ABSTRACT

This paper tracks the design, fabrication and assembly of Caret 6, a modern Gothic vault project designed using advanced digital software and CNC fabrication technologies. Though not a pure Gothic vault in the traditional sense—no Gothic project was—one—the project takes advantage of the formal, structural and organizational techniques employed by many Gothic architects. Every decision made in the design of the project was influenced by the inclusion of difference and asymmetry and balanced by the need for structural integrity, program and optimization. We relied on the use of current digital design tools to expedite the otherwise impractical fabrication and assembly process caused by the high level of differentiation of each piece (Figure 1).
THE COMPATIBILITY OF THE GOTHIC IN DIGITAL DESIGN

With the rapid development of new digital design and fabrication tools, there has been a steady reemergence of arched form vault projects. The capacity for computational tools to produce countless variations of a highly differentiated form has renewed an interest in Gothic architecture in particular. In their desire to capture the diversity and complexity of nature and in reaction to the inert and often opaque qualities of Romanesque architecture, Gothic architects used distorted and asymmetrical forms to create exaggerated vertical spaces. As John Ruskin noted, Gothic architects believed that “in all things that live there are certain irregularities and deficiencies which are not only signs of life, but sources of beauty. No human face is exactly the same in its lines on each side, no leaf perfect in its lobes, no branch in its symmetry. All admit irregularity as they imply change and to banish imperfection is to destroy expression, to check exertion, to paralyze vitality.”

The use of variation and asymmetry can be found in the work of many digital designers today, and generative algorithmic design processes lend themselves to the development of forms that perpetuate the core principles of the Gothic. The primary characteristics of the Gothic—the pointed arch and ribbed vault—lend themselves to the procedural approach of algorithmic design and the potential for formal variability. Countless forms can be generated and evaluated to achieve a result that best suits the demands of a particular project. Ruskin continues, “The pointed arch was not merely a bold variation from the round, but it admitted millions of variations in itself; for the proportions of a pointed arch are changeable to infinity, while a circular arch is always the same.”

CARET 6: PROJECT INTRODUCTION

Every year, TEX-FAB, a digital design alliance, holds a four-day event centered on digital design and fabrication run by four academics who each teach at a different school of architecture in Texas. As part of the event, TEX-FAB organizes a competition for the design of a full-scale installation themed around a particular construction method and material. The winner partners with an established manufacturer that helps build the final project. The competition brief for 2013 asked for the design of an advanced façade system using metal that would hold additional content for the winning design and complement it by using metal as the primary material for the installation and digital fabrication as the construction method.

The plan of the exhibition was driven by the need to draw circulation through a room with a single point of entry and exit. The desire to unveil content sequentially without revealing the entirety of the exhibition from one perspective informed the initial parameters of the design. As Bernard Tschumi observes in *Architecture and Disjunction*, space is defined through reason but experienced through movement. The final installation includes anchors that unfold sequentially to compel a person to follow a path that slowly exposes the exhibition content. To avoid the monotony imposed by a repetitive display of content on a fixed interval, the exhibition varies in plan and section with content scattered throughout. As Tschumi notes, “adding events to the autonomous spatial sequence is a form of motivation.” Only after moving through the entire space is one able to fully understand both the design of the installation and the content of the exhibit.

Though originally designed for the gallery at the University of Texas at Austin, a primary consideration for the design of the exhibit was that it be able to travel to other venues. Thus, the installation was designed to hold all exhibitions’ content, including prototypes of the full-scale winning project.

NEW GROUND

The demand for a freestanding, content-holding armature necessitated the design of a new ground from which the exhibition could grow. Without physical attachment to a surrounding structure, Caret 6 becomes its own site, prompting alternative interpretations of the project as it moves from one location to the next. As Mark Wigley argues, a building detached from site “does not stand on a ground that preceded it and on which it depends for its structural integrity. Rather, it is the erection of the building that establishes the fundamental condition of the ground.” By creating a new ground, the installation is mobile and reconfigurable, thereby opening new possibilities for variation in spite of the constraints imposed by preexisting conditions at each new exhibition site. The form can be modified according to its own logic and solve issues intrinsic to the design directly, unencumbered by external constraints.

