ABSTRACT

A group of Cal Poly Architecture students, led by the authors, envision lightweight high-performance fiber-reinforced polymer (FRP) unitized façade systems. Working with industry partners from architecture (Gensler Los Angeles), façade engineering and contractor (Enclos), and FRP fabrication (Kreysler and Associates), the design process outlined numerous constraints from fabrication and installation, to transportation logistics, to thermal and day lighting performance, while maintaining the aesthetic ambitions of working with FRP. The presence of these real world factors focused the design problem from which the complexity of design criteria for unitized facades was simplified through this integrated FRP composite system. The design process evolved from improvisational paper maché models to digitally fabricated prototypes and molds developed across multiple scales, culminating in refined proposals for integrated FRP unitized façade systems.
INTRODUCTION
Fiber Reinforced Polymers (FRP) in architecture are often linked to futuristic projects from Buckminster Fuller’s fiberglass Fly’s Eye Dome and Monsanto’s House of the Future to current theoretical proposals from Peter Testa’s Carbon Tower to Greg Lynn’s call for a “chemical architecture” (Lynn 2011). More than just a distant future, FRP’s potential can be seen through Snohetta’s design for the San Francisco Museum of Modern Art, now under construction, which employs the largest installation of an FRP facade in the United States. Developed as a joint effort between FRP fabricator Kreysler & Associates with facade design-build company, Enclos, the FRP is utilized as a rain screen cladding attached to a more conventional light-gauge unitized panel system. Consequently, it does not exploit the potential of FRP as a structural material from which a totally integrated unitized composite system could be developed.

Working with Kreysler and Associates, Enclos, and Gensler Los Angeles, we directed a group of students at Cal Poly Architecture’s Material Innovation Lab to envision a fully integrated FRP composite panel system. At the outset, working with FRP seemed to be almost limitless in the complexity of curvature as well as seemingly limitless panel size. However, in working with these industry partners and their experience on the SFMoMA panels as a case study, the design process began to identify and incorporate numerous constraints from fabrication and installation, to transportation logistics, to thermal and day lighting performance, while maintaining the aesthetic ambitions of working with FRP. The presence of these real world factors focused the design problem from which the complexity of design criteria for unitized facades was simplified through this integrated FRP composite system.

In *The Laws of Simplicity*, John Maeda identifies how thinness and lightness can be employed aesthetically to enable simplicity (Maeda 2006). While we, as many others, have sought out FRP for the complexity of form it can produce, in the end it was the thinness and lightness combined with the design parameters identified below which enabled simplicity from these complex variables: simplexity is the result.
We began this development from complexity to simplicity exactly as Maeda opens in his book: “the simplest way to achieve simplicity is through thoughtful reduction” (Maeda 2006). In the FRP industry this thoughtful reduction is referred to as “parts consolidation.” For us this began with a simple reaction to an exploded wall section of the SFMoMA. Rather than view the FRP as undulating rain-screen cladding supported by a complex unitized light gauge insulated panel with its own secondary structure, why not incorporate the strength of FRP to completely eliminate the secondary structure – let the FRP become the unitized system. Greg Lynn has identified this shift from assemblage to composite as “a shift from discrete, freestanding, detachable elements into layers of materials, blended or filleted connections, and smooth curvilinear transitions between elements” (Lynn 2010). Whereas Lynn continues with the highest potential of composites in which “there is no distinction between panel and frame,” the evolutionary approach proposed here maintains a clear separation between a simple primary structure and the composite unitized panel system. While complete FRP monocoque buildings remain a theorized potential, the approach taken here leverages the considerable parts consolidation in an FRP unitized façade system with a performative and aesthetic opportunity as a current market reality.

