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Volumetric Envelopes: Precast elements in building envelopes

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Abstract

By supplanting survival with comfort, the environmental technologies ultimately increased the dependence of the building design on *form* and *materials*, particularly those of its 'envelope.' The emphasis on *form* and *materials* is best seen in the Brutalism Architecture where the "honesty in structure and material" is exhibited through the envelope. Brutalist is relevant to today's digital fabrication techniques where materiality and fabrication methods are integrated with the realized building elements. For example, looking at 3D printed concrete, parallel and continuous layers of concrete placed on top of each other can be an indicator of the method, whereas seeing a smooth curved surface in a cast part can be an indicator of employing the molding method.

Casting a malleable material such as concrete has multiple steps: creating a positive reference part, conceiving the formwork as the negative of the desired part, then pouring the liquid concrete, and finally demolding the hardened part. By employing 3D printing for creating the formwork, the first step of this process can be eliminated. In addition, limitations that a wood or steel formwork may impose on the part can be lifted.

This paper looks at concrete elements used in building envelopes. It also reviews some recent projects regarding the design and fabrication of these modules with an interest in sculptural volumetric elements. It then provides an overview of students' projects designing a volumetric self-standing shading screen using computational design tools and digital fabrication techniques, specifically 3D printed formwork. The pedagogy investigates challenges that students faced to break away from designing a "brick" mindset to designing topologically interlocking elements. The pedagogy demonstrates the complexities and opportunities that today's advanced fabrication methods such as 3D printing can offer designers.

Keywords: Volumetric Elements, Precast Concrete, Building Envelopes, Concrete, Digital Fabrication

Introduction

Envelope and Performance

Expectations of building performance in environmental and structural design disciplines shift over time: Michelle Addington's *Contingent Behaviors* [1] focuses on the environmental performance aspects by discussing how the building was first perceived as a *shelter* to only ameliorate extreme conditions that were beyond the human body's ability for adaptation and not to provide *comfort*. She continues by explaining that comfort was introduced with the development of environmental technologies, particularly HVAC systems, during the late 19th and early 20th centuries when the building was freed from its role as environmental mediator. By supplanting survival with comfort, the environmental technologies ultimately increased the dependence of the building design on *form* and *materials*, particularly those of its 'envelope.' The sleek glass facades representing Modernism were only possible because the building siting and materials could be decoupled from the interior environment. The envelope has "morphed from its role as the mediator of surrounding conditions to the determinant of those conditions." [2]

Envelope and Glass

An example of sleek glass facades is the curtain wall systems developed in the 1950s in the United States. Architects, engineers, manufacturers, and developers were motivated to create a more economically efficient system with a progressive image. [3] As more curtain wall facades took over the streets, many critics expressed uneasiness about the alienation they thought curtain wall's repetitive panes might induce. In 1954, Saul Steinberg, an artist known for his New Yorker cartoons, turned an actual piece of graph paper into a gridded curtain wall structure towering above the only remaining structures on a block to lampoon the curtain wall and how such buildings were eroding the traditional urban fabric. "Graph paper architecture" was a derivative term used to describe these buildings, suggesting that anyone with neither art nor creativity but who could make a grid could design these structures (Figure 1). [4] However, what was the alternative? Many thought the answer was concrete.

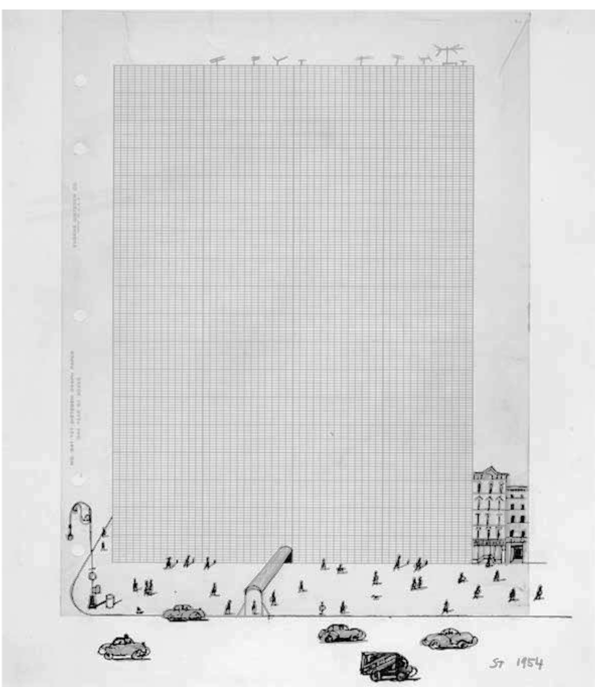

Fig. 1. Graph Paper Street: Saul Steinberg's drawing lampooning the curtain wall. [5]

