CONCEPT TO REALITY: COLLABORATIVE PARAMETRIC WORKFLOW FOR A FREE-FORM DOUBLE-CURVED CABLE STRUCTURE

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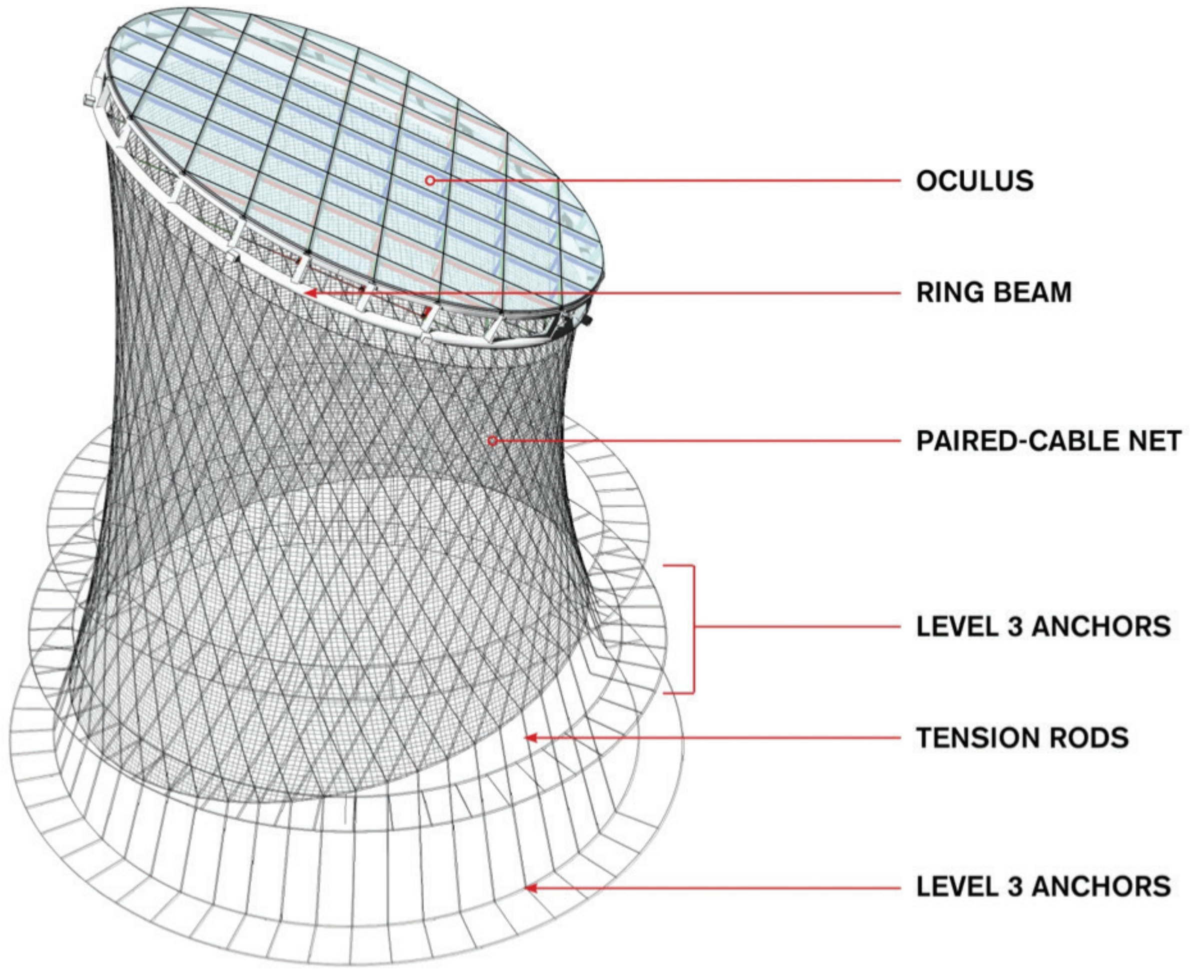
New York's Fulton Street Transit Center includes an above ground structure to improve the underground linkage of six subway stations and eleven subway lines in lower Manhattan. The construction includes an interior atrium shaped by a double-curved tensioned cable net clad by a perforated metal panel system. This Sky Reflector-Net© is an integrated artwork for the Fulton Center. It represents an artistic, architectural and engineering collaboration between James Carpenter Design Associates, Grimshaw Architects and Arup. The Sky Reflector-Net© was commissioned by the Metropolitan Transportation Authority Arts for Transit and Urban Design, and the MTA Capital Construction Company.

