LINEAMENT

MATERIAL, REPRESENTATION, AND THE PHYSICAL FIGURE IN ARCHITECTURAL PRODUCTION

EDITED BY
GAIL PETER BORDEN
AND MICHAEL MEREDITH

ROUTLEDGE

Figure 1.1 The memorial assembles 33 blocks of solid granite into a unified structure forming a shallow vault buttressed by five radial walls.

Figure 1.2 The conspicuous absence formed by a subtractive boolean operation creates a central space for reflection.

wedge-shaped "voussoir" stone elements, which compress together to form the arch. As a French term meaning "to turn," each *voussoir* turns the thrust of the mass from the structure's diagonal thrust towards the ground. Though the construction sequence for a stone arch involves the *addition* of individual stones to form a complete arch, the articulation of the geometry of the central void is produced through an operation of intersection and *subtraction*. The "part to whole" relationships of the unique individual stones cohere as a singular figure of the arch, transferring loads and circumscribing the absent figure of the central void.

The vaulting stone elements overhead structurally distribute load from the arch's center to the ground plane. The *inverted vault* formed on the smooth underside of the memorial is not part of the arch structure, but rather, provides a continuous surface into which the void is cut. Abutments provide space for a line of the text memorializing the tragedy: "In the line of duty, Sean Collier April 18th, 2013" and produce a shape akin to the inverted arches of Louis Kahn's circular openings in the National Assembly buildings in Dhaka that flicker between a material construction and platonic figure: part arch structure, part shaped figure. Charged with the purpose of marking the presence of the ovoid absence, the inverted vault serves a rhetorical purpose in the memorial's design. The tapered abutments *register the absence of stone* by intersecting with the central figure of the void. Like a *pantomime*, the absent figure is implicitly defined through the surfaces and gestures that define the shape's contours as they intersect with the five-buttressed figure.

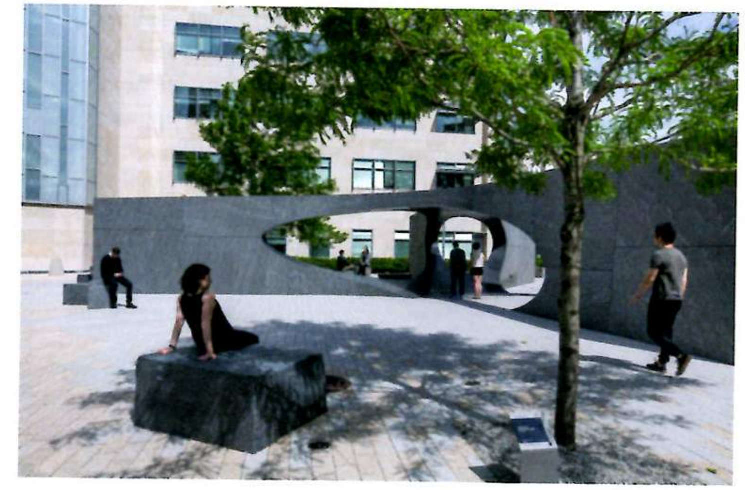


Figure 1.3 The forces, passing through the legs of the memorial and into the ground, trace the contours of the absent central figure and support the shallow vault.

The structure can be read as a translation from *force to form*, as a tectonic expression. But that would not sufficiently explain the inverted "arch" of the bottom half of the central void, as those concave geometries do not express load paths. The function of the bottom half of the memorial is rhetorical—it "reveals" the absent ovoid figure that hollows the stone to form the room (Figure 1.3). The buttress walls with the ovoid subtraction act like the walls and floors of the Parisian houses in Gordon Matta-Clark's Conical Intersect. The memorial buttresses trace the contours of the absent figure, marking a shift *from tectonic expression to operational tracing*.