Envelope and Concrete

In opposition to the glossy, reflective surfaces of the curtain wall, concrete, a material whose plasticity and opacity lends itself to expressiveness, was a viable alternative. [6] In a special issue of *Progressive Architecture* from 1960 devoted to concrete technology, the editor summarized the reasons for concrete's growing popularity as "changed economics of construction; impact of structural innovations in shell design; growing popularity of precasting and tensioning methods with their prefabrication possibilities; and—above all—tedium with the monotony of flat curtain walls and a desire for greater plasticity." [7] Concrete was becoming one of the leading materials used in the architecture discipline. Reyner Banham's seminal essay, *The New Brutalism,* first published in 1955, attempts to codify the then-emerging architectural movement. He defines the movement in three theses: "1, Memorability as an Image; 2, Clear Exhibition of Structure; and 3, Valuation of Material as found." [8] The emphasis on *structural form* and *materials* is seen through Banham's manifestation of Brutalism Architecture, where concrete's plasticity and structural capabilities allowed a new style of architecture to emerge.

This study focuses on precast volumetric concrete parts employed to bound the building: to act as a building envelope. The design of volumetric panels is rooted in Architectural precast concrete panels, which emerged as a new concept in precast concrete in the early 1960s. Unlike the first panels produced in post-war Europe, the architectural panel was subject to architectural design applied to singular and bespoke projects. [9] This study reviews the transformation of architectural 'panels' into sculptural and 'volumetric elements' installed on facades, resulting in remarkable buildings in Europe and the USA. A timeline of some building envelopes with precast architectural panels and volumetric modules is presented in Figure 2.

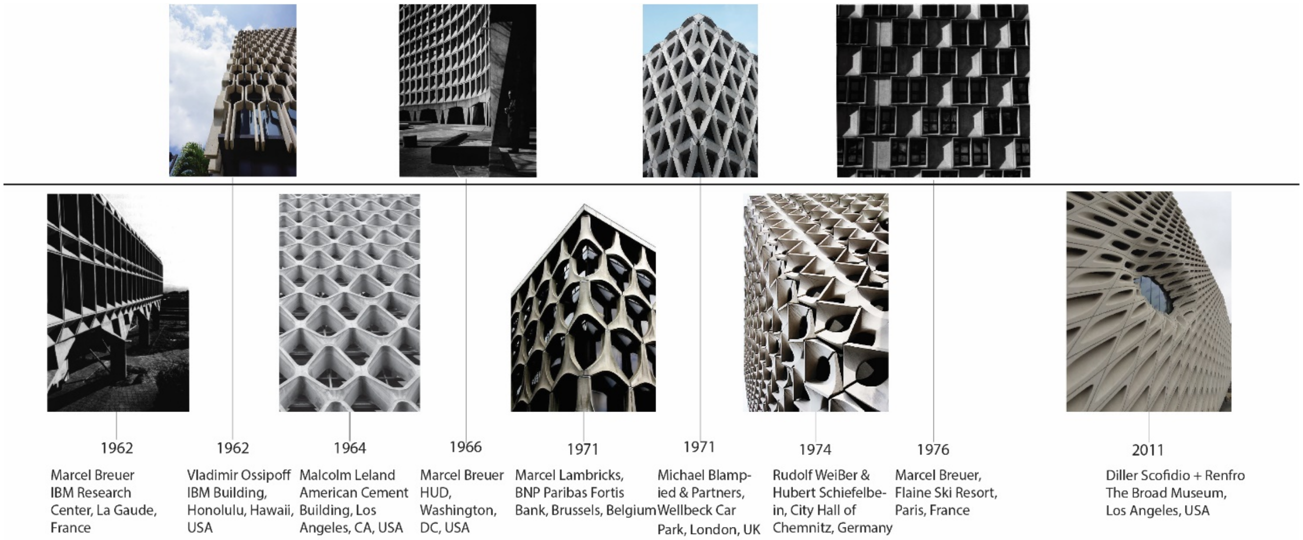

Fig. 2. A timeline of building envelopes made of prefabricated panels (by author)