Light penetrates the atrium through an oculus before being redirected into the depths of the Center, providing the subterranean levels with a connection to daylight. The interaction of the reflective metal panels with daylight during the day and artificial light at night will create an ethereal effect and glowing icon. Attached to the two-way cable net are 952 unique metal panels cladding 8,524 square feet of surface area. There are 17 rows along the height of the net, each with 56 nodes and 56 metal panels. The top and bottom rows consist of triangular panels. All other rows consist of rhomboid shaped panels cut planar and folded in halves to form two triangular facets. The fabrication of these metal panels is a challenging task, and therefore it was prudent to develop an automated process for producing fabrication drawings, information for the metal panels, stainless steel cables and components.

PRE-CONSTRUCTION ESTIMATING

When dealing with complex geometries and specialty structures it is critical to develop accurate estimating take-offs to put together a competitive bid. For the Fulton Street Transit Center proposal, an accurate bid for the interior cable-net feature was achieved by generating a 3D geometry model using nodal coordinate information from the structural engineer. The structural drawings received during the pre-sale effort included a table of 1056 nodal coordinates, each with an X, Y and Z component, to define the final stressed geometry of the tensioned cable net. Generating a model specifically rooted in these prescribed coordinates was advantageous in completing an accurate take-off. Once the control points were organized within Microsoft Excel (maintaining the original naming convention), a process was developed to stream this data into a dynamic three-dimensional model. By developing a custom component within Grasshopper (a parametric tool for Rhino), it was possible to stream the spreadsheet coordinates into the Rhino model automatically. After verifying the accuracy of the work-point population, these points were used to generate the centerlines for the



stainless steel cable members and tension rods which makeup the cable-net. The work-points and centerlines represent the control design geometry, but the finished surface of the metal panels is offset as the result of the component assemblies. The net geometry is offset to develop a finished surface in parallel to the original design surface. Using parametric input, the value can be changed at any point within the design process and all other tasks will immediately update.

The role of the model during pre-sale efforts was focused on estimating the cable lengths. This was managed by one design engineer. Furthermore, at this stage, the model served as a study of fabrication and installation means and methods. Moving forward in project delivery, the parametric model is used for structural analysis to predict the elongation of cable lengths when subject to loading, and used to automatically generate fabrication drawings for the 952 unique rhomboid and triangular perforated metal panels that wrap the net geometry.

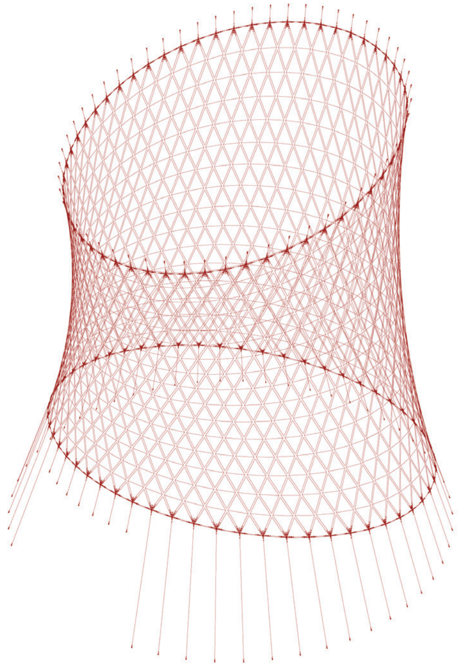
FIGURE 1
Solar reflector shell system components summary.