Operations

The memorial could be understood structurally and *materially* as a compressive stone arch, or *geometrically* as a figure intersection. The memorial is *understood operationally as a boolean exclusion*. The use of software commands to describe form drives contemporary design discourse and underscores the degree to which software operations and techniques influence the contemporary form-making enterprise. Shapes are no longer confined to the lens of Euclidian geometry, but rather, are understood through a system of *computational operations*. No longer confined to a strictly geometric origin, shapes subscribe to an expanded identity that includes operational characteristics. The three-dimensional modeling software commands in Rhino and Grasshopper have produced a series of formal trends that manifest themselves in a wave of projects, realized and unrealized. Operations such as "Split" and "Trim" are easily understood as commands that mimic physical operations for manipulating physical surfaces. Other operations such as "Extrude" and "Loft" are able to produce new surfaces out of relationships between elements. Similarly, "Boolean" as an operation is able to produce new types of surfaces and generate new mathematically derived forms. The Collier Memorial is not an ovoid in a star, but rather a boolean cut subtracted from an extruded five-pointed figure (Figure 1.4).

Structural design

Hooke's Law defines a reciprocal relationship between an arch in pure compression and a hanging chain in pure tension. Weighted physical models were famously used by Antoni Gaudí to form-find geometries in masonry and by Frei Otto to design the Olympic Stadium in Munich, Germany. The principle is demonstrated through a physical model that "computes" the geometry of an arch or membrane and tests the ability of the structure to support the range of applied loadings produced by self-weight and live loading scenarios. Methodologically, the design process for the Collier Memorial involves constant oscillation between the construction of physical models and simulations through digital tools. Analog methods of empirical testing complemented the digital modeling process, allowing the design team to verify calculations by multiple means with a range of load cases.

Originally conceived as a boolean operation within a 3D modeling environment, the conception of the memorial was initially material and gravity-free. The "digital vacuum" of the Rhino model initially allowed for a constraint-free geometrical exercise. Once the memorial took on material (solid stone) properties, and the curvature was understood as a compression structure, the geometry took on a new level of specificity. This translation was paralleled by the importation of the model into a finite element analysis model. Iterations of structural modeling simulations demonstrated that the preliminary design of the shallow arch was achievable with solid stone construction. Further modeling with a customized grasshopper definition allowed the design team to visualize the impact of adjusting the thinness of material, and the sizes of the blocks, while continuously updating the structural model and verifying its structural soundness and stability under a variety of load cases (Figure 1.5).

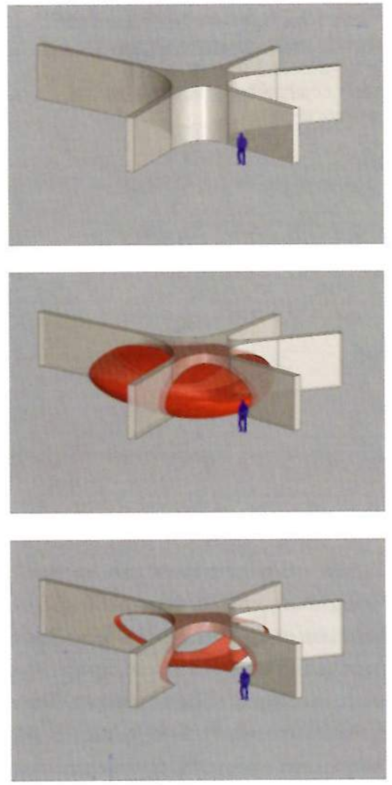


Figure 1.4 The memorial is understood materially as a compressive stone arch, geometrically as a figure intersection, and operationally as a boolean exclusion.

Central to the refinement and optimization of the design is the iterative analysis and modification of the force polygon, which maps and reconfigures all the force vectors in each stone of the vault. This method, generated with computational graphic statics, is typically performed on simple arch configurations in two-dimensions. The five-way vault arrangement requires the graphic statics calculations to be performed in five individual segments, dividing the vault into radial pie-slices. Computational tools developed by Ochsendorf DeJong and Block Engineering analyze the five-way vault to ensure the global stability of the structure under gravity loads (Figure 1.6). RhinoVAULT, a plug-in for Rhino, generates membrane solutions for shell structures to explore and compute three-dimensional compressive solutions within the stone.

