Matter, Making, and Testing: Designing with Next Generation Precast Concrete

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ABSTRACT: *Precast concrete panel design, fabrication, and assembly are the subject of a seminar being conducted at the University of Pennsylvania's Stuart Weitzman School of Design over the last four academic years. This seminar focuses on precast concrete and specifically it's complex history, materiality – how it is manufactured and the logistics of its assembly - and cultural affects through both its traditional uses within the constructed urban environment as well as new approaches to building typologies such as housing. Through a strategic partnership with the Precast/Prestressed Concrete Institute (PCI) and Northeast Precast, based in Vineland, New Jersey, students have gained access to places where precast concrete is made, formed, and put into action. The seminar has yielded unique opportunities for collaboration, where student teams work directly with project managers and engineers in the design and fabrication of formwork and work with these experts at the precast plant in the actualization of panels. The collaboration, however, is not one-way, as students engage in three-dimensional design software and imagine creative production techniques to develop their panels, finding ways of transmitting their goals electronically to the plant experts. The resultant workflow utilizes advanced Building Information Modeling (BIM) and direct-to-fabrication schemas. Students are present at the facility and participate in the fabrication and assembly of formwork, as well as the pouring of one panel. Unique to the seminar is the production of full size, as opposed to scaled, panels that address multiple formal and performance characteristics present in precast panel design. A primary interest of the seminar is to address the need in design and construction to limit material waste, supporting a more sustainable mode of both design and object production. Students are constrained materially to (2) 5'x10' stainless steel sheets they may use to construct a single formwork that must be re-used to produce two discrete 4'x8' precast panels. The process yields a two-way workflow between students and the precast project managers and engineers and allows for a bi-directional knowledge exchange, making the production process instructional for all parties as well as fun. This paper will address the educational objectives of the seminar, as well as introduce a case study produced by students in the fall 2021 semester. That project further explores surface and formal variation across the two panels by inserting voids into the formwork and varying the material expression in different zones of each panel.*

KEYWORDS: Precast Concrete, Education, Density, Building Information Modeling, Digital Workflows, Sustainability, Collaboration, Shop Drawings

1. CONCRETE AND PROCESS

Figure 1: Examples of panels produced in Matter, Making, and Testing, the seminar was held in the fall semesters of 2019 through 2022 and was each time enrolled by twenty (20) graduate students.

1.1 Precast Pedagogy

Introducing architecture students to material assemblies is a complex pedagogical endeavor. Such an introduction to materials, and more specifically construction technologies, should be grounded in history, environmental circumstance, as well as best practices in order to facilitate a more comprehensive understanding leading to a sound approach and selection process for future practitioners. Concrete, and especially precast concrete, has a rich history that includes its use as a simply composed mortar in antiquity, through the more chemistry- and engineering-grounded formations in the 19th and 20th centuries. The repurposing of post-war factory space in the mid-20th century led to the rise of modern precast technology, adding prefabrication and modularity to the positive criteria the material has accrued in its use.

That the material is plastic, that is, moldable to any form is topical to the educational objectives of many architecture schools and assists in the challenges of introducing concrete as a form- and performance-driven construction technology that continues to find worth in the 21st century. Taking advantage of this opportunity, at the University of Pennsylvania we have introduced a seminar in design and technology that engages the history and use of the material as well as giving students the opportunity to fabricate and pour precast panels by working directly with a local producer. Titled Matter, Making, and Testing: Designing with Next Generation Precast Concrete, the seminar has been held for the past four academic years and continues to be a popular course among the student body. Students generally enroll in their second or third and final year of their graduate studies, however, first year students have also been admitted to the course. The seminar was conceived with and enjoys the support of Northeast Precast, located in Vineland, New Jersey. Through this collaboration, we have had the opportunity to study the material historically, conceptually, and physically though a panel design and casting process undertaken with the precast sponsor. These efforts have also just been awarded funding over the next four (4) years through the Precast/Prestressed Concrete Institute.

1.2 Seminar Learning Objectives

The seminar has been conceived with three (3) distinct components which are equally divided in course delivery. Through the course of the semester, participating students build knowledge and content through:

1.2.1 Lectures on the History and Technology of Precast Concrete

A history of reinforced concrete from the turn of the 20th century, and more specifically the rise of precast in the 1950’s as part of an offsite, factory-based movement within the construction industry, are explored. Specifically, concrete’s relationship with both modernity and nature are considered. As both a material and construction technology, it is equally a product of advancements in the engineering and chemistry of 19th and 20th centuries – becoming synonymous with new architecture and various utopian movements; as well as a result of simple and time-tested labor operations requiring no special knowledge or expertise. A goal of precast construction was the use of tools, machinery, and other equipment, ideally automated, in the production of standard, interchangeable parts and products; this promised a restructuring of entire conventional construction processes.