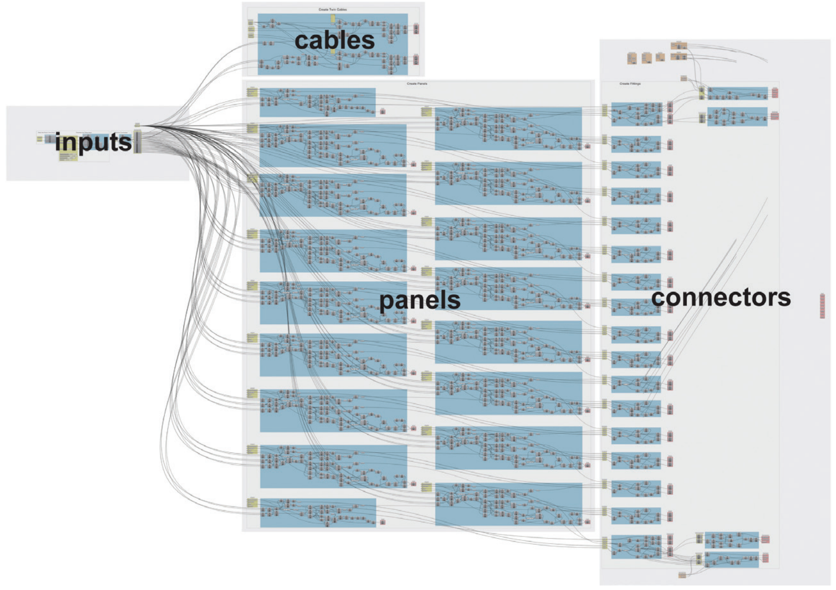
FIGURE 2
Grasshopper routine with development of system components (bottom) and parametrically controlled output (top).

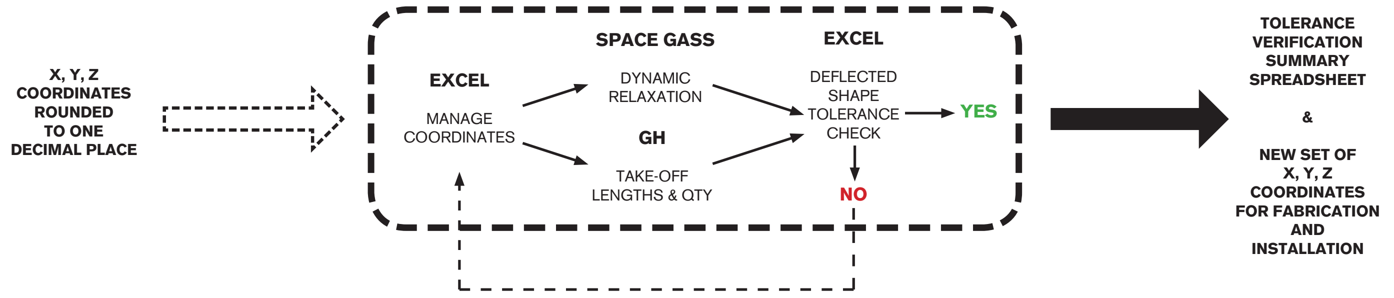
STRUCTURAL ANALYSIS AND CABLE DEVELOPMENT

The parametric model initially developed for estimating did not become obsolete once the project was awarded. In fact, it served as the source for two critical developments in delivering the constructed form. First, the Rhino 3D model information was streamed from a master Excel worksheet via Grasshopper into a structural analysis tool's database to validate the integrity of the construct under prescribed loadings. The structural analysis tool SPACE GASS was used to perform the structural analysis, but utilized the geometry and naming conventions common to the database so that the results could seamlessly integrate back into the workflow with a common nomenclature. This first development validated the component sizes and details for structural adequacy. Secondly, for fabrication purposes, one of the most significant contributions from the structural model was reverse engineering to determine the initial unstressed cable net geometry. This iterative analysis was used to predict (within an acceptable tolerance) each unique cable segment's elongation to determine the initial length of each cable. Additionally, the location of each cable intersection was determined to ensure the final form is within construction tolerances.

Following a successful completion of the structural analysis, workflow could advance to developing fabrication information for both the cable and panel systems. The unstressed cable geometry information was developed by the structural engineer to ensure consistency with the analysis model. A series of template worksheets were established so that all structural analysis output information could simply be pasted into a Microsoft Excel worksheet, utilize Visual Basic commands, and perform auto-lookup and auto-fill functions. The workflow development between Microsoft Excel, Rhino 3D, Grasshopper and SPACE GASS







was established by the aforementioned design engineer, but now included a structural engineer to carry out the repetitive development of cable-geometry. Working with Rhino 3D and Grasshopper was a first for the structural engineer, but once tools were established to make the structural workflow of a completely variant geometry, this individual grasped the value in handling the project's complexity and optimizing (or easing) their efforts.