Taxonomy of Precast Elements Used in Facades

Rows of precast hollow boxes

Many architects used prefabricated parts for building envelopes. As an example, GO.DB studio in Valencia designed modular parts for facades by extrapolating the hollow concrete boxes that were initially created for constructing social housing. Influenced by Miguel Fisac's "bones," they designed thin-profiled concrete boxes for facades. In 1963 and for the Ciudadela Building, the boxes were supported by and covered the floor to which they were attached (both top and bottom sides). Another profile is then attached to the inner face of the envelope, acting as an abutment to provide resistance to vertical and horizontal forces (Figure 3). [10] The precast panels in this example are designed to hold vegetation, and there is a distinct visual division between the rows of precast pot-holder panels and the rows of glazing.

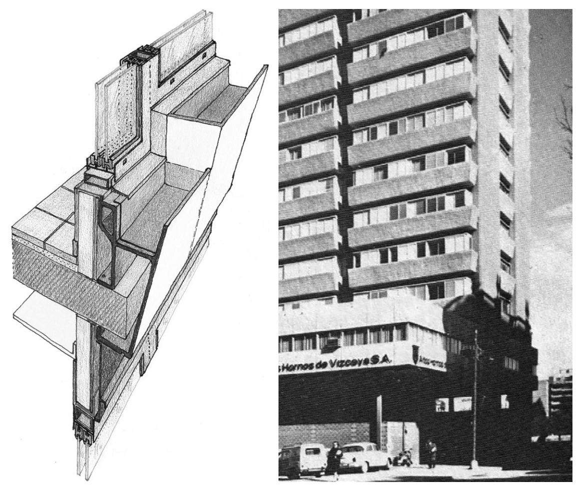

Fig. 3. Detail of the panels in Ciudadela building in Valencia by GO.DB Studio. [11]

Precast panels that incorporate windows

Marcel Breuer was an architect who supported the idea of architectural precast concrete panels. He attempted to show the advantages of using such panels: they could be designed to incorporate a window or shading devices such as a parasol or a lattice and reduce the manufacturing costs. [12] An example includes the IBM Research Center (La Gaude in Southern France, 1960–62), which had 2-meter-high modules with a setback of

90 cm from the external façade. “The paneling was load-bearing, carrying loads from the roof and upper floors down to the columns on the ground floor.” The panels were produced *in situ* using dovetailed timber boards. “The texture obtained with the timber boards is one of the features of in situ concrete.” He completed two more projects afterward: Flaine Ski Resort with 1-meter high, non-load-bearing panels that had an asymmetric pattern of trumpet-shaped holes (1960–1976); and the headquarters of the Department of Housing and Urban Development (HUD) in Washington with 3-meter high, load-bearing modules (1964–66).

Marcel Breuer was then appointed as the Chief Architect for Zone à Urbaniser en Priorité (ZUP) in Sainte-Croix, Bayonne (1964–1968). The structural concept of this building consisted of a cellular structure, with walls and floor slabs of reinforced concrete. The architectural panel types were limited to six: two windowed panels, two blind and plain panels, a recessed panel, and a long panel to form the roof. All panels in this building are 2.66 m high and 10 cm thick, and their widths vary from 3.14 to 2.56 m depending on the internal layout. A temporary central panel production plant was installed on site, where folding formworks made of steel sheets were used for casting concrete. Window subframes were placed in position before pouring the concrete. Once these panels had reached sufficient strength, they were hoisted directly into the space between the slab and cross walls. Concrete was poured to close the existing unfinished edges in the panels shaped to “allow them to fit together closely and avoid the need for additional formwork.” Pre-inserted connectors cast within the walls and slabs provided the anchoring of floors, walls, and panels to the main structure, forming a monolithic union.” [13]