During the initial design phase of Caret 6, the winner of the SKIN Competition had not yet been selected. We knew there would be a large digitally-fabricated-wall designed by the winning team and a series of smaller prototype models showing alternative assemblies of the project, but the dimensional specifications of the...
content were yet to be determined. In order to complete the installation within the semester that the design-build studio was offered, we had to design the project to be instantly reconfigurable to the details of the content, as they became known. To accommodate potential change, the ground-scape of Caret 6 was designed in Grasshopper. We developed several Grasshopper definitions to generate an irregular fractal growth pattern using a two-dimensional diamond shape extruding the height of each diamond according to a falloff map. In addition, we added a hinge to the midline of each extruded surface. The angle of the hinge varied proportionally to the diamond’s height and width. Once the winner 3xLP was announced, we updated the Grasshopper model to reflect the exact dimensions of each piece and began to locate the actual content in the field. The diamonds were then re-aggregated to reconcile the overall form with the new parameters (Figure 2).

The ground was simply the foundation on which content could be exhibited and a bridge between 3xLP and the vaulting portion of Caret 6. Though the ground tied everything together, the relatively two-dimensional diamond pattern had to transition to a three-dimensional volumetric space. The Gothic-inspired vaults of Caret 6 serve as a bookend to the overall exhibition and invite people to experience the exhibition in its entirety (Figure 3).

THE VAULT

The need to pull people around and through the Caret 6 vault led to the asymmetrical column plan. Had the plan been symmetrical, the path of circulation through the exhibition would have been less clear. However, asymmetry introduces conflicting forces that are challenging to resolve, especially when the column bases are not fixed to the ground.

To design the vaulting form and best resolve the forces within the geometry, we used Kangaroo, a live-physics engine that runs within Grasshopper. Using Kangaroo, we were able to generate a series of catenary curves connecting the three column bases. From the curves we developed secondary catenary arches forming surfaces that aggregate into a larger freestanding

CARET 6 AND THE DIGITAL REVIVAL OF GOTHIC VAULTS

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vault structure. The surfaces intersect along ridges that extend toward the center of the vault. Each surface is trimmed at the line of intersection forming a pointed arch that realizes a key component of Gothic architecture (Figure 4 & 5).

However, as with all particle-spring models, the surface is only an approximation of a perfect catenary. For Kangaroo to work, the springs need to stretch, therefore introducing small deformations in the overall shape (Figure 6). To ensure equilibrium, we worked with the structural engineering department at the University of Texas at Austin. Using Robot Structural Analysis, we were able to determine the shell thickness necessary to reduce deflection and the bolting pattern required at the base to transfer load from one rib to another. With the help of the engineers, we also introduced a set of cantilevering wings on either side of the main vault to balance the overall loads creating a set of inverted flying buttress–like wings. The wings extend from the primary catenary ribs and balance the overall form. The asymmetrical form of each wing reflects the irregular loading pattern within the vault and the asymmetrical plan organization.

OPTIMIZATION VS. ASYMMETRY

Caret 6 is the product of a delicate exchange between structural and performative optimization and asymmetrical differentiation of form. As described in Architectural Geometry, “most pure optimal hanging forms are rather limited in their formal language, and working with a mixture of optimal and suboptimal forms increases the vocabulary of forms.” Rather than limit the irregularities that resulted from earlier design decisions, we chose to embrace them for their formal and aesthetic potential.

However, one look at the overall form reveals an overlying bias toward symmetry. Though asymmetries result from local differentiation and some global variation, the general Parti remains nearly symmetric. This is partly due to the structural optimization of the vaults, but also to the lack of both internal and external catalysts that might cause an overall translation of form from its axes. Greg Lynn put it best in Folds, Bodies & Blobs with his observation of William Bateson on symmetry:

Bateson’s insight is that a loss of information is accompanied by an increase in symmetry.... The terms information and difference are almost interchangeable. Homogeneity is understood as sameness or lack of difference, while disorganization is associated with an absence of difference (information) and therefore of symmetry. In this way, difference, information and organization are related.... Bateson proposed an explanation whereby the decrease in asymmetry and the increase in homogeneity was a result of the loss of information. He argues that where information is lost or mutated, growth reverts...
to simple symmetry. Thus symmetry was not an underlying principle of the essential order of the whole organism, but was instead a default value used in cases of minimal information. Symmetry breaking is therefore a sign of incorporation of information into a system...in order to unfold its latent diversities.\textsuperscript{10}