AUTOMATIC PANEL GENERATION

Due to the variant nature of the metal panel geometries and perforations which clad the cable net, ensuring accurate fabrication was viewed as a potential challenge. The Grasshopper routine was refined to accurately and automatically model the panel geometries in 3D space, unfold along the seam into a flat pattern-cut geometry and place within an ordered drawing workspace. The engineering team developed custom components within the Grasshopper work environment using VB.NET programming language. When paired with many of the common routines built into Grasshopper the custom components are able to respond to changes made within the Excel worksheet, as well as through many "flexible" parametric controls which may be modified at any point during the project delivery.

The automatic panel generation was performed internally using the same x, y, z coordinate database. In a system that doesn't have one typical condition, but instead 1056 unique nodal conditions and 952 unique panels, designing the logic of the panel geometry reduction was more efficient than applying the logic on a case-by-case, panel-by-panel basis. Essentially, all panels were derived through the Grasshopper routine and can be baked into a model space, left as raw data for extraction, or both. For this project's delivery approach, the metal panels were supplied by a sub-vendor that performed an independent panel geometry reduction that was then corroborated with the Studios' parametrically developed data. This verification step was not an overlapping of models or evaluation in three-dimensional space, but instead it was a series of dimensional data extract summarized in tables for comparison between entities. This is an example of where there are still opportunities missed in maximizing the digital information directly to the fabrication process, often times as a result of contractual or legal uncertainties. Nevertheless, the parametric workflow lent a set of quality control measures without any additional work beyond what was necessary in the aforementioned phases. By this point, a third member of the parametric workflow collaborative had been integrated and was leveraging the workflow for coordination of fabrication data with material vendors.

BETA-PHASE: THE MOCK-UP

One challenge in transforming the Grasshopper tool from a spreadsheet table into 952 pattern-cut drawings for a fabricator is grasping the sequencing of logic from one work environment to another. In order to validate the accuracy of the tool and serve as a beta test for the engineering team, the custom process tools for automatic panel generation and structural analysis was applied to the project mockup. A section of the cable net including 20 work-points and 13 metal panels was drawn for fabrication and visual mockup. One engineering team performed a manual derivation of the panel geometry in parallel with the automatic panel generation tool by a second engineering team. Any inaccuracies in the manual model or automated fabrication drawings could be identified and resolved before extrapolating the routine across the entire geometry. The accuracy of the tools in the mock-up phase served as a beta test for the engineering team of the custom process tools for automatic panel generation. Ultimately the project management and leadership became comfortable with the new workflow model as a widespread project approach moving forward.

At this phase, the information generated out of the parametric workflow was feeding fabrication information to the stainless steel cable/rod

