PARAMETRIC WORKFLOWS FOR COMPLEX ENCLOSURE STRUCTURES°

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Architectural designs are articulating increasingly complex forms, challenging the AEC community to overcome classic paradigms of form, structure, collaboration and project delivery. The rampant integration of parametric tools and digital workflows is well documented.[1, 2] Often these views highlight the architectural development, environmental analysis, optimization studies, geometric rationalization exercises and supporting analysis during design development. Additionally, the turnaround associated with consultants' engineering analysis to drive architects' decision making continues to accelerate, thus shortening the feedback loop.[3] What is often missing in this dialogue is the role of parametric processes in the delivery of scope by the contractors who fabricate and install the elements that make-up the architecture. This paper seeks to describe how parametric workflows support the design and delivery of complex enclosures from the perspective of a facade contractor.

Projects with increased geometric complexity present the facade contractor with an opportunity for early involvement to understand the architectural concept, influence the enclosure design, bring key constructability drivers to the forefront and integrate parametric tools early in the design development. This support role is intended to aid the design towards a rationalized solution within project constraints: material, fabrication and shipping limitations; project budget and schedule; and system performance requirements. The parametric tools are used to provide expedited information and design responses during an iterative development process. This dynamic process requires a structured approach to interdisciplinary communication, three-dimensional model exchanges and a familiarity of the parametric tools used by the architect. This process is increasingly carried out in a 'design-assist' project delivery where an intermediate phase is established for the contractor to collaborate with the design team, working towards a buildable solution within target performance and budgetary metrics.

PHILOSOPHY

One key advantage about parametric modeling is that it anticipates change throughout design development. It can avoid the burden of drastic overhauls and minimize repeating time consuming documentation steps. A parametric approach aims to build a model up, logically, with a firm understanding of geometry and the relationships between it and the subsequently designed items that make up a building enclosure.

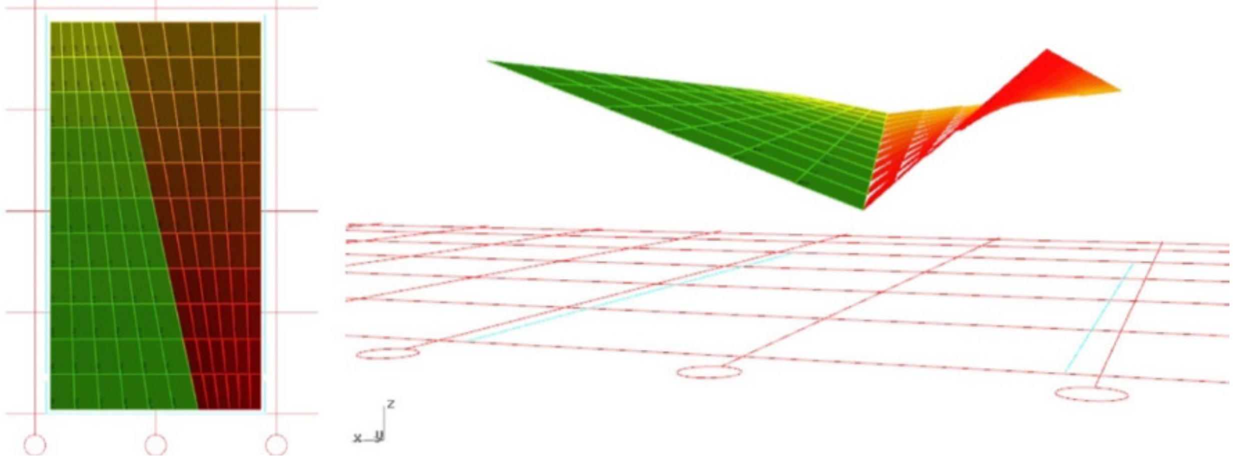


FIGURE 1
Warpage analysis of panels on a hyperbolic control surface for a canopy structure.

