limitations include higher production times, rationalization of geometry to ruled surfaces and inaccuracies caused when dealing with the material itself.

Multi-axis waterjet cutting of masonry has been used for Thin Shell Vaulting (Kaczynski et al. 2011). This project uses a 7 axis Kuka KR 100 HA (high accuracy) robot to manipulate a custom built abrasive water jet nozzle for cutting twisted planar surfaces in sandstone. These precedents demonstrate that each fabrication method is heavily influenced by geometry and prototyping material. The resulting outcomes illustrate the existence of a direct relationship between fabrication technique with both the initial shape and the capacity of the machine.


Planar and ruled surface geometries for interlocking joint surfaces can be efficiently fabricated and assembled, shown in the above precedents. Non-planar or multidirectional joints based on sinusoidal geometries for complex vaulting or dome structures require more research. As a further investigation into new approaches to stereotomic practice, the Robotics Research Group at the University of Sydney explored robotically fabricated joint typologies. Two particular strategies were investigated; a universal multiple-face joint with variable modules in a form and force fitting connection of three intersecting domes (Jung et al. 2016); and a wave jointed block capable of an extended structural ability, concealing the majority of the cutting effort inside the joined blocks (Weir et al. 2016).

Consecutive studies were conducted focusing on workflow when transferred to abrasive wire and waterjet cutting. Sedimentary, metamorphic and igneous stone types are examined in both simplified and complex wave joint geometries. This study utilizes multiple criteria to examine both wire cutting at 1:2 scale (≥12kg of stone) and waterjet cutting at a smaller 1:50 scale (≤400g of stone). The scale is a measure human lifting capacity so that the stone blocks can be efficiently transported. The smallest 1:50 scale blocks measure at approximately 30mm x 30mm x 50mm which is suited for the waterjet machine capabilities.

3.1. GEOMETRY

Further investigation into wave joints, the complex interlocking geometry was simplified to two reverse semi circle arcs (figure 4), due to machine limitations. Block
A is complex in geometry and cannot be cut using the 3 axis waterjet machine, however Block C is the simplified version, a simple parallel extrusion designed for the 3 axis waterjet machine. Block B with a 60° taper resulted in the aggregation of arched structures (figure 5).

Figure 4. A: Complex wave; B: Simplified wave with 60° taper C: Simplified wave extrusion (Image source: Fernando 2016).

3.2. METHOD AND MACHINE
The waterjet machines used to fabricate the 1:50 scale blocks include the Omax A-Jet multi axis, Marchetti Group Axqua 5 axis and the Maxiem generation 1 1515 with a 30Hp pump (table 1). The smaller test specimens were cut using the Axqua 5 axis due to its availability and proximity to local Carrara marble and granite supplies in Italy (figure 5). The Sydney sandstone specimens were cut using the 3 axis Maxiem and multi-axis Omax A-Jet. 30mm stone sheets were used to cut the modules. The machine settings are summarised (table 1).

Figure 5. 5 Axis Abrasive Waterjet Machine at Material Cutting, Minucciano, Tuscany, Italy.
Table 1. Waterjet machine settings for cutting wave blocks comparison table.

<table>
<thead>
<tr>
<th>Machine</th>
<th>OMAX A-Jet 6 Axis</th>
<th>Axqua 5 Axis waterjet</th>
<th>Maxiem 3Axis waterjet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>Pressure</td>
<td>345MPa</td>
<td>400 MPa</td>
<td>345MPa</td>
</tr>
<tr>
<td>Abrasive Flow</td>
<td>0.45 kg/min</td>
<td>0.48 kg/min</td>
<td>0.635 kg/min</td>
</tr>
<tr>
<td>ParticleDia (Micron)</td>
<td>145microns (80 mesh)</td>
<td>177 microns (80 mesh)</td>
<td>177microns (80 mesh)</td>
</tr>
<tr>
<td>Nozzle Diameter</td>
<td>0.40mm</td>
<td>1.20mm</td>
<td>0.42mm</td>
</tr>
<tr>
<td>Stand Off Distance</td>
<td>2.0mm</td>
<td>1.0mm</td>
<td>1.8-2.0mm</td>
</tr>
<tr>
<td>Speed</td>
<td>96mm/min (approx.)</td>
<td>250mm/min (approx.)</td>
<td>400mm/min (approx.)</td>
</tr>
</tbody>
</table>

3.3. MATERIAL

Simplified geometry block B were cut in a small test series, by using the Axqua 5 axis waterjet machine. These were fabricated from both granite and Carrara marble sheets with a 30mm depth and loosely assembled into arches to test configuration (figure 5).