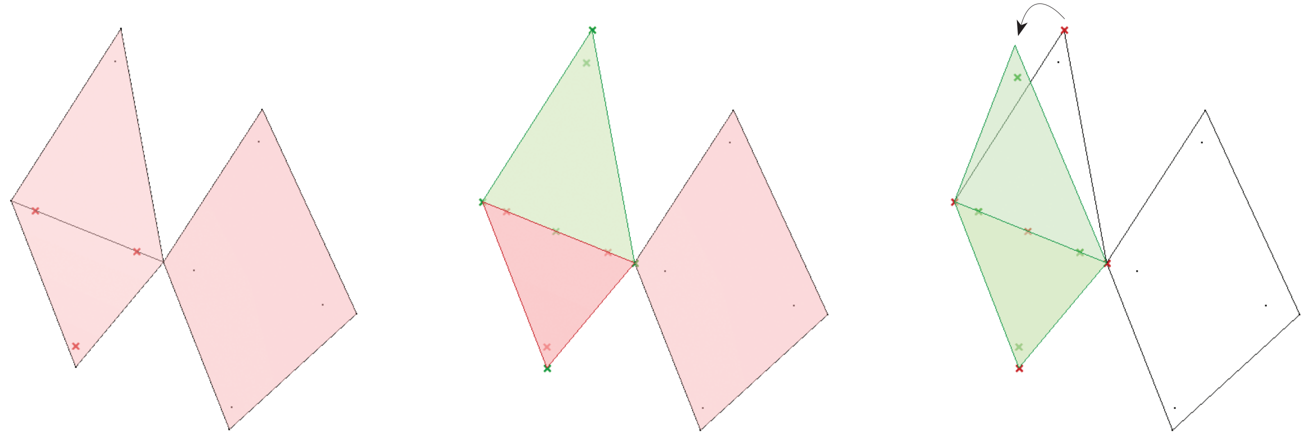
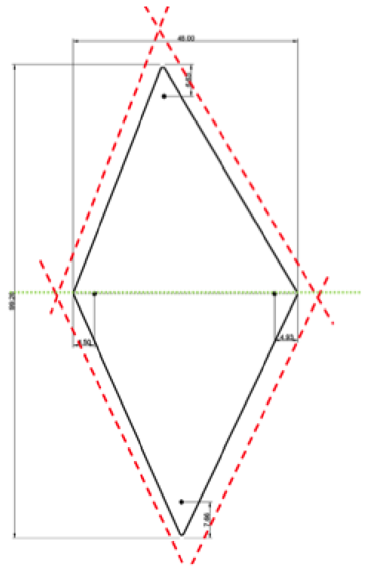
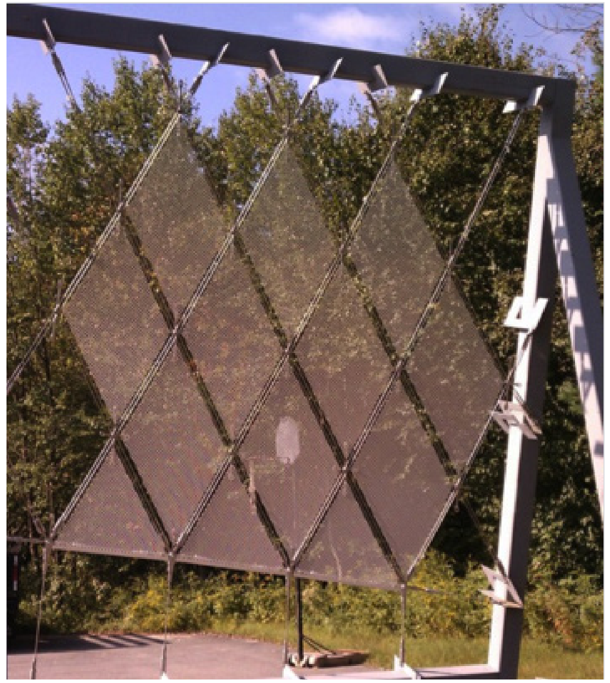


FIGURE 3
Workflow process for structural analysis sequence with input (left), feedback loop (center) and output (right).

FIGURE 4 + 5
Process of re-orienting the folded panel into a planar geometry for metal panel fabrication pattern cuts, unique panel geometry logic and coordination dimensions (right).





supplier, used to verify independent models from the metal panel fabricator, assist in survey crews' evaluations, and coordination with the project management and field team. The mock-up served as formal approval for the system's erection quality, and a confidence builder in the understanding of the parametric workflow's effectiveness, quality and accuracy.

COMPONENT CONSIDERATIONS

Along the way there were a number of detail modifications from bid documents that were introduced due to heightened performance requirements. One such change required a larger bolt connector at the panel-to-paddle interface than what was initially intended. As a result, the universal paddle's built in tolerance – already minimal and sensitive in its initial design – was reduced beyond an acceptable limit. This spawned a series of parallel evaluations, both internally and by the structural engineer, to evaluate the universal paddle connector's linear nature across the double-curved panel geometry and its bolt hole locations. This virtual back and forth exchange was a blind development of Grasshopper routines with Excel reporting to find the parts of the cable-net that were most affected by what was deemed co-linearity. These evaluations of the fixed horizontal paddle geometry exposed different understandings of the bolt hole configuration early, but it wasn't until a face-to-face meeting between the two parties that both sides came to fully comprehend all concerns, arriving at a collective solution utilizing the universal paddle connector, and preserved the desired field tolerances without creating over-sized holes.

With 1056 nodes all using a whole or part of the universal paddle connector, it was important to understand the fit, adjustability and scale of the assembly. Three-dimensional printing was performed to create 1:1 scale prototypes of the assembly for the project very early on. This allowed the project team to visualize the system, understand how it could be universally applied to a free-form surface, and communicate its intricate nature.