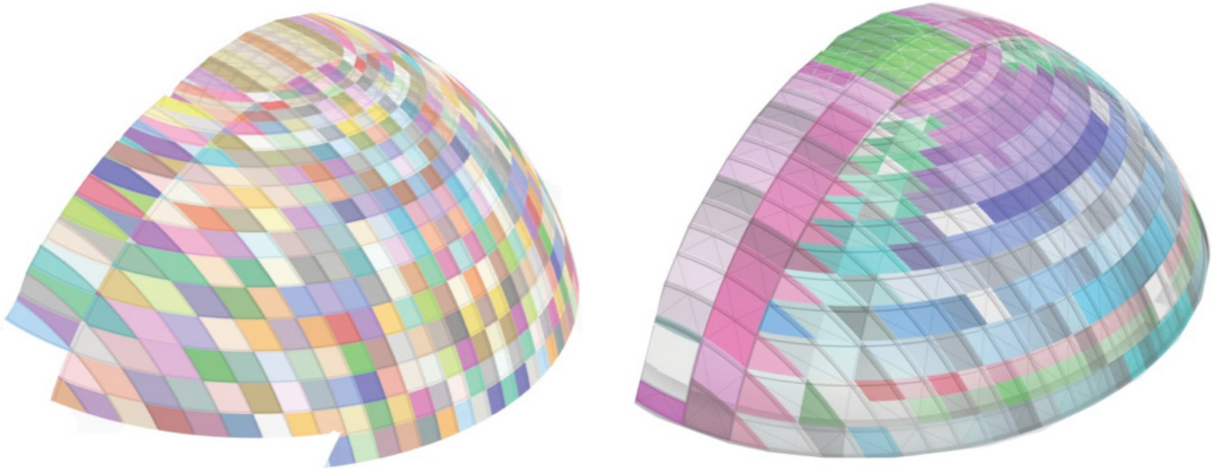


FIGURE 2
Subdivision study that shows spherical subdivisions that 1) refine an initial subdivision to get all glass lites to be within manufacturable dimensions (left), and 2) an alternate subdivision that decreases variability through subtle modification to the subdivision logic (right).

DESIGN-ASSIST DELIVERY

The design-assist process has proven to be effective in mitigating the risk posed by unique and complex design requirements, and the use of emergent materials and specialized technology. The process involves the following steps:

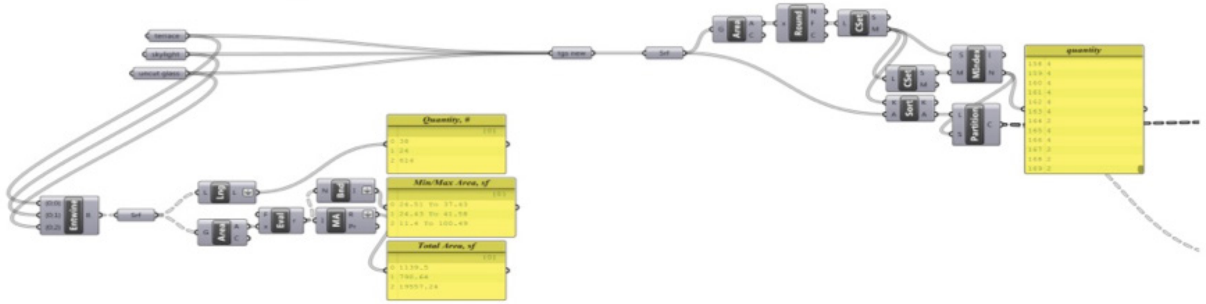
1. development of a clear scope of work, budget, schedule, aesthetic and performance goals,
2. qualification and selection of a design-assist contractor,
3. collaborative research and development of project specifications and documents with the design-assist contractor performing most of the work with direction from the architect,
4. confirmation of scope, budget and schedule by the contractor for the developed design,
5. contracting of build services with the design-assist contractor.

INTEGRATING PARAMETRIC WORKFLOW

Establishing a simple central core of control information that serves as a basis to build upon is vital. This core is generally rooted in a set of control coordinates or a control surface established by the architect. Identifying this overarching control platform early — during pre-sale activities — is essential to successful post-sale maturation of the parametric model and information. Grasshopper — a visual algorithmic software linked to a 3D modeler — is an effective tool at linking this core.

PRE-SALE ESTIMATING

Integrating Grasshopper with cost estimating and material take-off efforts makes efficient use of the data-centric side of parametric programs. While Grasshopper has powerful tools used for form creation, manipulation, and rationalization, it also stores information about each operation being conducted and can easily produce quantities, sizes and relevant geometric information. This information can be visually displayed on drawings or diagrams for clarification, or just as easily exported as raw data into spreadsheets. Specific routines can be created within Grasshopper to find very detailed pieces of information, including panel size and cut dimensions for pattern cut lites, number of atypical units, and number of unique panels. Furthermore, if continuous estimation is to be conducted with a developing design, the initial investment of building a parametric model can drastically reduce time and resources required for pricing updates at design checkpoints. As changes are made to the project, take-offs are automatically updated, reflecting price and quantity changes at the same speed as design.