At the beginning of the 20th century, the material was chosen by Thomas Edison as a solution for worker housing in the steel towns emerging in the Midwest including in Gary, Indiana, where a series of single-family concrete houses were produced with reusable steel forms. Edison patented a process in which a concrete house could be formed with a single pour. The prototype was designed by New York architects Mann & MacNeille in 1909. The fact that Edison chose them for the house prototype is telling, as his concept was most broadly explored in the 1910’s in Gary, Indiana, which was a company town with concrete worker houses planned and constructed by the United States Steel Company, which was formed in 1901 when JP Morgan and Andrew Carnegie merged their steel interests. In 1913, Walter Gropius published, in the German magazine Deutscher Werkbund, images of large reinforced concrete grain elevators from the United States, captivating European architects and ushering in a 20-year period associating the material with modernity. While some architects and inventors in the US and Europe, including Le Corbusier, further explored the material as a solution for houses and housing, the trajectory of the material would be for more industrial and large-scale uses, including roadway and infrastructure construction.

The association with these projects further separated the material from housing, and the 1960’s and 70’s saw a conscious move away from the material’s use in housing, with modular housing solutions being proposed in either timber or steel. There was one notable experiment, however, completed in 1975 in Jersey City. Summit Plaza, which provided 486 affordable and precast concrete housing units in several multifamily building configurations across a 6.35-acre site. The dwelling units were built by a now defunct company called Shelly Systems and was commissioned by the Department of Housing and Urban Development (HUD) at one of nine (9) sites developed country wide. The project was part of a HUD initiative called Operation Breakthrough, a three-phase demonstration project that tested innovative building materials and construction methods with the goal of removing obstacles to large-scale affordable housing production in the United States, bringing quality housing to all income groups. Operation Breakthrough ultimately worked with 22 system producers that provided some 2,900 housing units, all delivered using off -site construction methods. The selected producers utilized housing systems ranging from precast concrete- or wood-framed modules to units constructed largely of plastic or metal, supplied by companies including Alcoa, Levitt Technologies, General Electric, and Republic Steel. Some systems were already in production when selected, while others were new and untested.

Lectures also engage contemporary issues including sustainability, carbon entrapment, and concrete's relationship to ecology; and are supplemented through a variety of readings.

1.2.2 Introduction of Novel Precast Precedents

Building precedents are introduced throughout the seminar that range in scale from houses to larger buildings of various typologies. Case studies have included the Church of Notre Dame du Raincy (1922-23) by August Perret, the Rudin House in Leymen (1996-97) by Herzog & de Meuron, The Perot Museum of Nature and Science (2012) by Morphosis, and Steven Holl's Rubenstein Commons at Princeton (2022), as well as work by the instructor. The precedents are paired with weekly readings that introduce both concepts surrounding the buildings themselves as well as the design workflow that produced them. Projects are selected not only for their cultural and technical novelty, but for the unique and increasingly digital and collaborative processes that led to their formation. For these case studies, student groups organize brief presentations following a lecture that links the building/precedent to a weekly reading. It is expected student teams understand both the architectural and technological significance of each case study, as well as the design and collaboration workflows entailing their production. The case studies also offer the students an opportunity to study the three-dimensional modeling of panels ahead of their own panel design. Several of the case studies were produced by the precast concrete company giving the students access to production and logistics data, and supply shop drawings for those projects.

1.2.3 Group Collaboration / Development of Digital Content / Mock-ups

Students are ultimately responsible for a precast mock-up that is produced in collaboration with and at the facilities of Northeast Precast. Working in teams of three (3), students work collaboratively to produce all virtual information required to realize the precast mock-up at full scale, as well as a panel schema with joint patterning and formwork images that will position the mock-up within both larger and more local scales. Final seminar deliverables are the mock-up panel itself, produced in conjunction with Northeast Precast, as well as documentation including shop drawings and other studies that express the mock-up production process and simulations that study panelization and structural feasibility. During the seminar's two scheduled workshops at the precast plant, students have access to the sponsor's various CNC capabilities, including a plasma cutter, multi-axis routers, and wire-based foam cutters, and a full metal fabrication shop. Formwork material had generally been either coated ¾" plywood, or milled high-density foam, or a hybrid of both. Students have also explored Autodesk's Structural Precast Extension for Revit as a basis for shared documentation.

The ability for students to engage the precast team and facilities has ensured consistent interest and participation in the seminar and to date, some ninety (90) students have had the opportunity to interact in various ways with the precast sponsor. The primary deliverable of the seminar has been a full-scale panel, and the constraints applied to this work have varied by semester. In the fall of 2019, the initial semester the seminar was offered, students worked to produce a 4'-0" x 8'-0" flat panel that specifically dealt with issues of formal variation, aperture, and insulative performance, as well as lightness. In most cases, panels were imagined as an architectural façade component, so students developed concepts that addressed aperture and cladding.

Based on the initial success of the fall 2019 work, the fall 2020 course introduced a more specific construction constraint – the corner. Instead of one 4'-0" x 8'-0" panel, students were given the task of designing two (2) 3'-0" x 6'-0" panels and were asked to consider their joint and design a corner – an architectural condition that is specifically topical to precast concrete design that also has a rich architectural history in terms of both construction and detail approaches. In this instance, one precast precedent was removed from the course so that a student team could study the history of the corner instead. This work was presented to the group in class prior to the commencement of the panel design process.

