AIA TAP AWARDS 2015

THE BRIDGE
OVERVIEW

The D-Bridge is a yet-unbuilt architectural project and experimental structure that serves as an extension to a private gallery and residence in the Philadelphia area. Our office worked in close collaboration with facade and BIM experts, as well as several other fabricators and consultants in the greater Philadelphia region. A design team of between two and three worked on this project, primarily in the Summer of 2014.

It is our intent to present the Bridge as a case study in small-office technological design and information management. The desire to design and construct a project like the D-Bridge grew from a BIM-like philosophy that is a founding ethos of our office. The knowledge and tact to execute the project grew from close collaboration with contemporary BIM experts, as well as adopting tools and expertise from the burgeoning open-source community around Rhino and Grasshopper.

We were thereby able to transform our primary tool for geometric control into our organizational system for the entire project—which we used in totality from formal experiments, to visualization of data, to coordination and design of building systems, to fabrication management, to delivery logistics and construction scheduling. All managed from within the software we already use for 3D modeling and drawing.
The D-Bridge (Bridge) is a single-story, single-room, 1200SF building that acts as an enclosure along a path between an existing residence and an Art Gallery. The building is a thickened shell with canted glazing and six door openings—it is environmentally controlled, and it provides both a programmatic link between living and gallery spaces, and a series of smaller, more intimate porch-like spaces around the boundaries of the buildings.

The core feature of the Bridge serves as both its form and structure—in this case, over 1000 laser-cut, folded cells made from flat sheets of stainless steel (voxels). Each voxel is easily handled by an individual, starting around the size of a shoebox (8\"x8\"x10\"), up to about the size of a lawnmower (32\"x32\"x14\"). The voxels form a shell, a pelt of sorts, which wraps the enclosed volume under a complex honeycomb of tightly-interlocking, riveted-together metal parts. The interior surface of this shell was the primary geometric component onto which all other geometric controls were grafted and grew. The edges of the shell fit snugly into the details of the adjacent buildings, and it carries its load down to three legs which touch down in the surrounding meadow. The overall shape of the shell was finely controlled for its external connections, its internal constructability, its structural capacity, the interior and exterior views it provided, and the experiences inside and on site that it engendered.
CULTURAL CHANGES

In this project, we developed cultural changes in practice, in which we were able to engage everyone involved in the project in a way that was consistent with a set of principles we, and the client, cared about in the beginning of the idea.

We were able to convince our collaborators, often (usually) in positions of assuming more risk than us, that the project could keep moving forward despite ongoing uncertainties that were still in development. This marks a change in our relationships with collaborators.

By being robust about developing the engine for BIM in Grasshopper, and by being rigorous about providing constant material and maps about our process and goals to our partners, we were able to create comfort zones where there normally were none.

Another important cultural shift we felt in this project was the communication and collaboration with the online community of individuals developing the Grasshopper platform.

Our work built directly on the work of Grasshopper’s developers, following closely with the content that is released for free online, and talking openly about our work with the community of mutually interested people on the Grasshopper forum site.
ON GEOMETRIC CONTROL

When we speak about geometric control in the Bridge project, we mean both the act of generating and manipulating the shapes of the model, and also the hierarchy of data relationships that depended on that geometry. This concept is the basis of a BIM system—what made our process special was the extent to which we tied almost all design components and outputs back to the base geometric process.

This primary geometric control is in our case a scripted process in Grasshopper that is adopted from work that is just being developed in 2014, and which is free online for anyone to use. These scripts form part of the substance of what is now the Kangaroo Physics engine, a plug-in for Grasshopper that has already exhibited amazing potential in both architectural design and engineering.
ON GEOMETRIC CONTROL, continued

That script takes a mesh geometry and simulates forces on its vertices to reshape the packing of the mesh. These forces are behind what is known as a “circle packing,” a well-researched mathematical problem that can be visualized as the optimal tight packing of circles into a 3D surface. The circle-packing script, as adapted to our design intentions, has two very important functionalities. First, it allows us to specify regions of more densely or loosely packed parts. Then, it pulls those parts into the best-balanced spacing possible within our constraints. These two functionalities were extremely important, and the crux of the power of the BIM engine driving the project.

The latter quality, the balanced spacing, allowed us to improve the structural properties of the shell in broad strokes, toward the requirement of it being supported by the metal voxels alone. The former quality, the regional densification, also had structural consequences—but more importantly, it allowed us to adapt the packing of the shell to a comprehensive set of other constraints on the building. This packing informed the efficacy of the insulation and waterproofing systems for the shell, provided detailed paths for air conditioning ducts and diffusers, met the glazing line and roof edges structurally as a series of stiffened plates, and created a highly diverse environment of visual effects on the outer/under surfaces of the shell.