DESIGN ITERATIONS

When the facade contractor is introduced during a design-assist initial phase, it is anticipated that the design development will go through a number of iterations. It is the contractor's opportunity to bring constructability constraints as well as material or vendor limitations to the table. Parametrics have proved useful in performing the following analysis throughout design and pricing iterations inherent to a design-assist phase:

- *Panelization*: optimizing surface subdivision through alternate approaches,
- *Warpage Analysis*: assessing the warped magnitude of panels in a hyperbolic surface,
- *Size Constraint*: reviewing panels to see if they adhere to minimum and maximum size requirements,
- *Reducing Variability*: develop alternate subdivisions to increase repetition,
- *Automating Model Steps*: generating repeating details within a 3D model space.

The figure above below is an example of a panelization study that uses a Grasshopper routine to extract information about the initial subdivision pattern of double-curved glass lites as well as provide an alternate approach aimed at reducing variability. As much as parametric tools are thought of as an intelligent design tool, they are also a critical data extraction device.

ENGINEERING

Parametrics have proved useful in performing and supporting structural engineering tasks during design development, including:

- *Analytical Model*: assist the rapid generation of simplified, segmented, single-line and surface (where applicable) models for import into structural analysis software,
- *Iteration Comparisons*: rapid processing and overlays of multiple design iterations,
- *Visualizing Analytical Output*: visualizing structural model output data within parametric 3D model for heightened manipulation of data legibility and context.

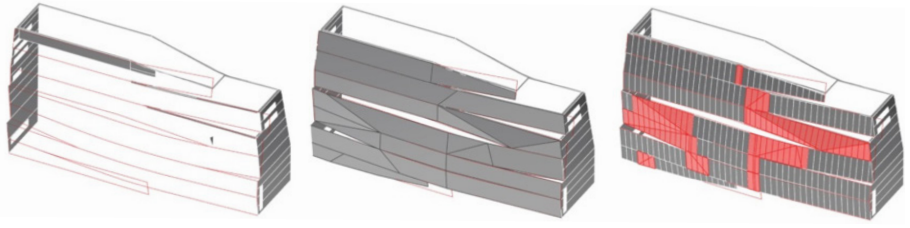
FABRICATION

Automating the generation of details that may use repeating parts or common logic, but occur at a variety of conditions (e.g., many angular instances on a complex surface that have intersecting nodes) accelerate documentation tasks that previously were labor intensive. Related to the facade, this could include anything from glass pattern cut sheets, minimum block sizes for glass fabrication, variant anchorage conditions, structural nodes in a gridshell and more.

CONSTRUCTION

The parametric model serves as a tool to educate field installation crews prior to arrival on site as well support on-site activities. These include:

- *Virtual Construction*: model geometry from very detailed parametric models can be used as the basis for 3D animation sequences that outline the installation approach for a job; a crucial hurdle on every project, but even more so when dealing with a complex geometry, unusual structure, tight field constraints or unconventional installation methods,
- *Mapping Survey Data*: receiving extensive coordinate data on a non-rectilinear structure from on-site laser surveys (e.g., as-built anchor locations) can be an even more daunting task that can be eased by a parametric workflow's ability to integrate survey coordinates for comparison against theoretical design locations so field adjustments may be made.



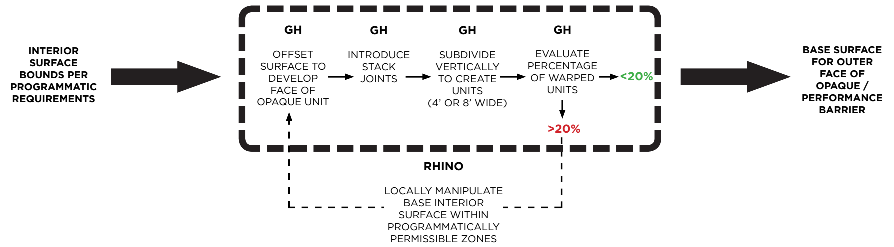


FIGURE 3
Development of back of system control surface for the FRP wall on the San Francisco Museum of Modern Art's slab edge lines (left) planar interior control surfaces (center), and subdivided panels (right) with red indicating units consisting of multiple planes (right).