If we consider all deviation from symmetry to be the result of local and specific design conditions, we can identify an irregularity as an important moment. Every system has information underlying its static state, but the manifestation of information-driven change remains dormant until activated. Heterogeneous forms lie within seemingly inert geometries, awaiting triggers to draw them forth. However, a wholly heterogeneous form lacks a framework by which to evaluate differentiation against, thereby rendering all information as noise. As Mark Taylor notes, “for information to be conveyed, there must be neither too much nor too little redundancy. If everything is predictable, no information is conveyed; if there is little or no redundancy, which can determine the parameters of possibility and probability, uncertainty cannot be resolved and once again no information is conveyed.”\textsuperscript{11}

SURFACE INFILL

The asymmetry of the overall form of Caret 6 can be primarily attributed to curatorial decisions related to circulation and the optimization of form. Surface differentiation, on the other hand, was driven by the overall asymmetry, structural design and local conditions intrinsic to the geometry. Though the subdivision of the surface could have been designed to eliminate the appearance of seams, the realization of a flat continuous surface would have been entirely anti-Gothic. Furthermore, the absence of an unvariegated surface, regardless of the overall formal asymmetry, would have reduced the information-carrying capacity of the surface, obviating the spatial and aesthetic potential offered by a differentiated surface. The untethering of components from the plane of the surface exposes additional parameters that unlock new design opportunities. As Jesse Reiser notes, “in becoming too smooth, in reducing difference to total homogeneity, the model actually loses qualities,”\textsuperscript{12} and the loss of qualities—or parameters—limits the project’s potential.
If the ambition of Gothic architecture was to balance the beautiful and the sublime, the inclusion of both smooth forms with graduating variations and sharp, disjunctive moments is core to the resolution of the project. In Caret 6, the overall vault retains the character of a smooth, curved, arching form, while shearing at the subdivision of the surface renders a salient difference at the scale of the unit. To emphasize the variegated geometry at the local scale, we wrote an aperiodic packing script that tiles the same diamond pattern used for the ground surface within the triangular outlines defined by the ribs of the overall vault. Unlike uniform tiling of repeating units, which is constrained by the limits of self-similar adjacencies, aperiodic tiling introduces flexibility in how cells are distributed across the surface. Large cells can pack next to bundles of much smaller cells (Figure 7). An infinite number of packing solutions offer the potential for new patterns to emerge through iterative testing. As Jane and Mark Burry note:

Recent architecture has explored the adoption of some younger mathematical discoveries, including aperiodic tiling (patterns that have a small number of repeating units, but whose arrangement is such that the resulting pattern, unlike orthogonal or hexagonal grids, cannot be superimposed upon itself through translation). Here is an element of mystery and wonder, of intrigue and hope: patterns that can be known by their generators, but never known top-down in a stultifying or all-encompassing way—-their manifestation by its nature unpredictable, offering visual and aesthetic sustenance.

Although we used the same diamond pattern for the ground surface aggregation and the vault subdivision, the applications were different. The ground surface is bound only at the end where it connects to the vault. From that constraint, the pattern grew to accommodate content and circulation. The tiling of the vault, however, was limited by the location of the primary ribs. To help mitigate the difference between the two aggregation techniques
CARET 6 AND THE DIGITAL REVIVAL OF GOTHIC VAULTS

Axonometric Plan (Bieg 2014)

Rib Structure (Bieg 2014)
and to reinforce continuity between the ground surface and the vault, the tiling was executed in plan. Had the pattern been applied to the normal of the vault surface, each diamond would have stretched to resolve the misalignment between the curvature of the surface and the outline of the shape; the distortion of each diamond would have caused too great a rift between the ground and vault pattern. Only objects that are projected orthographically retain their original shape. The orthographic projection of the diamond pattern vertically through the thickened vault surface causes an elongation of the cell within which the diamond is framed. The height of the elongated cell is exaggerated where the surface of the vault nears the fixed point of the catenary thereby affirming the Gothic aspiration to accentuate the verticality of space.

To avoid an overly synthetic relationship between the curvature of the vault and the differentiation of the cell, we modified the Grasshopper definition used to hinge the surface infill on the ground. Rather than project the hinge orthographically from the plan, we projected it from the normal of the surface. Had the hinge been offset from the planar projection, the oblique angle of the hinge would have further alienated the ground pattern from the vault. Offset from the surface normal, the hinge retains the parametric relationships between ground surface diamond width and hinge height.