PREPARING FOR THE FIELD

As the project neared installation, a heightened priority was placed on honing installation techniques and sequences, as well as developing a strategy to validate that installed positions are within tolerance. Surveying the installed geometry would be a challenge due to the dynamic form and intricate locations of work-points. Coming full circle to the original estimating model developed in pre-design, an Excel spreadsheet was paired with incoming survey data from the field to verify tolerance and adjust fabrication drawings to the as-built net geometry where required, specifically at the 56

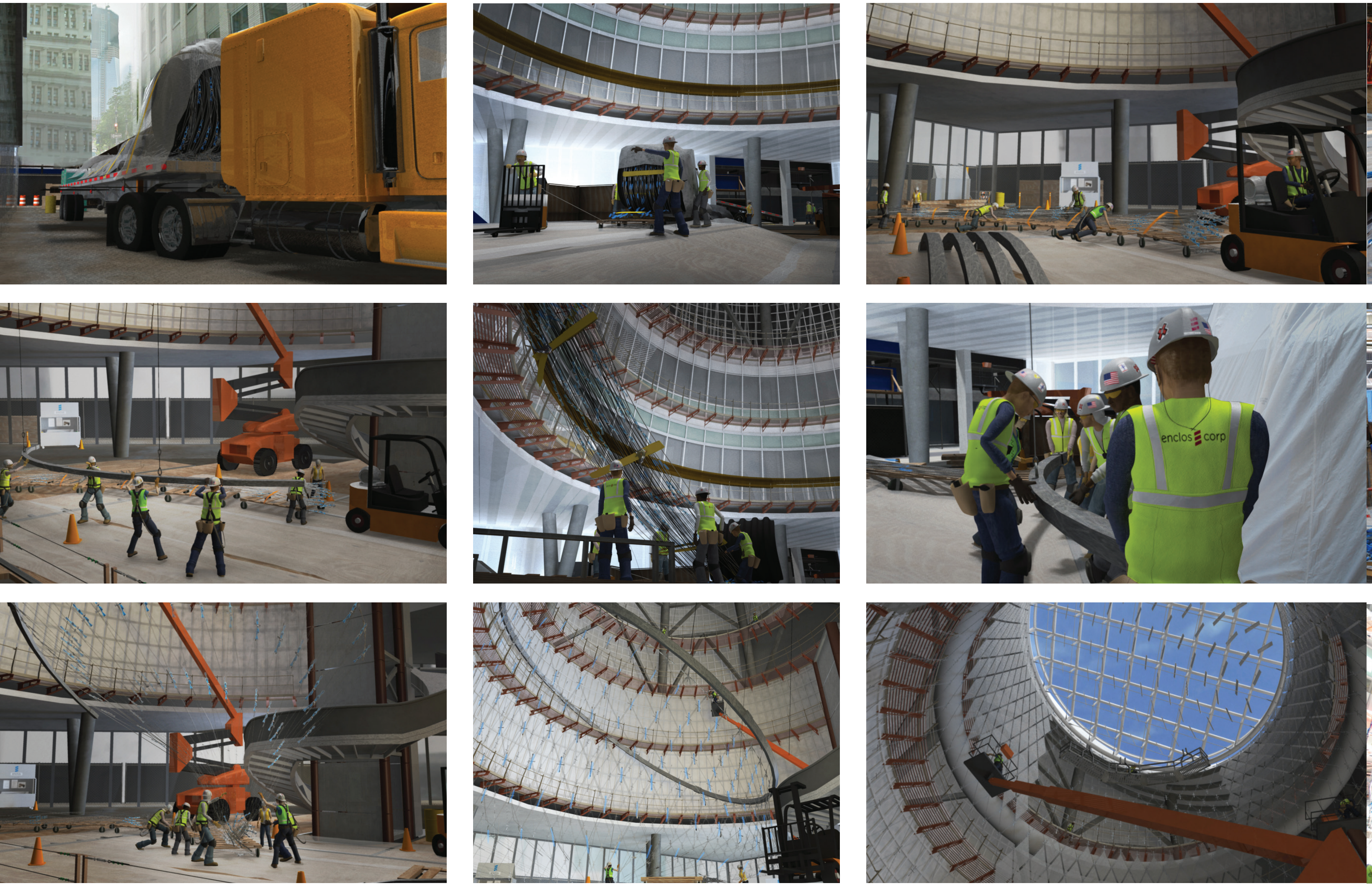
FIGURE 6
Installation of the universal paddle-connector components (left) and the overall assembly with perforated metal panels (right).