Going further, we linked material properties, costs, and fabrication logistics from our partners into the BIM engine as well. This we called the secondary geometric control. Having this layer of control allowed us to get instant feedback on how changing the geometry slightly could effect substantial changes in cost, time, and feasibility. This extended even to the physical logistics of on-site equipment and ease of constructability—this is to say, we used the geometric control to guide the design of the Bridge into a set of parts that was within the specific cutting, storage, shipping, and building capabilities of each of our partners (including using the fabrication resources of our own office).
BENEFITS OF BIM METHOD

We were able to adapt and internalize the model management work that normally would have been billed to consultants. This helped us clarify all parties’ scope, while keeping everyone connected and open to bigger conversations about design and data. This spared the project costs on fees while creating an environment to learn.

We were able to alter material specifications and assembly plans to adapt to the capabilities of fabricators. This allowed us to significantly reduce estimates on construction by working within size constraints that alleviated the need for large jumps in scope and price—such as bringing heavy equipment on site, or keeping builder teams small to handle building parts.

We tied the structural analysis and geometric packing of the shell tightly in the BIM model. Then, tying the outputs from the model to information on costs from fabricators, we were able to see live updates on cost, and fine-tune changes in the shell that could see large drops in cost. We were able to cut some early laser cutting estimates in half.

We recreated the functionality of other softwares (used by fabricators) like Solid Edge in Grasshopper. So, instead of solving the problem in terms of data interoperability, we made our BIM process speak directly in the language of the fabricators’ tools—cutting out the need for backend work on software on the fabricators’ end. We reduced their scope, and thus costs.
**PROCESS CHANGES**

We consider our BIM environment, created and driven in Grasshopper, innovative for several reasons.

It has the functionality expected in other BIM workflows—of controlling construction drawings and schedules directly from the front-end manipulation of simple parameters in a digital model. This is manifest in the direct link between the base geometry (of the slab, and shell), and documents like the final glazing schedule.

For a small practice, we believe this is innovative, in that it appends the type of BIM power wielded by larger teams onto a platform (Rhino) that is in common use and within the grasp of individuals. We were able, with a team of two, to communicate fluently in the languages of both Front Inc. and our client, with drawings and data that were flowing from Grasshopper.
Deeper, at its roots, the BIM system is designed with the expectations of massive design and engineering changes along the way—changes that can trace backwards through the workflow, reinforcing and re-actualizing the project as we went. This, to us, is the core philosophy of BIM. We went further, and used the D-Bridge to test some of these “holy grail” notions of BIM (an Architecture Butterfly Effect), and to try to test the limits of automation and parametric data management for a small practice, in a project of reasonable scale and scope.
Having developed a pathway for design input via the PGC, the design development of the structural voxels evolved.

The term voxel was adopted for the concept of a volumetric pixel. It is a three dimensional structural unit which nests together to create a continuous structural shape (think igloo on crack). For this project the voxel was an attempt to use our ability to control the data set in order to inexpensively develop a structural shell.

We had considered making the shell in a more monolithic manner - using either field constructed plywood shell such as a fuselage. We also were interested in using basic boat building techniques to make an epoxy resin and fiberglass (or carbon fiber shell). Both means of construction had longer lead times and a larger duration of on site work.

With the Voxel concept of construction, the geometry of the shell is captured in each individual unit (voxel) so that when assembled the shape emerges. To us this is the moment of “embodied intelligence”, where the voxel is derived as an intelligent part. With each voxel holding a place in the shell and a known relationship with its neighbors (which can be indexed and mapped), the order of construction operations is no longer held to a linear timeline.
Since the Design Surface is a relatively fixed surface area – the density of the polygons is also established via an interpretation of ranges of sizes, overall polygon count, and number of sides to each polygon.

- Early studies were ranging between 460 polygons packed to 1200 polygons.
- Size limits were developed by speculating the overall weight per “structural unit”.
- Beam lengths for the faces of each polygon were to be held under 3 ft.
- Visual density played a role as well in determining overall count goals.
- The fabrication time and cutting costs were also interpolated into the setting counts.
- There were also inputs as to the range of the number of polygon sides.
**TOP PLATE VARYING MATERIALS**

- Independent top allows variable gauge thickness for mapping structural performance & cost of production / material
- Each top plate is drilled or laser cut with the hole pattern which relates to the folded tabs of the rolled section assisting in the cost, ease and precision of the fabrication
- Tops would be indexed with related voxel neighbors information for a built in assembly map, this is not only good sense for coordination – it also directly reduces cost by shifting the “nature” of the crew required to assemble the sets into shards using a riveter.