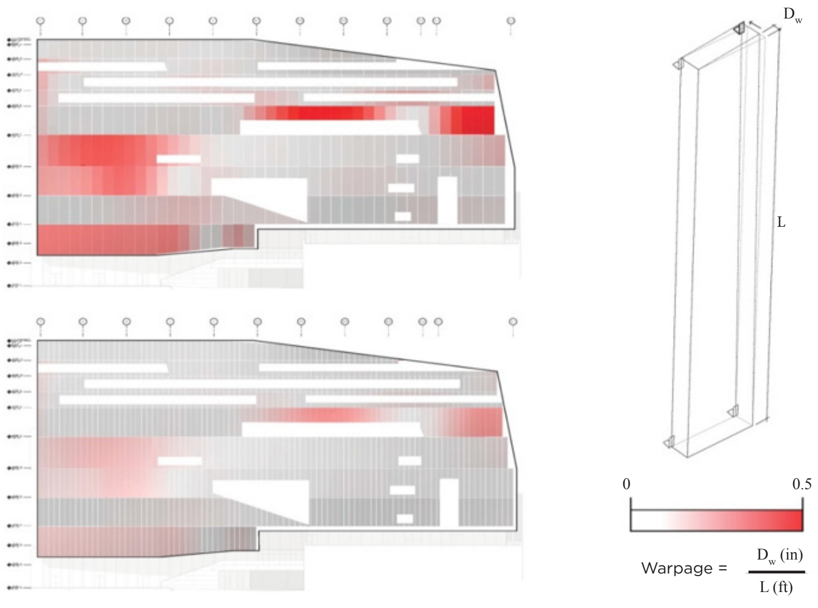


FIGURE 4
Warpage analysis of backup unit at 8 feet (top) and 4 feet (bottom) wide modules.

CASE STUDY

OVERVIEW

The San Francisco Museum of Modern Art's expansion features a wall consisting of a composite assembly of an opaque fiberglass reinforced polymer (FRP) rain-screen panel in front of an insulated unitized backup system. The project was being designed under a design-assist contract with the architect, meaning the design would undergo many changes and would need periodic updates to cost estimates and material take-offs to validate targets were being met. The architect provided standard architectural drawings and a development BIM model to start with. The information given was based off the beginning of design development and would knowingly change multiple times throughout the design lifespan of the project. The design team worked collaboratively to narrow in on a design solution that achieved architectural desire within budgetary constraints and material limitations.

The make-up of the enclosure was a juxtaposition of two key layers: 1) an outer rippled surface made of contoured fiberglass reinforced polymer (FRP), and 2) an insulated opaque performance barrier with interlocking curtainwall technology and 4.5 inches of insulation. The outer ripple surface required each panel to be a unique geometry, thus requiring intensive CNC milling technology of unique molds for each of the 700+ panels out of polystyrene blocks. The inner performance curtainwall maximized off-site, shop-controlled assembly to maximize quality control of key features. Following fabrication of the FRP panels, they were transported to the curtainwall assembly shop where the two systems were mated prior to delivery to site. Both shops were within 50 miles of the project site.

BASE SURFACE DEVELOPMENT

The initial starting point was to define the interior surface of the outer skin. The location of this surface was driven inwards out due to programmatic requirements and defined slab edges. Factoring an offset between back-of-system and the slab edge, a set of interior control surfaces were established. The control surfaces utilized several large triangulated regions (highlighted in Fig. 3) to create planar regions—in lieu of warped surfaces—between floors with significant inward/outward steps between respective slab edges. With control surfaces in place, the next step was to introduce joints. Maintaining a constant relationship between top of slab and stack joints was desired, so the horizontal datums were established first. The maximum floor-to-floor unit height is 26 feet tall. With the surface and horizontal joints established, the next step was to integrate the control surfaces into Grasshopper and introduce vertical joints and iterate the unit warpage.

OPAQUE UNIT CHECK

The initial rationalization of the opaque surfaces planned to cold-warp units into position. Various panel widths (between 4 feet and 8 feet wide) were analyzed in Grasshopper (Fig. 4) to determine the spectrum of warpage that would result from the respective subdivisions. A goal of <20% warped units was the project target during design-assist.