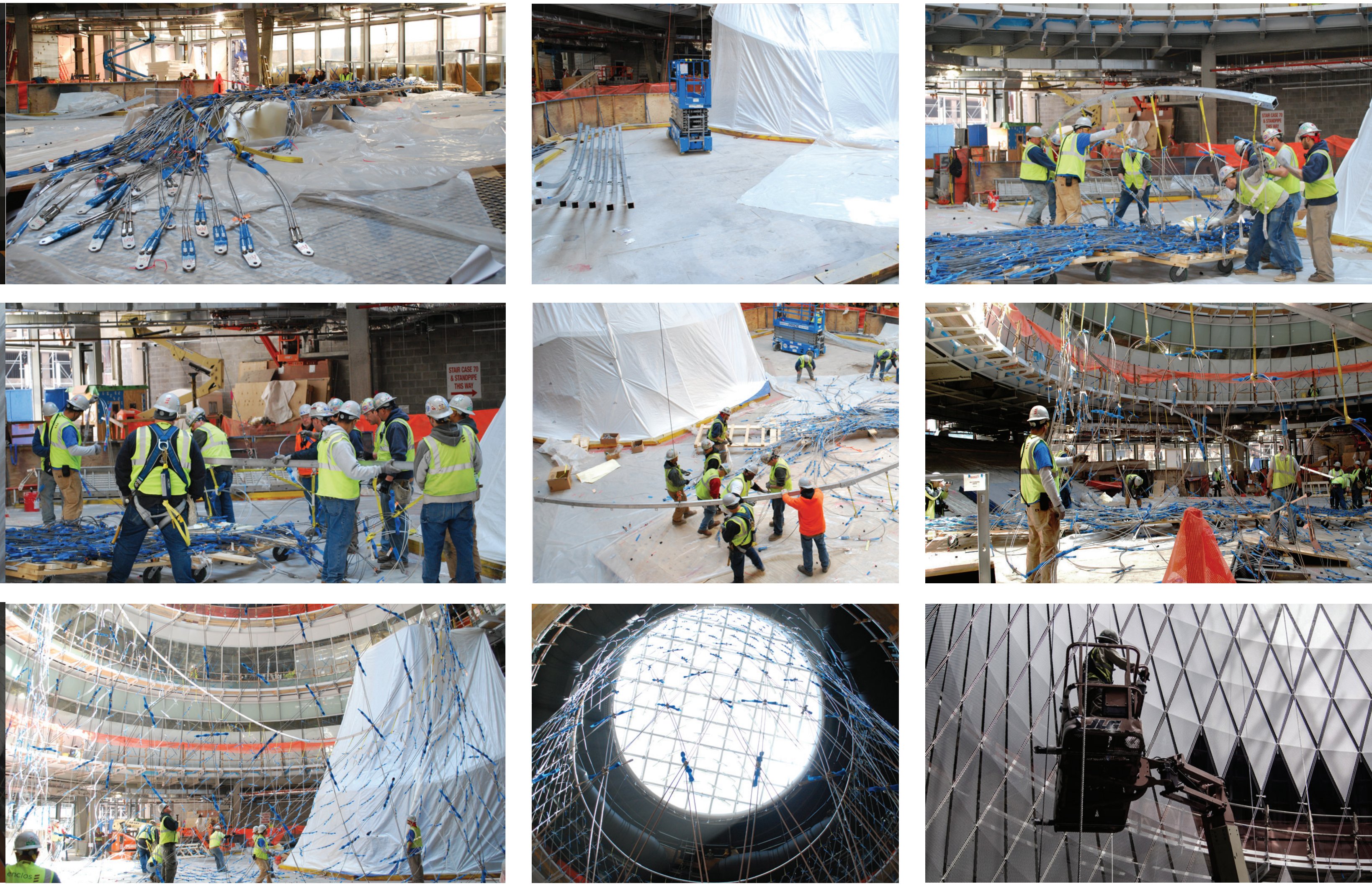
FIGURE 7
A 3D printed prototype of the universal paddle-connector component.