The geometry of the thrust lines is translated into the memorial in the joint lines that are inclined to be perpendicular to the thrust lines of the arch. The joints between stones are typically normal to the thrust lines of the force vectors. The shape of the central keystone is an irregular five-sided figure that is derived from the perpendicular thrust lines of the five buttress legs (Figure 1.7). The joint lines in elevation form a radial pattern normal to the force trajectories of the stone blocks under self-weight scenarios. The joint lines render the structural thrust legible at the scale of the memorial.

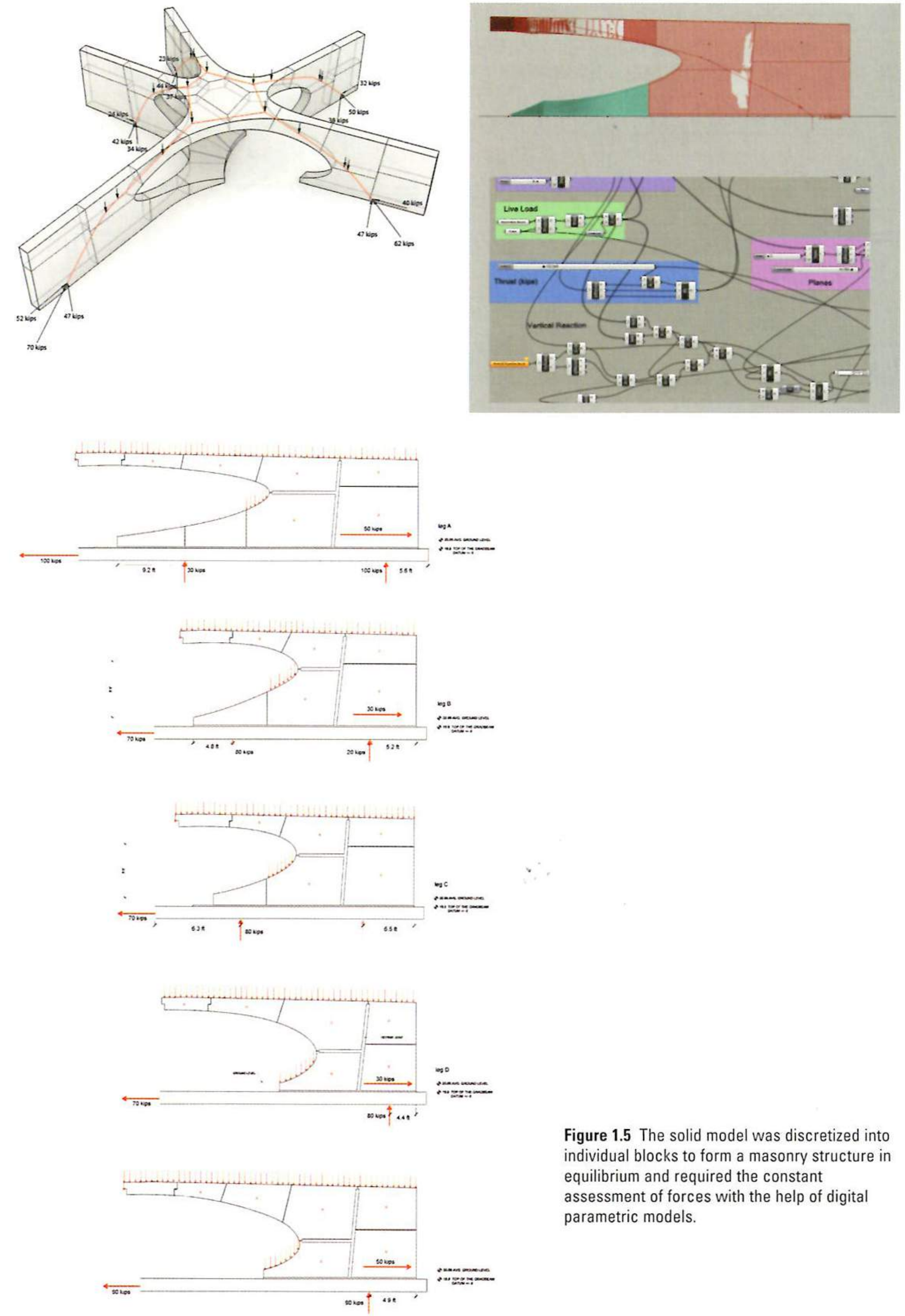
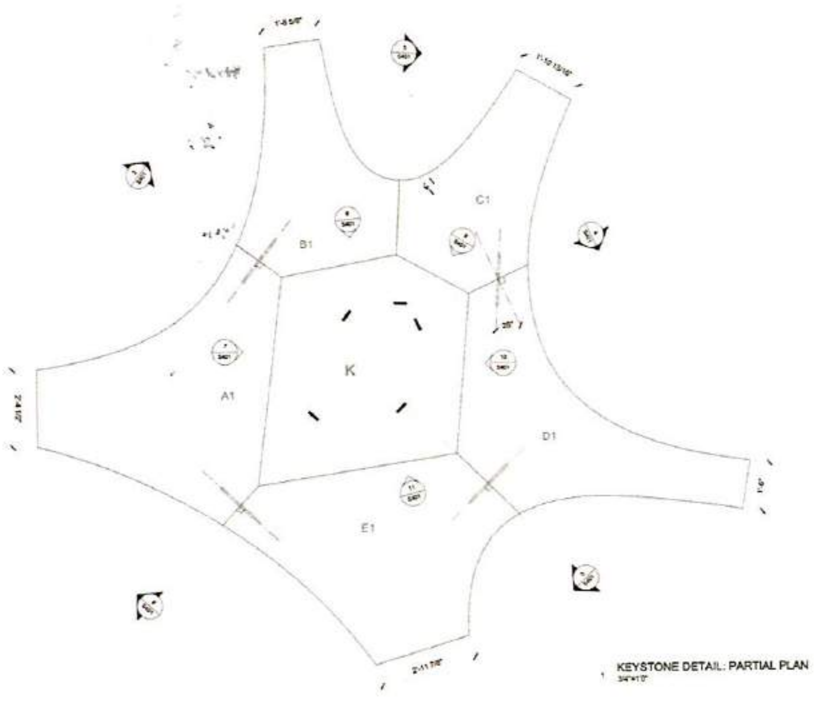