**MATERIAL: SURFACE**

The overall asymmetry, the variability of each cell and the transition from the relatively flat ground surface to the volumetric surface of the vault enabled the resolution of the project within the tenets of Gothic architecture. Materials for the project were selected to either emphasize these qualities or mitigate conditions that were in conflict with the overall project goals. The use of three different materials, rather than a single composite, in Caret 6 increases the number of adjustable project parameters and enriches the experiential potential of the space. As Mark Taylor argues, “differences are neither independent nor indifferent, because reciprocal determinations render them mutually constitutive. The differences that form identity can only merge in a unified whole that is in some sense more than the sum of its parts. Parts and whole exist in and through each other in such a way that each brings forth and sustains the other. Parts create the whole, which in turn, creates the parts.” Each material is integrated into a cohesive assemblage in which no material can be excluded but remains identifiable.

Polypropylene was selected for the translucent infill on both the ground and vault surface to further ease the transition between the two. Though the material is the same, the passage of light through the infill surface can be seen only from below the vault, offering a range of unpredictable visual effects as one circulates through the project. The location of light fixtures, light type, depth of rib and angle of surface promote additional differentiation beyond what the aperiodic tiling already provides. Translucency exaggerates the depth of each cell by multiplying and projecting shadows across the surface and ribs. At the same time, the shear caused by the aperiodic tiling of cells exposes the rib at the seam between tiles so the ribs are not completely obscured by the translucency of the surface. After all, another core tenet of Gothic architecture is the expression of the rib.
MATERIAL: RIB

In his essay on the nature and history of curved lines, Lars Spuybroek highlights the importance of ribs and their use in Gothic architecture. As opposed to the curves used in Art Nouveau, which are fixed at one end and allowed to flow freely at the other, Gothic curves are fixed on both ends and variation occurs in the middle (Figure 8). The variable potential between the two ends provides opportunities for lines to branch while maintaining structural integrity. In so far as the primary line is resolved at both ends, additional lines may branch from the middle of the primary line "at any time, precisely because the systemacy encourages the sharing of tangents . . . In Gothic tectonics, everything is created out of ribs." 17

Alpolic, a rigid composite material made of polyethylene sandwiched between two thin sheets of aluminum, was used for the ribs (Figure 9). Though the primary ribs are continuous catenary curves, the secondary and tertiary ribs are for the most part discontinuous. The secondary and tertiary ribs are formed by the aperiodic tiling of cells and curves extracted from the secondary catenary surfaces that were used to generate the surface of the overall vault form. Although the organization of secondary and tertiary ribs is stable in multiple configurations, the need to disassemble and reassemble the installation in a short period of time necessitated changes to the original Grasshopper script. This feedback led to the integration of some secondary ribs that were continuous between primary ribs. By including continuous secondary ribs, the installation can be disassembled into twenty partial assemblies. The entire vault surface can be disconnected and then reassembled in a matter of hours. For longer trips and storage, Caret 6 can be broken down to individual components and flat-packed in a relatively small space (Figure 10 & 11).

CONCLUSION

The most surprising moment of the installation occurs at the transition between ground and vault. At this point, the installation is neither volume nor surface, but something in between. Where the highly differentiated surface of the vault meets the irregular pattern of the ground, a new form begins to emerge. The conflicting geometries achieve resolution by multiplying the varied conditions of each, exhibiting a quality akin to wrinkles in a cloth. As famed illustrator Burne Hogarth writes, "Wrinkles are not independent, exclusive agencies of form. The divisions of wrinkles and folds... [are] part of a coherent system of movement and response." 18 Loads are not transferred to the ground surface from the vault, so the integration of the two is not motivated by structural requirements; it is the formal resolution between the two halves that ties the installation together.

While the tenets of Gothic architecture are clearly conveyed in the vault, surface and rib structure, the transition between vault and ground fuses the project’s features into a synthetic new representation of the Gothic. The wrinkle is not a breakdown of Gothic articulation, but a new form of Gothic exuberance. Tschumi argues:

The recent widespread fascination with the history and theory of architecture does not necessarily mean a return to blind obedience of past dogma. On the contrary, I would suggest that the ultimate pleasure of architecture lies in the most forbidden parts of the architectural act; where limits are perverted and prohibitions are transgressed.... Exceeding functionalist dogmas, semiotic systems, historical precedent or formalized products of past social or economic constraints is not necessarily a matter of preserving the erotic capacity of architecture, but disrupting the form that most conservative societies expect of it. 19

To merely re-appropriate the core principles of Gothic architecture does not acknowledge the foundation on which Gothic was based, nor does it engage current tools and techniques. By using emerging digital design and fabrication technologies in the design of new forms of Gothic architecture we pay tribute to the original principles of the Gothic, while also advancing them.

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