**SIDE WALLS 16GA STAINLESS STEEL**

- Used as an edge and angle guide for the roll up operation
- Independent bottom plate allows variable gauge thickness for mapping better structural performance more granularly
- Bottom plate was designed to have a large hole in the middle of the plate – this allowed for post assembly work to be done in the proper sequence.
- The bottom plate hole played a role in the development of the visual voxel system set. It was understood that the profile of the hole edge was liberated to perform as a secondary geometry reference.
- The flange area varied according to the voxel size and also in relation to the overall structural analysis.

**BOTTOM PLATE VARYING MATERIALS**

- The primary geometric element of the voxel – is developed to share planer faces with each of its neighbors – thus the pyramidal shape of each voxel.
- Each web section has a face to face relationship that required a rationalization of the geometry in order to be certain the faceting of the polygon faces on the design surfaces would be compensated for in the tapered faces.
- Each web section has a variable depth – the depth is influenced by:
  1. Structural performance
  2. Air passage (sections of the voxels are used as the primary ductwork for the delivery of conditioned air) the sidewalls have knockouts which are based on a developed airflow performance.
  3. Interface with architectural systems, glazing, hvac, trim conditions, and structural systems.
- Each sidewall is indexed for coordination with neighboring units.
- Each sidewall would be cut or drilled for the voxel to voxel connections – this is key to the preservation of the shell shape overall and retain a “known” faceting of the shell (this is important in the development of the insulation on the outside of the shell, the step where the design surface wants to be reestablished. Compensation for faceting.)
- Each web section also had cut into its flattened profile – all of the necessary tabs which would provide attachment points for the top and bottom plates. These tabs were also predrilled to coordinate with the holes in the top and bottom plate – acting as a geometry check as well as a fastener.

**STRUCTURAL VOXEL PARAMETERS**
In all, the job requires about 300 sheets of 60” x 120” sheet metal. About 200 of these at 16GA and 100 are 12GA. These figures are rough, and bound to change slightly before the final order.

The linear amount of laser cutting is about 400,000 inches. This includes dashed cuts along the edges to assist bending, and the cutting of all rivet holds.
TYPICAL FLAT SHEET
Showing nesting of three unrolled sidewalls and one top cap.

WEIGHT AND MATERIAL MANAGEMENT SHEET
Note sizes of MAX, MIN, and AVERAGE voxels.
Average voxel is about 18” and weights about 22 lbs.

MATERIAL EFFICIENCY READOUTS
<table>
<thead>
<tr>
<th>VOXEL</th>
<th>Summary Totals</th>
<th>1107</th>
<th>4474.641</th>
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<tr>
<td>voxel type</td>
<td>name/description</td>
<td>voxel count</td>
<td>web area (FT2)</td>
<td>top plate area (FT2)</td>
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<td>S06</td>
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Seals + Gaskets

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<tr>
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<th>part length (FT)</th>
<th>part volume (FT³)</th>
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<td>S002</td>
<td>Weatherproofing Silicone (Dow 791)</td>
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Hardware

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Steel Sheets

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<th>name/description</th>
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<th>part area (FT²)</th>
<th>Weight (LB)</th>
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</table>

*approximate sheet area based on 30% waste yield

** hardware + steel sheets counts only reflect S01 counts. Paramaterization of additional typologies under development
CONSTRUCTION LOGISTICS + BUILDABILITY

Each voxel could in theory be made in the same day in many different places and then converge upon the site to be assembled into a shell. With our goal of limiting site time we knew the voxels could also be aggregated into larger pieces in an offsite fabrication space - we refer to these first stage assemblies as "shards".

The shards can be any size but for the purposes of this project we were looking to limit the shards to a size manageable by hand with four people. Thus our earliest work was to establish an intuitive understanding of voxel size ranges and sheet metal gauge weights in order to extrapolate loose guidelines for assumptions regarding the overall composition of the shell. This influenced early packing assumptions and mapping influences into the packing of the surface.
The basic premise of the voxel geometry was to link the top surface (TSV) to the design surface and allow the sidewalls of the voxels to extrude from the polygon shapes developed in the packing/mapping exercise using the PGC.