Figure 1.5 The solid model was discretized into individual blocks to form a masonry structure in equilibrium and required the constant assessment of forces with the help of digital parametric models.



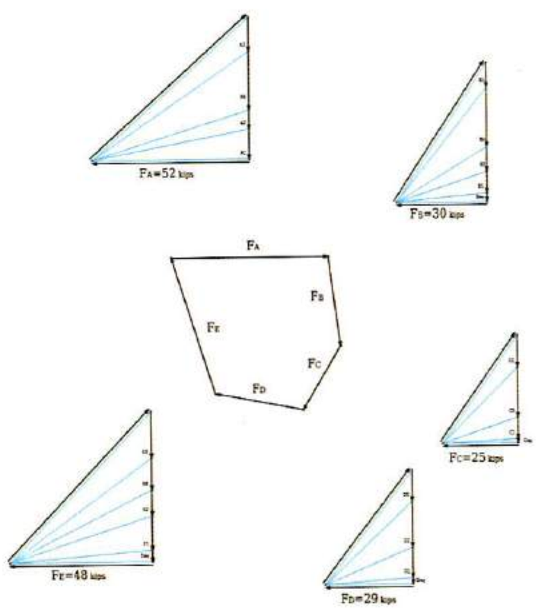


Figure 1.6 Computational graphic statics refined and optimized the force polygon of the keystone to produce a stable five-way vault.