As would be expected, the wider unit module resulted in a greater absolute warpage as well as a greater relative warpage with respect to the unit's height. The initial panel subdivision considered (8 feet wide) resulted in an excessive number of warped units. An objective of the design-assist process was to reduce the extent of warped units. The alternate considered at that time was a 4 feet wide unit module that essentially doubled the total number of units while drastically reducing the quantity of excessively warped units. However, the quantity of warped – or non-planar – units still exceeded the targeted threshold of less than 20%.

In the end, after many subdivision iterations, what was learned was that the target threshold was met by a combination of planar units in mild runs with exaggerated transition zones. These are represented in Figure 5 as grey for the opaque base geometry (or planar units) and gold for the transition units. The initial iteration of this approach maintained a 8 feet wide module and required 25% of the units to be transitions that have a faceted assembly folded across the diagonal. The second iteration of this approach implemented a 4 feet wide module and required only 6% of the units to be transitions. This approach however had disadvantages of a greater extent of FRP material used in the returns, more aluminum in the opaque system's mullions, more anchorage locations to be coordinated with primary structure and greater labor associated with the installation means and methods. The final solution struck a balance between material/install optimization and limiting the extent of transition units. The final panel widths ranged from approximately 4.9 feet to 5.6 feet resulting in over 700 unique units, of which, approximately 9% are transitions. The extensive use of a common base surface as the driver in a series of parametric iterations was key in evaluating the ramifications of unit subdivision schemes.

FRP RIPPLE SURFACE GENERATION

As the system was developed, means and methods drove the system to a more unitized system that did not require extensive cold-warping. To trace the initial ripple surface with planar units, the FRP panels were utilized to make up the double-curved surface within the first 20 inches (500 mm) off the face of the planar units. Where the curvature exceeded the bounds of the FRP, faceted transition units (seen in gold in Fig. 5) were utilized to re-align the next set of planar surfaces with the architect's control surface. Grasshopper was utilized to link the base control surface geometry to a series of routines that 1) subdivided the planar surface regions with equally spaced modules to create zones with common-length mullion pieces, 2) automated the generation of each unit's control geometry, 3) offset the control surface to create constraint volumes where the outside face of the FRP ripple surface was to occupy, and 4) minimize the number of faceted transition units. The planar units were permitted to have FRP occurring within a 20 inches (500 mm) offset volume while the faceted panel of a transition unit encroached within this depth and thus reduced the permissible FRP offset volume to 12 inches (300 mm) in these zones. These limits were implemented to minimize atypical details, FRP material required for returns at joints and supplemental support structure.

These zones of opportunity were generated for the architect to create the contoured FRP ripple surface within. Using Grasshopper to develop a logic routine aided the facade contractor in rapidly reviewing the architectural FRP ripple surface during rounds of design development and quality control. The iterative process was a refinement of the initial opaque unit surface informing the subsequent FRP ripple surface until a balance was struck where all constraints were met by both the opaque and ripple surfaces. The final byproduct of the design-assist phase is a master geometry control Rhino model that is acceptable to the architect and thoroughly vetted by the facade and FRP contractors.

PRODUCTION ENGINEERING

At the conclusion of the design-assist phase, control of the enclosure modelling is wholly transitioned to the facade contractor with the