This approach to parts consolidation reduces construction related complexity, reduces cost of redundant materials, and potentially provides for a significant reduction of the overall weight of structure, while at the same time, provides a unique design opportunity due to the formal flexibility of FRP. This approach not only provides a great deal of formal flexibility, it relies in part on curvature for strength. From a market perspective, there is a large demand for façade retrofit projects due to an aging building stock, often which cannot add to existing dead loads, in which an FRP unitized façade system provides a lightweight, high-performance envelope, with minimized on-site disturbance, while providing new expressive design opportunities for buildings with serviceable structures but underperforming facades.

In Living with Complexity, Don Norman describes that “complex things become simple after we have mastered them, after we understand how they operate and their rules for interaction” (Norman 2011). Our primary purpose here is to identify the design parameters developed through this process, with several case studies of potential applications, and the structural feasibility of this proposed system.

**DESIGN PARAMETERS**

The basic design parameters for an FRP unitized façade system were not known in advance of undergoing this design process, but in fact evolved over the course of design development with input from industry partners representing architectural design, FRP fabrication, and unitized façade system design and engineering. Defining these design parameters required the convergence of FRP’s material properties (maximum curvature, strength, workability, watertightness) and the constraints of unitized façade construction (panel size, assembly sequencing, thermal breaking, expansion, seismic movement). Due to its fiberglass lay-up, FRP is largely limitless in size (as exemplified by the sheer size of FRP wind turbine blades), and there is an interest in maximizing the unitized panel size in order to minimize field connections.
However, in consideration of a system that could be more universally deployed, we limit the size of our unitized panels to conventional trucking constraints in the United States, of approximately 10’x44’. As FRP is a waterproof material, these monocoque units can be employed as a barrier wall system, or it could be used as a rain screen system, as is the case with the SFMoMA. While keeping in mind that this evolutionary approach would clip back to a primary structural frame, we identified three basic types of unitized façade construction: floor-to-floor spans, twin spans, and column-to-column spans (Figures 1a-c).

APPLIED RESEARCH

Four student design teams, advised by the authors, explored a range of potential applications for FRP unitized façade systems within these parameters. Design teams used a combination of messy hands-on prototyping, parametric design software, and digital fabrication processes to iteratively develop these FRP façade systems (Figure 2). In addition to exploring the formal possibilities and environmental performance of these façade systems, each scheme addressed the manufacturing processes used to produce them. For example, while continuous variation of units is a commonly desired outcome in contemporary digital design practices, the process of producing unique custom molds is costly, time-consuming, and generates tremendous waste. These investigations aimed to produce maximum perceived variation with minimum material and labor.

SYNERGY

Influenced by the strength created from creasing and pinching fabric, Synergy created an undulating façade punctuated by apertures of varying sizes. This team approached their barrier wall design as a composite sandwich panel (Figures 3a–b), consisting of an FRP shell, sprayed-in polyurethane insulation, and an aluminum backup panel that could be clad with a range of interior finishes. Panel size was maximized relative to building structure in order to maximize efficiency of assembly. While this scheme had a low degree of surface curvature, multiple apertures (with built-in FRP glazing units) introduced significant rigidity to the panel, due to the FRP returns at each aperture that acted as stiffeners. Two reusable forms were used to provide a consistently tessellated panel geometry, while more variable formwork inserts served to blank off different aperture systems.

RELAXED

This bay window style panel employed relaxed surfaces to maximize material efficiency and surface rigidity (Figures 4a–b). The bay window style panel was designed to be added to existing buildings as a façade replacement system, increasing energy performance while adding usable square footage. Integral FRP glazing units, oriented perpendicular to the building face, acted as structural stiffeners to the FRP panels while creating intimate niche spaces with fragmented views while bouncing light across the continuously curved surfaces. Spray-in insulation added further stiffness to the panel. Despite its visual variation, this scheme utilized a single re-usable mold with the economy of a twin-span panel.