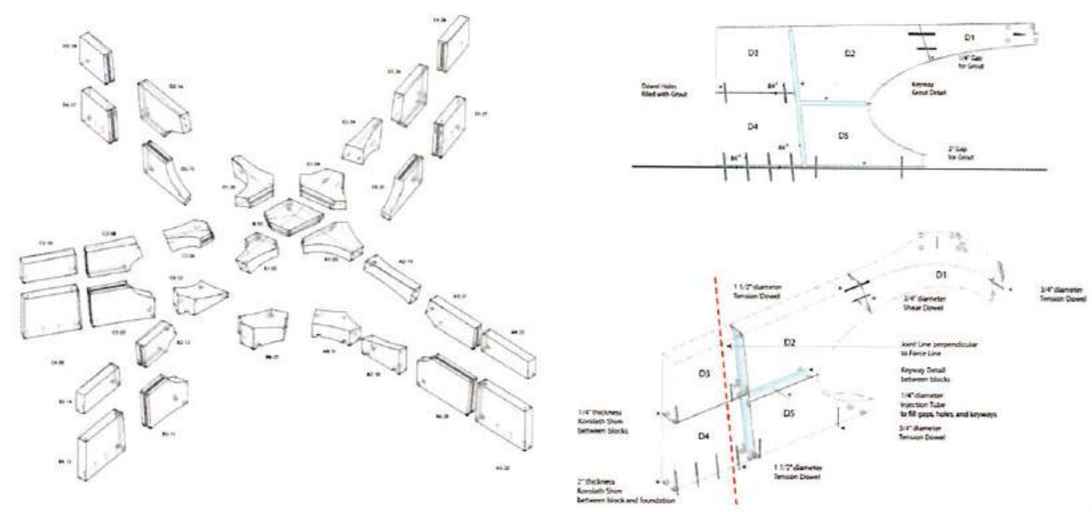


Figure 1.7 The loads are laterally transferred from the central keystone into five irregularly arrayed buttressing walls.

Fabrication

The fabrication, assembly, and construction of the Collier Memorial is a combination of *traditional hand methods and digital manufacturing*. Production of each stone block relies on the combined efforts of robot, technician, and mason to register, manipulate, cut, and finish the material. The exacting tolerances demanded by the arch configuration required blocks to be within fractions of millimeters of precision. The procurement of a limited number of blocks suggested that there was no room for damaged block or for re-cutting a block.

The fabrication process, performed at Quarra Stone, entailed the careful handling of stone blocks and the successive techniques of milling, sawing, and grinding of the material. Before robotic cutting begins, masons had to register and physically orient the stone to correspond with its digital model. Once the position of the stone was communicated to the robot it was cut into parallel-faced slabs by a single-axis robotic block saw that had a 3.5 meter blade that weighed 81 kilograms. A series of milling (sawing) steps removed material to within 2–3 millimeters of the dimensions of its corresponding digital model. Each directional cut required a physical reorientation of the stone block by masonry workers. Once the rough, exterior geometry of the stone was revealed, the piece was examined by masons and moved to either a fixed-bridge CNC milling machine or a KUKA 500 robot (Figure 1.8). Relatively smaller dimensioned stones fit into the work envelope of the CNC, but larger pieces had to be placed on a rotating table and cut by the KUKA 500 robot whose joints could accommodate a load of 544 kilograms and move the stone at a rate of 2.5 meters per second. To satisfy the geometric complexity of particular *voussoirs*, robots had to have the capacity to cut job files in an uninterrupted cycle for weeks at a time.

Design of the Memorial relies on the exact fit of 33 stone blocks to cohere into a singular form. To ensure the visual continuity of the central void across multiple stones, joints were constructed at the minimum ¼″ size, which required extreme precision in fabrication. The robotic milling process produced final pieces that are within a 0.5 millimeter tolerance between the physical stone and the digital model. The need to achieve such a high tolerance during stone fabrication presented unique challenges: the precision of each cut needed to be verified in tandem with physical measurement of the stone during fabrication.