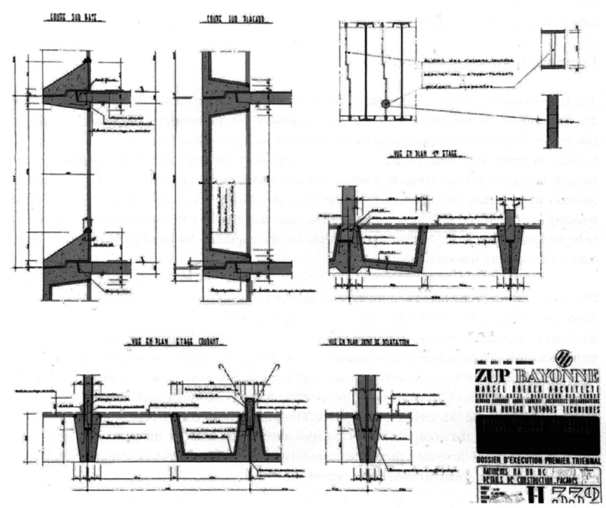

Fig. 4. Marcel Breuer’s ZUP details the attachment of the main structure with the precast panels. [14]

Sculptural volumetric precast elements placed in front of transparent facades

The other precast modules for building envelopes consist of sculptural precast modules assembled in front of a transparent façade. This assembly forms a separate layer yet is connected to and supported by the building’s structural system. Sculptors like Erwin Hauer developed a series of modular structural sculptures with prominent interior voids bounded by continuous surfaces used as self-standing room dividers. [15] Other sculptors like Malcolm Leeland collaborated with architects to use modular volumetric elements in building facades. The American Cement Building in Los Angeles is designed by Daniel, Mann, Johnson and Mendenhall (DMJM) in collaboration with Malcom Leland (1964). The 450 precast sculptural concrete “X’s” cover its north and south façade like an exoskeleton. [16] As seen in Figure 5, the corners of the elements allow them to hook onto the edge of the top and bottom slabs. The pre-installed rebar seems to be in place to create a monolithic union through on-site concrete pouring once modules are placed.

Fig. 5. Malcolm Leeland's X elements are covering the American Cement Building.

Contemporary volumetric elements

The use of precast modules in building envelopes is extended to today's architecture, using concrete or alternative materials. One of the differences between the contemporary cases and the concrete modules of the 1960s and 1970s is the design variation among these modules. The use of computational and parametric design tools has allowed designers to design complex and non-identical elements for facades. [17]

An example is Morphosis Team's design for Kolon's Industries Incorporation in Seoul. The brise-soleil system on the west side of the façade is made from a glass fiber-reinforced polymer (GFRP) fastened to the curtainwall. This "woven fabric" was parametrically shaped to balance shading and views. [18] Prosolve 370e is another example, one in which decorative architectural modules made of lightweight thermoformed plastic are attached to a steel system in Mexico City. [19] The Broad Museum, designed by Diller Scofidio + Renfro Studio, marks a snapshot of the current architecture of this type and shows its departure from the 1960–70s precast facades. Its glass fiber-reinforced concrete (GFRC) panels were precast using custom CNC-formed molds. As stated by project director Kevin Rice, they were "studying the capabilities of digital fabrication and wanted to move the design of concrete facades beyond the brutalist facades of the 60s and 70s." [20]

Digital Fabrication techniques such as CNC cutting and, more recently, 3D printing is used to create molds for casting concrete or alternative materials. Examples include the Domino Sugar Site A redevelopment in Brooklyn that employed 3D printed reusable molds, [21] Smart Slab that employed 3D printed sandstone bespoke mold, [22] and eggshell for a column that employed 3D printed ABS mold [23] among, many other examples. Using 3D printing as the primary fabrication method for creating volumetric parts for building envelopes has formed the core concept of a seminar offered at School of Architecture at Louisiana State University in Fall 2019. The following section delves deep into the pedagogy and outcomes of the course.