DROOP

This team used a catenary curve form-finding process to determine surface curvature that would resist wind loading while providing ambient, diffused light to interior spaces (Figures 5a–b). These twin span panels met the floor slab at their only moment of zero curvature,
thus reinforcing their weakest point and creating a straight joint at slab edge. Three exterior panel types were optimized to create conditions of light/view, light/no view, and no light/no view (maximum insulation); a fourth panel type was used as an interior partition that could spatially extend the façade. While a gravity-based, moldless forming process was initially explored, the need for precision required a CNC-milled foam formwork. Unlike the previous two schemes, this fabrication method retained the expanded polystyrene foam formwork as integral insulation (lost mold approach).

TESSELLATION ANIMATION

This rain screen assembly studied complex tessellated patterning both within individual panels and across the façade (Figures 6a–b). A wide range of variability was achieved by combining four basic mold types with customized waterjet cut apertures. FRP panels were layered with primary and secondary structural systems in a cohesive geometric framework to provide visual depth.

FEASIBILITY ANALYSIS

A comparative analysis was developed by The Advanced Technology Studio at Enclos to test the structural implications of this composite approach. The primary goals of this analysis were to compare the structural performance of panel geometries to find whether the strength of the panels was coming from their surface curvature or their composite structure (FRP and foam). A simple distributed load of 30 psf was applied perpendicular to the main span of the panels to represent wind loads.

The Droop panel (large scale double curvature) and Synergy panel (small-scale double curvature with openings) were analyzed relative to a flat composite panel (a standard 6” foam insulated composite panel 10’ wide and 28’ tall spanning across three floors) to test for allowable stress and deflection. Each of these panels were analyzed both with and without foam. As a composite panel, the load sharing between panels reduces the deflection by a factor of 10, bringing even the flat panel close to allowable deflection. While most of the strength is coming from the sandwich panel, the curvature does matter. In the Synergy panel, which we anticipated as failing due to the numerous openings, the openings in fact had the opposite effect acting as “returns” connecting the front and back panel to stiffen the composite assembly through increased load sharing. While the Droop panel was
derived from a catenary section working against the lateral wind loads of the façade, the thrust of the arching action is not able to resolve itself into the primary structure as this would require dead load anchors at all four corners of the façade which does not allow for the differential movement between façade and primary structure. However, the catenary shape of the Droop panels stiffened the panels vertically like a cylinder.

JOINT

Much of the theoretical discourse on FRP in architecture privileges seamlessness as an aesthetic desire but is short on the realities of construction. Conversely, pursuing a unitized system foregrounds the issue of the joint. Maximizing the unitized panel sizes ads to the simplicity of the system while minimizing on-site erection time. However, it adds complexity to the joint to provide primary and secondary seals while keeping the fasteners completely blind. Enclos proposed an integrated shop-applied aluminum snap-lock at the jamb which also acts as an edge stiffener and connection point to the primary structure (Figure 7).

CONCLUSIONS

While developed in the context of a digital fabrication seminar, the design process developed from messy and improvisational experimentation with paper maché, to refined physical prototypes and studies in pattern tessellation to detailed wall sections. Working with industry partners, the design parameters were teased out of the design process at the convergence of FRP’s material properties (maximum curvature, strength, workability, watertightness) and the constraints of unitized façade construction (panel size, assembly sequencing, thermal breaks, expansion, seismic movement). Through the numerous design parameters that developed over the course of this design process, the feasibility of FRP as a unitized façade system developed as one that can incorporate the complexity of numerous real-world constraints through the aesthetic simplicity of formal continuity.

REFERENCES

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IMAGE CREDITS

Figure 1a-c. By the authors.
Figure 2. By the authors.
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Figure 5a-b. Kristin Akin-Zimmerman, Clara Lee, Phillip Sweeney, Droop, 2014, California Polytechnic University, San Luis Obispo.
Figure 6a-b. Burcin Nalinci, Emmanuel Osorno, Zahra Safaverdi, Tessellation Animation, 2014, California Polytechnic University, San Luis Obispo.
Figure 7. Image credit to Authors (2014).

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