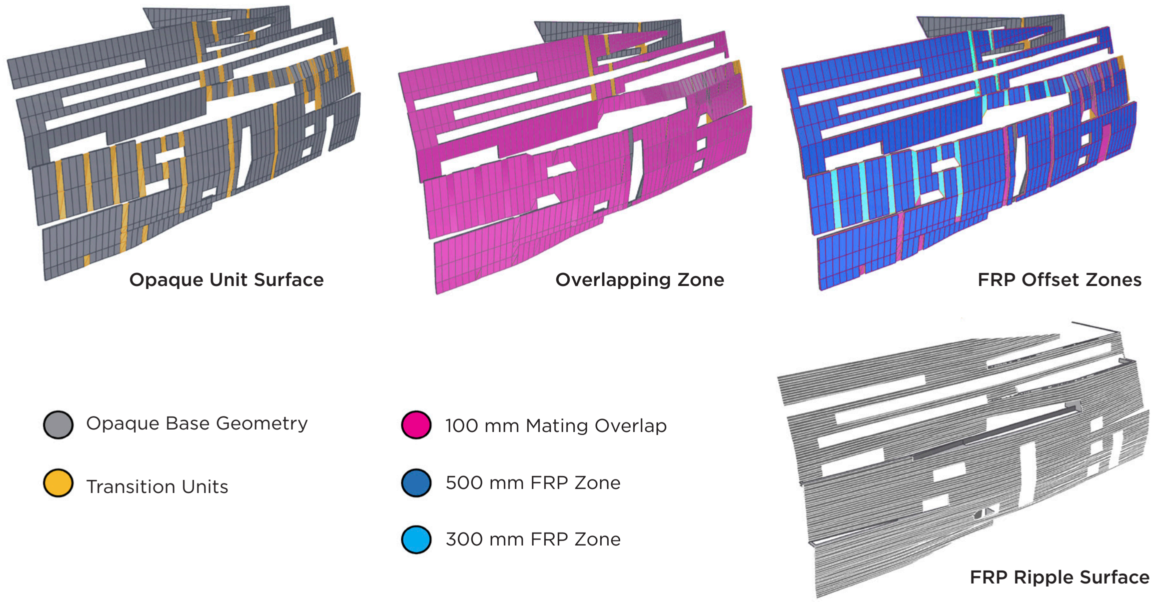


FIGURE 5
Development of opaque outer surface, overlapping zone, FRP offset zones and final ripple surface.