Table 2. Material / Machine Matrix for Wave Block cutting times, minutes/scale block.

<table>
<thead>
<tr>
<th>2a) Waterjet machines</th>
<th>Material Properties</th>
<th>OMAX A-Jet (USA)</th>
<th>Axqua 5 Axis (ITALY)</th>
<th>Maxiem 3 Axis (AUS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Specimen</td>
<td>Young's Modulus(E) kg/cm²</td>
<td>Density g/cm³</td>
<td>Block Weight g</td>
<td>A</td>
</tr>
<tr>
<td>Sedimentary Rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sydney Sandstone:</td>
<td>8.9</td>
<td>2.27</td>
<td>400/240</td>
<td>2 mins 75mm/min</td>
</tr>
<tr>
<td>90 White</td>
<td>8.1</td>
<td>2.23</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>Sydney Sandstone:</td>
<td>8.1</td>
<td>2.23</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>Gossford Buff</td>
<td>8</td>
<td>2.2</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>Metamorphic Rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White Carrara Marble</td>
<td>8.1</td>
<td>2.7</td>
<td>300</td>
<td>1 minute 250mm/min</td>
</tr>
<tr>
<td>Grey Calacatta Marble</td>
<td>7.5</td>
<td>2.6</td>
<td>300</td>
<td>1 minute 250mm/min</td>
</tr>
<tr>
<td>Igneous Rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block Granite:</td>
<td>7.0</td>
<td>2.7</td>
<td>320</td>
<td>1.5 minutes 200mm/min</td>
</tr>
<tr>
<td>Aluminaum</td>
<td>10</td>
<td>2.7</td>
<td>250</td>
<td>5 mins</td>
</tr>
<tr>
<td>2b) Wire Cutting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPS Foam (A)</td>
<td>0.00036</td>
<td>0.8-0.9</td>
<td>250</td>
<td>20 mins</td>
</tr>
<tr>
<td>Sydney Sandstone:</td>
<td>8.9</td>
<td>2.27</td>
<td>15000</td>
<td>-</td>
</tr>
<tr>
<td>Mt White (A)</td>
<td>8.9</td>
<td>2.27</td>
<td>250</td>
<td>-</td>
</tr>
</tbody>
</table>

As is displayed in table 2, the cutting times, stone types and geometries were further explored, with a particular comparison between the waterjet cutting process at 1:50 scale (table 2a), versus wire cutting machine times comparing sandstone and EPS foam at 1:2 scale (table 2b). Working with the assumption that the cutting time is dependent on a variety of factors including scale of block, material density and method of cutting; this demonstrates how criteria impact on the machine processes and end result (figure 6).
Abrasive wire-saws are only suitable for cutting larger scale modules, and each of the cuts usually require further finishing, while waterjet cutters do not require further finishing as the accuracy of the cut is finer. Furthermore, CNC milling of sandstone takes slightly longer than abrasive wire cutting, when tested in 1:2 scale wave block (CNC approximately 4 hours with 3 tool changes).

3.4. WORKFLOW

Consistencies and differences between the primary steps involved in the procedure of cutting with wire and waterjet methods are also of importance (figure 7). The diagram shows the processes and relationships of constant feedback loops between a calibration for each geometric model and the respective cutting machine.

What is significant here is that different profiles for wave joints could be sufficiently tested through the benefit of software versatility that allows changes to the base geometry, while at the same time allowing for different fabrication protocols and material selections.
Figure 7. Workflow diagrams showing relationships between methods/machines/programs.

4. Discussion of Results

The transfers between models, machines, file formats, programs and people naturally caused a number of errors which occurred anytime between early design and the final fabrication stages. These are in the following grouped into modelling, machine and material error, and further discussed.