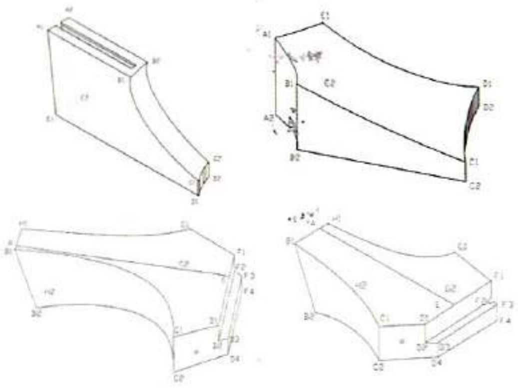


Figure 1.8 Stone fabrication involved the precise subtraction of materials from the rough cut quarry block. A combination of saws, CNC machines, and robotic machines removed material from the blocks to the exact geometry of the memorial units.

The manufacturing process modified both material *and* tool. Material properties of the granite wore away the cutting edge in proportion to the rate at which the stone was being cut. The gradual deterioration of both stone and blade had to be considered before each cut in order to achieve the degree of precision necessary for structural stability between blocks. Fabrication required a constant re-calibration of the blade to establish the position of the robotic cutting tool in relation to the stone.

The Collier Memorial is assembled using a historically reverse construction technique of centering, in which placement of the keystone initiates the erection sequence. The sequence involved locating the keystone in space, and verifying its position through digital surveying. The second step was the surrounding of the keystone with the "ring" stones, also located and verified by surveying (Figure 1.9). By starting at the center and working outward, any tolerance issues could be "shed" towards the legs where adjustments would be easier to make as the leg required a lower number of interfaces with other stones.

Physical models allowed the structural design to be tested mechanically and the erection sequence to be rehearsed. Assembly of the structure and its setting sequence occurred in tandem with the fabrication of each stone piece. Stability tests and rocking simulations ensured the safety of the memorial. Digital models allowed the design to be optimized and analyzed for material conservation and code compliance. The development of digital tools to produce contemporary forms with archaic building techniques highlights the methodological diversity that characterizes contemporary design that does not privilege any single design tool, but rather benefits from both digital and material computation techniques. The correspondence between the material properties and the designer's ability to manipulate them geometrically is highlighted by the methods of translating force into form with computational tools and high precision robotic fabrication.

The Collier Memorial marks a paradigm shift in which contemporary methods of fabrication move away from instruction-based making, and towards a behavior-centric construction approach in which the

Figure 1.9 As the stone blocks arrived on site, they were assembled sequentially from center to periphery, requiring the five-sided keystone to be "placed" first as the supporting buttresses were built around it.

Figure 1.10 The fabrication and installation process required an intense interaction of man and machine as blocks were cut, measured, finished, handled, set, and placed.

Figure 1.11 The memorial creates a new gateway to the campus, the absent figure at once framing and allowing passage through the site.

material is treated as an active variable, even if derived from solid rock. Registered by both man and machine, the granite blocks of the Collier Memorial transcend conventional prescription in which material is merely a neutral base on which machines operate. Fabrication of the Collier Memorial conceits that robots and masons alike can no longer depend on a set of rigid instructions or a digitally dictated code. Conventionally disparate roles of architect, mason, robot, and material converged into an explorative series of real-time interactions in which all parties and elements sensed and processed their relationships to each other (Figure 1.10).