Pedagogy: design and fabrication of topological interlocking elements

A seminar entitled "Stereotomic Permutations" was offered at the intersection of *digital fabrication*, *building envelopes,* and *material* at the School of Architecture at Louisiana State University. This course was an elective seminar open to upper-level undergraduate students in their fourth and fifth years and third-year graduates from Architecture and Landscape Architecture with instructor permission. The course investigated the design and fabrication of volumetric components that create a self-standing screen wall in front of a low-rise glass envelope. The course met once per week for three hours and involved weekly readings and discussions on concrete and labor, stereotomy, patterns, building envelopes, and digital fabrication. It also involved a workshop held by precast/prestressed concrete institute (PCI) and

Formliner company for creating patterned rubber molds. Finally. The seminar included an introductory workshop on 3D printing and essential steps for preparing the CAD files.

The course involved two projects. The first project provided an opportunity for analyzing an existing case study with a focus on developing students' mold-making and digital fabrication skills. The second project allowed students to investigate digital design and fabrication of a self-standing interlocking wall.

Project one: Sunscreens

The first project was entitled "sunscreens" and asked students to computationally model and prototype a volumetric envelope that was previously built. Students were provided with a list of case studies from which they could pick one, or they could pick a non-listed case study along the same lines. Each student analyzed the *module geometry* and *module propagation* logic embedded in the module's design of their chosen case study. Afterward, they used Rhinoceros for computational modeling of one or multiple modules before using 3D printing to prototype that module(s). Formlabs Form2 3D printers, which have a bed size of 5.7 by 5.7 inches, were used for 3D printing. Due to these size limitations, modules that fit within a square were limited to having dimensions of 5 by 5 inches or smaller. For modules that did not fit within a square, the largest dimension was set to 5 inches, and the other dimensions were adjusted proportionally. Once the finalized reference piece was 3D printed, students used that module and rubber mold material to design and create a one- or two-part mold. This process is shown in photographs of student's project in Figure 6.

This first project provided students with the knowledge of designing modules in building envelopes as well as skills of mold making and 3D printing that were necessary for the second project. Many students were introduced to 3D printing for the first time through this project, and there were many iterations between designing and 3D printing the modules. Many topics related to mold design, such as draft angle and orienting the mold pieces, were introduced via this first project as well. This caused other parts of the analysis to fall short, in particular, the way that modules are propagated and attached to a building system.

Once the mold was created, students cast plaster to create multiple instances of the modules before assembling them into a vertical screen. In summary, this project demonstrated how design and fabrication are interconnected in architecture. It shed light on the process of designing complex building envelopes seen in facades with volumetric shading elements.

Fig. 6. (left) 3D printed reference piece placed in the two-part rubber mold; (middle) one cast plaster module; (right) assembly of cast modules. Work by (Image © Logan Osborn).

Project two: Topological Interlocking Screens

The second project asked students to design a topological interlocking sunscreen and digitally fabricate the molds by 3D printing elastic resin before casting the screens' component modules. The concept of topology versus geometry was introduced to students, followed by the introduction of topological interlocking assemblies (TIA). In addition, students were familiarized with joining methods for volumetric and sheet materials, namely masonry and wood structures. Afterward, they were asked to design a topologically interlocking volumetric sunscreen. The sunscreen was required to be self-standing without a supporting structure. Both sides of the screen were assumed to be exposed, drawing attention to the design of both sides, as opposed to assuming a front and back side. The screen was required to allow a view from one side to the other and allow light in. The challenges of this project are summarized below under the design of the module and 3D printing a mold.

Designing the module: At first, students were asked to design one module and test the assembly of the modules by creating four instances of their module. They were required to 3D print the final modules using clear or white resin to present the prototype.

One of the challenges of this stage for the students was designing the interlocking mechanism for the parts. Many students started their design by creating brick-shaped modules that were stacked on top of each other with male-female connections. Just like a "brick" where mortar is replaced by wood-type connections! It took a lot of iterations to sway their thinking away from re-inventing a "brick" and pushing the ideation towards changing topology for interlocking the modules. At some point in the design phase, students were asked to bring modeling clay and knife to the class and prototype the modules with the clay. This approach helped them to replace keys as module connectors with interlocking mechanisms.

Another challenge was the strategy for allowing light to pass through the shading wall. Many students had subtracted patterns from the blocks with rectangular borders for bringing light into the space to differentiate it from a "brick." It was emphasized that creating positive and negative spaces by changing the boundary curves of the modules instead of subtracting a pattern from the module can be a viable approach.