4.1. MODELLING ERRORS

The wave block was initially modelled based on sinusoidal curvature (figure 4), which altered to curvature based on B-Splines. This block was designed with the constraints of the machine to cut sharp angles in stone without breaking (figure 2). The modelling programs used include Rhino 5, Grasshopper, Blender, and plugins including Kuka|PRC. The workflow from Blender to generate the KRL directly to run the robot involved the writing a python script which uses the Blender API to conveniently query the geometry. The simulation of the robot for collision detection in this case made use of Kuka|PRC. Both NURBS (Non-uniform rational B-Splines) and Polygon (mesh) modelling were utilised in the initial design phases of the wave block.

Modelling errors include the initial NURBS geometry modelled in Rhino as simple loft extrusions which was not based on ruled surfaces. Other inaccuracies included using the Rhino transformation tools which are not specifically related to angles and dimensions, but rather are intuitive and based on aesthetic. Parametrising the process of generating the curvature for the cuts in a program such as Grasshopper enabled more controlled outcomes. The most efficient method, was
mesh modelling based on quads which allows the designer to determine the directions of the tool paths. This was particularly effective for both the CNC milling and diamond wire cutting process where the striations became an aesthetic feature and/or assisted in the process of hand or machine finishing the final surfaces.

4.2. MACHINE ERRORS

The machines used to fabricate the 1:2 scale wave blocks include the 6 axis Kuka KR10 with custom hot wire end effector and 11 axis ABB (T&D robotics) Foundry II with abrasive wire-saw. CNC milling had to be utilized in the finishing stages for some of the 1:2 scale blocks due to wiresaw tolerances. Tool wear and tear becomes an issue over time which can alter the final result if not detected early and considered. Laser scanners are used to detect the wear of diamond tools and spindles in the stone industry.

The errors which resulted from these different machines include slightly different workflow, settings and software integration which caused inaccuracies in outcome dimensions. Other specific errors include the machine stalling and fractures of the nozzle or water tubes which causes inaccuracies during cutting.

4.3. MATERIAL ERRORS

Material errors and inconsistencies have to be accounted for when designing in the initial phases of the process. Outcomes alter based on the material density, sheen and grain, and material response to tooling techniques, even when geometries are only marginally modified (figure 8).

At the outset, material characteristics differ in natural appearance, as no two sets of stone blocks are the same. When applying the same geometry (by waterjet cutting sheets of white Carrara marble), outcomes differed visually (even using the same material). Furthermore, materials are affected by tooling techniques, visible in striations evident in both the foam and stone wire cut 1:2 scale modules. Material errors then may include chipping at certain weak points, kinks where there was a machine error or mechanical failure and cracks in the material itself (figure 2, 6, and 8). The optimisation methods should then allow for adequate wire tolerances in the modelling stage of the workflow. In addition, a secondary finishing process is required to make modules fit and interlock. This produces a ‘gap’, which results from the combination of material, method and machine errors. When this is integrated as a ‘shadow gap’, this material error can become a design feature. Material glitches thus can work in favour of outcomes, in an aesthetic sense or as functional aspects. Certain striations or ‘kinks’ in cut stone can actually assist in creating more friction between joint contact surfaces thus delivering better structural stability when joined together, which opens a potential for future research.
Figure 8. Left: Glitch/error/kink in cutting path; Middle: Waterjet cut sandstone striations and erosion due to water pressure; Right: Misalignment of waterjet cut marble modules.

5. Conclusion and Future Research

This paper has discussed the utilization of machined cutting techniques, processes and workflows of fabricating joint systems for arched and vaulted surface geometries. In a comparative study, the multiple criteria of geometry, method, material, machine and workflow for stereotomic fabrication of such wave joints were investigated. The results of these multiple criteria comparisons and case studies illustrate and emphasize inconsistencies, but also opens opportunities. Where a particular challenge arises from the fact that material consists of differing properties that in conjunction with a projected geometry reacts to manufacturing processes. This will need to be further analyzed in relation to how structural performance can be integrated with machine and methodology. Future research in this area will include varying joint geometries informed by both physical and digital structural simulation analysis. It is anticipated that this will consequently impact the cutting method and overall workflow.

Acknowledgements

This research has been supported by industry grants and scholarships from Gosford Quarries, Garfagnana Innovazione, Material Cutting, Omax, T&D Robotics, The Faculty of Architecture, Design and Planning, and the Faculty of Civil Engineering, The University of Sydney.

References