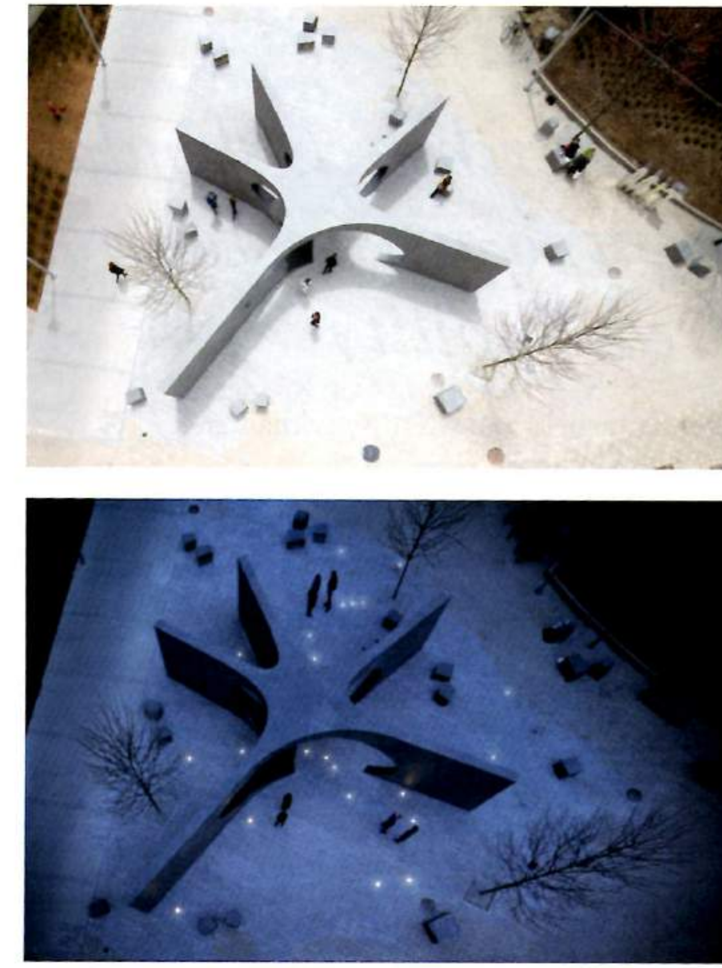
Perception

Standing on the corner of Vassar and Main Streets, the memorial gives the *uncanny impression of an absent figure* at the center of a walled structure. The absent figure is glimpsed as a contour, visible only through cues from the polished faces of the "cut" stones. The effect is made legible through the articulation of the memorial's polished interior edges, which are in contrast to the textured flamed exterior finishes. The textured flamed surfaces of the granite are light gray in color, while the high honed interior surfaces are almost black in color. The white colored figure in the Virginia Mist granite is a three-dimensional running through the stone, which is also appreciated as the figure turns the corner of the solid blocks (Figure 1.11). The subtle figure of the stone acts as a clue that the stone is in fact solid. This perceived solidity contributes to the impression that the memorial is massive and heavy.

At the same time, the shallowness of the arch and the thinness of the buttress walls gives the impression of lightness. Like a gothic flying buttress, the memorial translates a substantial web of masonry thrust vectors into light and surprising expression. The gothic "special effect" of verticality and dissolved materiality of the cathedral is interpreted by the memorial as an almost horizontal shallow arch, that is simultaneously massive and light.

Another surprising effect of the Collier Memorial, is the sense of familiarity with the type of geometrical effect of an operational technique of the Boolean command. The operational logics of modeling software have transformed commands such as "Loft", "Split," and "Boolean" into a vocabulary for describing a wide swath of contemporary architectural production. As a "Boolean" operation form, the Collier Memorial is "familiar." Its central void is one of hundreds of operational outcomes within the space of a three-dimensional modeling environment of a computer. However, the memorial becomes completely

Figure 1.12 Point lights set into the pavers permanently inscribe the constellation of stars in the sky the night Sean Collier was killed.



unfamiliar when encountered on the corner of Main Street and Vassar Street. The massiveness of *voussoir* stone blocks and the textured finishes of the Virginia Mist granite are without precedent. The Collier Memorial is uncanny precisely because the physical memorial strangely resembles its computer model but occurs outside the typical design sequence in which the rendering precedes construction. It is both familiar and completely new at the same time.

The essential properties of a material do not translate directly into predetermined architectural forms—bricks do not inevitably become arches—the relationships between materials, geometry, and fabrication are subject to new possibilities. The outcomes may be inflected by the operational logics of the software, as much as by the inherent properties of the material logics (Figure 1.12). The absent figure at the center of the Collier Memorial did not emerge as residual space left over from robotic operation. The void is an intentional component of an operational design logic—the "Boolean"—that is applied to the site, material, and situation of the memorial. The arched gateway of the memorial visualizes thrust vectors in the arch construction while the conspicuous absence of the voided figure inscribed in the buttresses serves a different communicative and rhetorical function, even as it evidences the trace of the technique inscribed in the mass of the stone.