Another challenge was not incorporating design freedom in all three axes when designing with a malleable material. Many initial design iterations of the modules and their assembly consisted of two flat surfaces on both sides of the shading wall. Students were only considering the design of the modules in the x and z direction and keeping them flat on the third axis. Again, it seemed that escaping from the "brick" mindset was challenging. Attention was drawn to the plasticity of the material and the opportunities around creating a mold that can create complex shapes and curvatures in all three axes.

Finally, resolving the resolution and scale of the modules was a design challenge. Students used the DIVA plugin for Rhino to assess the daylighting performance of the screen wall and observed the lighting and shading patterns created in the interior space. Simulations assisted students in seeing the amount of daylight that enters the space. Some screens were too thick that they were blocking all the light. Some other shading screens were not having adequate porosity or were too porous. In some cases, the scale of the modules was too fine or too coarse. The lighting and shading simulation studies helped students to adjust the thickness and scale of the modules, as well as the porosity of the shading screen. There were many iterative loops between design, clay model making, computational modeling, and daylighting simulation before students developed and presented the 3D printed instances of their modules for the screen wall.

3D printing a mold for the module: Once the design of the module was finalized, students started to develop the computational model of the mold to be 3D printed. The curvatures and edges of the modules were constantly evaluated to test how the parts could be released from the molds while alternative draft angles were considered. Some students used clay to test undercuts and the best directions for placing their reference pieces. Many had to make changes in the design when they considered casting and undercuts for demolding. The design of two-, three- and four-part molds were all considered.

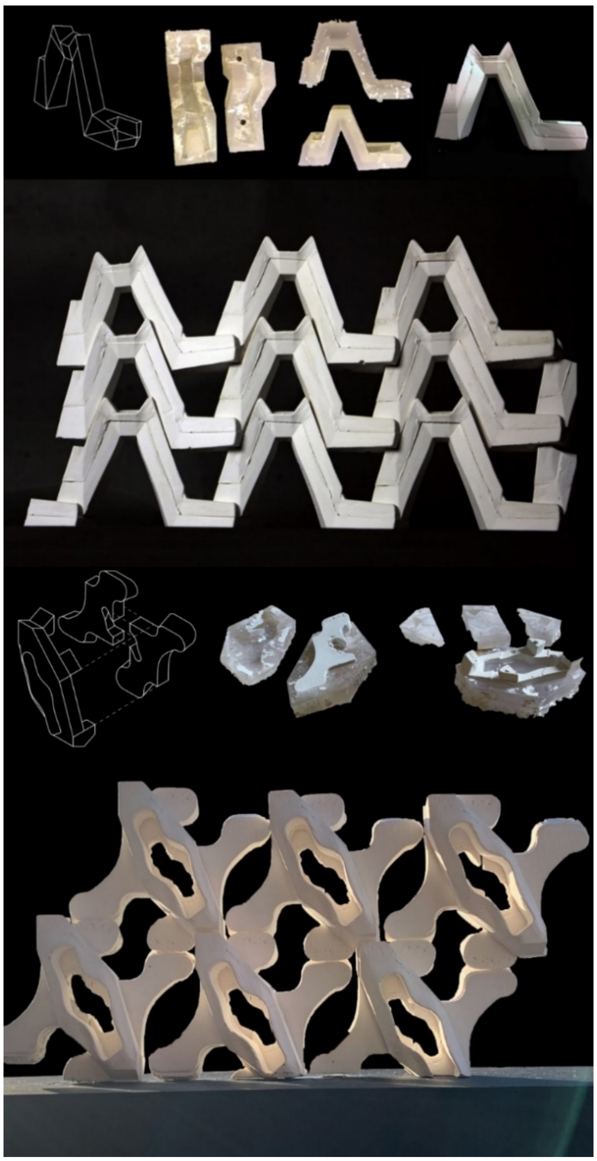

Fig. 7. 3D printed elastic mold and the cast pieces shown in the assembly work by Logan Osborn (top) and Jack Burleigh (bottom).