The bottom of structural voxel (BSV) is based upon a secondary design surface. That surface has been developed in the context of the variables associated with:

- Structural depth – related to interpreting and linking stress mapping in the shell to the overall depth of voxel.
- The visual appearance of the overall shell geometry
- The walk through experience of individuals in the space.
- Relation to secondary systems such as ductwork (the voxels are to function as the ductwork themselves and therefore have a min effective opening)
- Ability to develop thermal performance through insulation
- The evolution of the visual voxel design work.
- The primary geometry of the polygons is projected onto the secondary design service while being mindful of the taper in relation to the geometry differences and curvature. This is done through an evolved “rationalization process” which insures that adjacent voxels share a clean planer face.
The material properties of sheet metal have enough variability in physical properties, material type, thickness, simple tooling, weld-ability, etc. without changing the evolving design strategy or the design/fab strategy. We have simultaneously considered multiple gauges of material thickness to relate to overall shell strength (relating to structural analysis models), while relating back to secondary impacts on the process in time and dollars.

Our second opportunity for utilizing embodied intelligence in the construction/fabrication process was in the consideration of the development of each voxel unit. The design criteria for the sub units of the overall structure were relatively simple: lightweight, strong, inexpensive, flexible as a system, workable by our team so we could maintain the one to one feedback loop.
FACTORICATION

SIDE WALLS
ORDER OF OPERATIONS

Bending Tabs  Rolling  Aligning Tabs

TOPS & BOTTOMS
RIVETING
ASSEMBLY
Though the structure is a self-supporting shell, it does not act like a true vault. The aesthetic intention for the roof profile is that of a low-sloping curve, thus falling in the domain between that of a conventional portal frame and a true arch or vault.

The structural requirements are therefore not universally dictated by compression or flexure, but by the combined interaction of the two. Analytical studies were aimed to resolve the effects of flexure and compression in aggregations of voxels, both at the global and local scale.

In general, flexural resistance is developed via the depth of the shell; the deeper the shell, the greater flexural capacity. A global assessment of the required flexural strength could then allow for the optimization of the shell thickness. Compression failure occurs via buckling of the voxels, which is related to the voxel diameter, another parameter than can be optimized. In summary: flexure is controlled by depth, compression by voxel diameter. The studies described herein examine the effect of these loads at many scales, ranging from global analysis to the scale of individual components.
The engineering of the structure is executed with a rules-based approach, such that the design input can be altered and the engineering output regenerated with minimal overhead. By implementing a rules-based approach throughout the various stages of the workflow, each stage can be developed independently without breaking the chain of information. This allows multiple parties to engage and own varying portions of the project workflow, while maintaining a consistent informational framework. Ultimately, design, engineering, and fabrication can then progress simultaneously and in parallel, thereby compressing the overall project timeline.

Structural Consultant

1) Compression at corner  2) Bending at corner
3) Compression perpendicular to face  3) Bending perpendicular to face

Parametrically Generated Voxels of Varying Aspect Ratio
01. We drastically reduced the number of absolute, independent parts in the building. This allowed us to talk clearly about changes that needed to be made. After that, we had amazing freedom to experiment with geometry, construction logics, and formal effects of the dependent parts of the building. By keeping certain pieces simple, we were able to let the downstream pieces run wild to complex effects.

02. We were likewise able to design the mechanical systems through our own BIM engine, with advice for general parameters and paradigms from our consultants. This kept the billable hours with MEP consultants to a minimum, while increasing the value (and fun) of the time we did spend with them.

03. We were able to work with our collaborators and consultants on sets of deliverables that supported a range of architectural solutions—rather than singular, terminal, engineered answers. We were able to glean intuitive data from Front Inc that allowed us to take specific steps forward ourselves, without the expertise that Front has.

04. Along those lines, we were able to liberate the idea of tolerances, alleviating fabricators, suppliers, and builders from the assumed risk of conforming tightly to our highly complex set of parts. We went from fabricators expecting a hundredth of an inch, to us giving them a foot. This was perhaps our strongest tool in pulling down cost at several stages of the project.

05. We were able to build and keep design at the same time, so that metal parts were coming off the line while other conditions were still being finished in the model—and all the while we could make design changes that would instantly be updated and reflected in the process of making parts downstream. This let us collapse several timelines into one. The Dantchik Bridge went from sketch in Rhino, to ready-to-build in just over two months.
thank you!