FIGURE 8
A full-scale installation mock-up prior to actual installation.

top and 56 bottom stainless steel tie rods. The intended approach was to accurately set the top and bottom tension rings (made up of tension rods) to their design location, regardless of any deviations of the primary steel tieback points at the Oculus ring beam (top) or Levels 2 and 3 (bottom). When tieback points at Level 2 and 3 were identified as wrongfully located in the as-built condition, new tie-back rod lengths were developed and fabricated. Anticipating this would be likely, the tensioned tie-back rods were withheld from fabrication until updated as-built data and revised rod lengths were set. Ultimately, each rod has a built in adjustability to address construction tolerances. This is an example of disconnect between digital and parametric tools/workflows and the reality that most of the construction is still executed on some level by the accuracy of the human hand.

To maintain efficiency at the constrained project site, the project team undertook multiple practice lifts at the cable vendor's shop to validate that the way the net would arrive on site – as a whole object – could be lifted into position using a custom set of rigging strategies. These tests proved very beneficial and provided full-scale, hands-on lessons that allowed the team to avoid potential obstructions later in the field.





SEQUENCE 1
Animated installation sequence used to educate field crews on installation and safety tactics. Additionally, lifts of large objects through small spaces were studied to ensure proper clearance in the field.

SEQUENCE 2
The installation sequence of the double-curved cable structure with universal paddle-connectors pre-located within the tight, enclosed confines of the project site. The sequence includes the arrival of the net as a single piece, which was then attached to the ring beam and hoisted with a high precision lift to avoid damaging already installed structures. The entire installation of the net from the truck to a hanging position was done in one day, using one lift.

INSTALLATION SEQUENCE

The installation sequence of the Fulton Street Transit Center's solar reflector shell is summarized in the sequence below. This execution was carried out on a constrained site with the following top priorities: safety, efficiency and minimal obstruction to adjacent trades.

- Cable net is installed using a series of hoists and pulleys.
- Field crew installs upper tension ring from swing stages.
- Pulleys are placed in eight predetermined spots on the upper tension ring.
- The hoists are anchored to the Level 4 catwalk (during install, there will be crew stationed at each location).
- The swing stages are lowered before cable net is lifted.
- The packed cable net is wheeled into the center of the atrium floor on a series of dollies.
- Field crew assembles picking ring.
- High side of cable net is attached and test lifted.
- Once attached, the crew assembles more parts to the picking ring and more of the cable net is attached.
- This continues until the picking ring is complete and the net is clear of tangles.
- Cable net is ready to be hoisted.
- The high side lifts first angling the picking ring and net away from the elevator.
- Once clear of the elevator the ring is stabilized.
- Once lifted into place, boom lifts reattach the 12 o'clock and 6 o'clock swing stages.
- Field crew begins attaching the cable net from the 12 o'clock and 6 o'clock swing stages.
- Once attached, the 12 o'clock and 6 o'clock swing stages are lowered and 3 o'clock and 9 o'clock swing stages are lifted.
- After cable net is attached to upper tension ring, the bottom tension ring will be installed using scissor lifts and boom lifts.
- Once tensioned, field crew will begin installing reflector panels.
- The 12 o'clock and 6 o'clock swing stages are lifted and panels will be installed from top to bottom. Meanwhile panels at the 3 o'clock and 9 o'clock sides will be installed from bottom to top via boom lifts.
- They are then switched: the 12 o'clock and 6 o'clock swing stages are lowered and 3 o'clock and 9 o'clock swing stages will begin panel installation from the top. Meanwhile, crew will complete the 12 o'clock and 6 o'clock areas from bottom to top.
- Crews will not overlap vertically for safety.

CONCLUSION

Dealing with a complex form with the goal of automating part generation can be challenging. In the case of this doubly-curved shell there is a complex logic to the form which must be understood, in addition to the logic of the automation routines. Developing tools that communicate between organizational tools (i.e., Microsoft Excel) and 3D modeling environments (i.e., Rhino3D with Grasshopper) tends to require intense upfront efforts to beta test and trouble-shoot definitions and routines, but are extremely adaptable to unforeseen changes or applications downstream in the project delivery process. Enclos' multi-disciplinary, collaborative engineering team successfully implemented various parametric tools within the Fulton Street project workflow. Moving forward, the company's culture and integration of parametric tools is more widespread, including experimentation with various parametric tools to find appropriate project workflow applications, as well as understand the mediums for design in which architects and engineers continue to generate form.

FULTON STREET TRANSIT CENTER

owner
Metropolitan Transportation Authority

commissioned by
MTA Arts for Transit and Urban Design

architect
Grimshaw Architects

artist
James Carpenter Design Associates

engineer
ARUP

construction manager
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