Students then used slicing software to create a g-code for being sent to 3D printers. Students used elastic resin for 3D printing, which provides flexibility and durability for demolding the cast parts. Students had to work with tolerances in the process of 3D printing. One of the problems of 3D printing a mold from elastic resin is that the print can be “squished” while on the bed. The supports that are 3D printed using elastic resin may not be adequate to support the weight of the solid 3D-printed piece. This will cause inaccuracies in the printed pieces themselves, which negatively affect the cast piece. Adding more supports and increasing the touchpoint size can help to address this issue. Cupping is another issue with resin 3D printing. Including vent holes in the mold overcomes this. Once students had successful 3D prints of their parts, they cast multiple modules and assembled them into a self-standing wall. Examples of student projects are presented in Figure 7. Students’ final assemblies, along with drawings of one module, assembly of the self-standing screen, mold design, and daylighting performance of the screen, were exhibited as a group exhibition at the end of the semester.

Conclusion

This paper reviewed the building envelopes with volumetric modules in the brutalist era and contemporary practice. It then reflected on the modules’ geometry and structural performance. This knowledge was then situated within contexts that can establish new directions for architecture to consider building.

The pedagogy of a seminar in which students were asked to design volumetric topological interlocking modules as a self-standing shading screen was reviewed. The structure of the course consisting of a case study analysis project followed by a design project, worked very well for building skills and then employing those skills during design. In the future iterations of project one, there will be more emphasis on analyzing combinations of the panels, the baseline grid used for the propagation of the panels, and the way that the panels connect to a structural support system. For the second project, there will be more emphasis on design strategies to avoid redesigning a brick to help students consider the properties of a malleable material earlier in the design process. In addition, performance criteria for critical evaluation of the modules will be added to the project, such as meeting a minimum daylighting level or avoiding specific glare criteria. These criteria will allow the evaluation of modules beyond design complexity and digital fabrication success. From a different standpoint, having workshops and outside voices was very helpful for expanding students' perspectives. Engaging with Formliner company through a workshop that they offered on creating rubber molds was helpful for students to learn about the state of the art in the precast industry and will be repeated in future iterations of the course. Graduate students from the Sculpture department were invited for midterm reviews, and in the future, their involvement will be increased. In summary, this seminar was successful in integrating multiple aspects of design through designing a topological interlocking shading wall. One of the seminar's goals was to demonstrate the inseparable role of a designer and a builder, and students constantly evaluated the contingencies of building by using advanced digital fabrication techniques.

Acknowledgements

I would like to acknowledge the intelligence and hard work of students enrolled in this seminar.

Notes:

[1] Addington, "Contingent Behaviours."
[2] Addington.
[3] Rohan, "Challenging the Curtain Wall."
[4] Rohan.
[5] Steinberg, "The Saul Steinberg Foundation."
[6] Rohan, "Challenging the Curtain Wall."
[7] Rohan.
[8] Banham, "The New Brutalism."
[9] Etxepare, Uranga, and Zuazua-Guisasola, "Marcel Breuer and Jean Barets in Bayonne (1964-68): The Use of Architectural Precast Concrete Panels in Large Public Housing Schemes."
[10] Figueres, Mananos, and Garcia, "The Development of Prefabricated Envelopes by GO.DB. Architects Studio for the Construction of High-Rise Residential Buildings in Valencia in the 1960s."
[11] Figueres, Mananos, and Garcia.
[12] Etxepare, Uranga, and Zuazua-Guisasola, "Marcel Breuer and Jean Barets in Bayonne (1964-68): The Use of Architectural Precast Concrete Panels in Large Public Housing Schemes."
[13] Etxepare, Uranga, and Zuazua-Guisasola.
[14] Etxepare, Uranga, and Zuazua-Guisasola.
[15] Hauer, *Still Facing Infinity: Sculpture by Erwin Hauer*.
[16] "Malcolm Leland."
[17] Culver, Koerner, and Sarafian, "Fabric Forms The Robotic Positioning of Fabric Formwork."
[18] Su, "Interwoven: The Kolon One & Only Tower."
[19] "A Pollution-Eating Facade."
[20] Stoughton, "A Porous Building Skin for Downtown Los Angeles."
[21] Love et al., "Feasibility of Using BAAM for Mold Inserts for the Precast Concrete Industry ."
[22] Aghaei-Meibodi et al., "Smart Slab."
[23] Burger et al., "Design and Fabrication of a Non-Standard, Structural Concrete Column Using Eggshell: Ultra-Thin, 3D Printed Formwork."