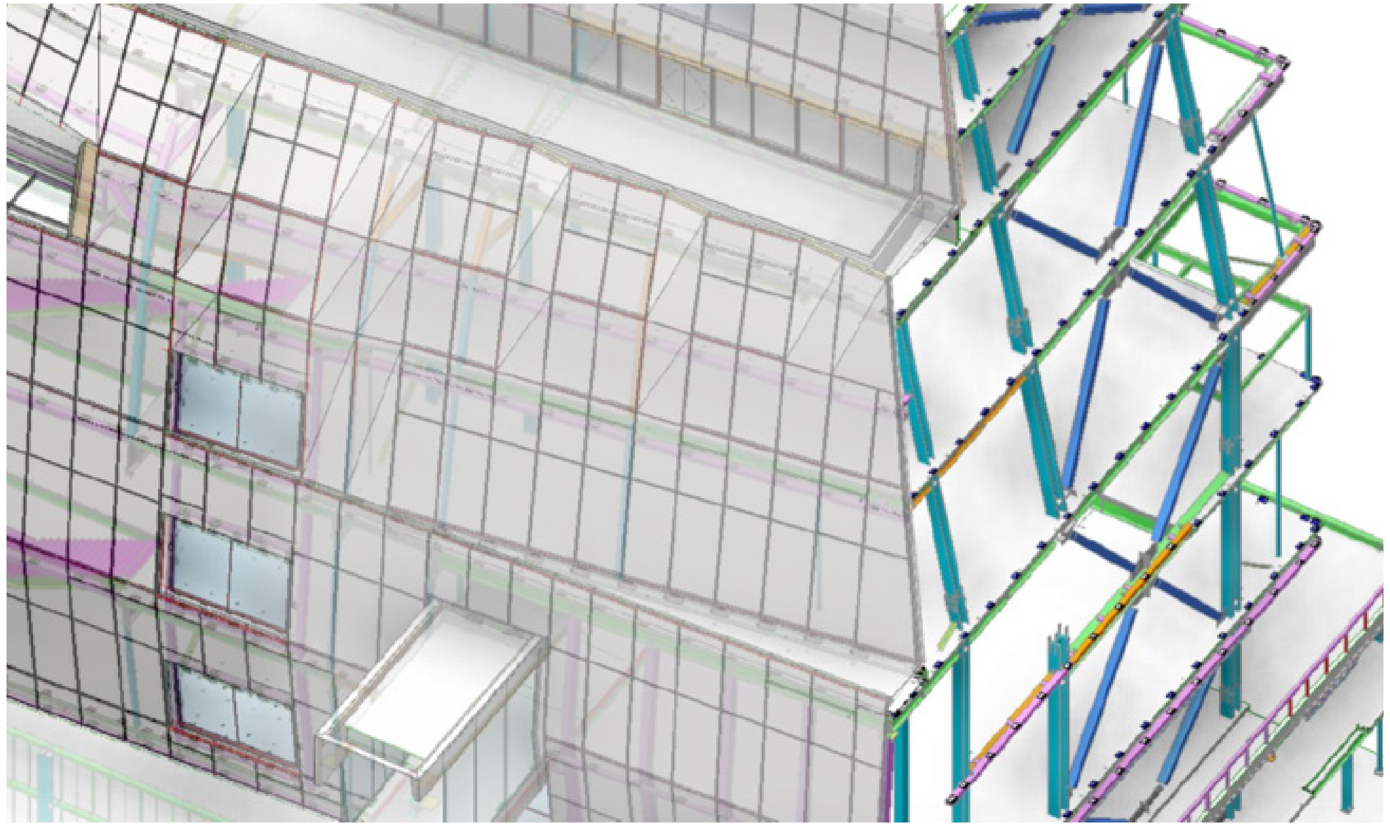


FIGURE 6
Overlay of curtainwall system coordinated with anchor locations on primary structural concrete and steel (Revit model with integrated IFC from steel fabricator).

design development Rhino model serving as the basis for a production model maintained in Revit to assist in coordination and clash detection with other trades. The Revit model developed by the enclosure team served as the host for the geometry coordinate wireframe that was fed into Inventor for the development of individual unit assemblies and part drawings for fabrication. The level of detail in the Inventor unit models has all information regarding parts and preparations for fabrication and assembly, but far exceeds that required for coordination with the broader project team and other trades.

CONSTRUCTION

The FRP and insulated curtainwall unit assemblies arrived on-site as single entities that were 4.9 to 5.6 feet wide and up to 26 feet tall. The articulated ripple contours travel across the vertical and horizontal joints of the unit subdivisions (Fig. 7), so it was essential that field installation occurred at the highest level of precision. Tight tolerances across large unit dimensions were demanding, but the result is a facade that embodies a timely sense of digital technology and craftsmanship.

FIGURE 7
Photos from the enclosure installation at the project site: detail of contours and joints (left), unit size during rigging (middle) and continuity of ripples across units at lowest level (right). A full animation of the delivery is available at https://vimeo.com/174560737.

CONCLUSIONS

The processes aided by parametric concepts for the San Francisco Museum of Modern Art's enclosure included but were not limited to: warpage analysis of the control surface iterations, panelization of the base surface into units, estimating material takeoff for different panelization schemes, automation of offset volumes for the FRP ripple surface to occupy and quality control when reviewing the contoured surface for size constraint and offset compliance. Utilizing Grasshopper to establish routines for each of these steps eased the demand and expedited the effort to process and review over 700 unique panel geometries.

Dealing with a complex form and the goals of automating processes, such as part drawing generation, can be challenging. Developing parametric tools tends to rely on intense up-front efforts to test and trouble-shoot definitions and routines, but are extremely adaptable to unforeseen changes or applications. Moving forward on future design-assist delivery projects, parametric-infused estimation and material take-off can inform the design process more readily.

Within this case study, a design solution for panelization, warpage, and many other constraints were reached not by the initial subdivision and sizing ideas (8 feet subdivision) or the next alternative (4 feet), but rather discovered through an understanding of the early results and attempting more iterations—taking the best pieces of many ideas to combine into one optimal solution. At the root of this process—design iterations fueled by parametric software—is the ability to rapidly increase the size of the solution space, finding the very best design solutions; some that may not have been initially thought of at all.

Overall, parametric software enables cost estimation, material take-off, design development studies, engineering tasks and review of survey data to be completed quicker and more accurately. On some complex projects, the geometry would otherwise be difficult to extract information from. The rapid accessibility to data and efficiency of digital models ensures that time can be spent refining designs rather than manually documenting.

ACKNOWLEDGEMENTS

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COMPLEXITY

BUILDING COMPLEXITY: DESIGN APPROACH BEHIND A PREFABRICATED DOUBLE-CURVED FACADE

NOVEL USES OF METROLOGY ON GEOMETRICALLY COMPLEX FACADES

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[0] *This article is a reproduction of the research that comprised a paper — under the same title — delivered at the Advanced Building Skins 2015 conference at Graz University of Technology.*

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DELIVERY

A VISUAL BREAKDOWN OF THE FLYING GANTRY ANIMATION

SUSTAINABLE APPROACH TO UNITIZED CURTAINWALL PACKAGING DESIGN

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