In 2021, the course was reimagined again, taking advantage of a new CNC plasma cutter installed at the precast plant. In that instance, student teams were given two (2) 1/8" thick 5'-0" x 10'-0" sheets of steel. This flat stock would be utilized as the primary material in the production of panel formwork. Student teams were permitted to use CNC-cut foam inserts in some instances, but the goal of the exercise is to introduce reusability of the formwork as a material engagement and management strategy. Foam inserts would allow a certain amount of difference in panels cast from the same formwork, a response to the formally ambitious panels previously produced in the course utilizing coated plywood, a material that is usually discarded after a single use. To prove reusability in this exercise, Northeast Precast agreed to produce two (2) panels per team, each poured from the same formwork. A requirement of inter-lock was given that would allow students to vary the formwork with the foam inserts.

1.3 Workflow

The specific workflow utilized by the students in each semester varied by team and goal(s) of each panel. In some instances, a portion of a building already designed by a student or team was selected for further development and panelization, and in others, panels were developed specifically for the course. This phase of the work commenced with a visit to the precast plant which included presentations regarding various capacities of the company including insulated sandwich panels, Superior Wall-type panels, as well as specialty and architectural precast. Students were asked to consider each of these as criterial for the design of their own panels. Following the plant tour, students were initially tasked with imagine the positive form of their panel designs using modeling software. These models, as well as their surrounding negative geometry – an initial attempt at formwork - were transmitted to Project Managers (PMs) selected by Northeast Precast to work with each student team. The file data, sent as raw geometry and initially unformatted, was viewed in a 3D environment and commented on by the team at Northeast Precast. Around this time, lectures focused on the production of shop drawings, with examples of two- and three-dimensional graphics shared with the students. Once the PMs and students arrived at a final design that met size and shape capacities available, students embarked on rationalizing their work into a series of shop tickets that specified reinforcing bar size, layout, and location within panel thickness, as well as the location of any anchors and lifting hooks for eventual stripping. It was an important goal of the course for the students to imagine a comprehensive design, fabrication, and stripping process, so the utilization of components for the lifting and setting of the panels were understood as an integral part of the panel conception.

2. STUDENT'S PERSPECTIVE ON SEMINAR

2.1 Case Study Project

The fall 2021 course ultimately brought objectives from previous seminars together with the key object of a reusable formwork. In addition to this set of course criteria, teams implemented their own series of design goals and rule sets that helped guide the formation and development of their panels throughout the duration of the semester. The student team of Riley Engelberger, Lisa Knust, Madison Tousaw, and Lauren Hanson built upon the specification of a reusable formwork and the effect this would have on panel variability from a single form. For the course, the team produced two 4' x 8' precast concrete panels that are unique from one another, join at a 90° corner and introduce two possible finishes in a precast setting – sandblasted and revealed aggregate (fig. 2).

2.2 Design Team Goals and Approach to Initial Digital Geometry

The student team started with the joint condition and pursued a design that could accommodate a 90° corner. This is complex given course constraints permitted the production of a single formwork. To achieve a second panel that would notch into the first at the corner, it would have to rotate in one plane at 180° and in another plane at 90° (fig. 3). Had the geometry of the notches at the corner been horizontal rather than diagonal, the panels could simply slide into each other. The team desired a more complex joint, and the notches occur at a diagonal, which ensured the two panels would fit together, allowing the joint edge to be mirrored along the vertical axis, with the top half being the negative of the bottom half. Because of the diagonal the second panel had to be installed from above the first and slid down into the notch. As long as these parameters were adhered to, the design of this joint could have many alternative expressions. Secondary to the notching is a faceting of the corner in order to lessen the harsh 90° that would otherwise exist. Once this corner was resolved, the design of the faces of the panels were explored (fig. 4).

The team used curved form profiles developed in previous work while reimagining and implementing these elements under new constraints, which turned out to be so great that the curves altogether were re-worked into straight lines that were only slightly curved at each turn, responding naturally to the bend radius of the machine that would bend the 1/8" thick stainless steel sheet material used to create the formwork. The larger radius curves in the initial design option (fig. 5) would have been faceted to meet the constraints of the production method and directions received from our project managers at Northeast Precast. Because of this, the team chose to pursue the second design option, which did not require to facet larger radii curves and would lead to a cleaner final set of panels. There was some design disappointment in losing the original curves, but the team learned an important lesson — that they must sometimes alter design intent in order to meet the constraints and requirements of the fabrication process. Though a simpler option was engaged, there were still important fabrication considerations, as the bent profile could not be achieved in a single sheet, but rather multiple cuts that would then have to be welded together (fig. 6). Of course, these were obstacles that would ultimately be tackled by the Northeast Precast fabricator, but it was important that the team considered the welds for the sake of design and fabrication efficiency.

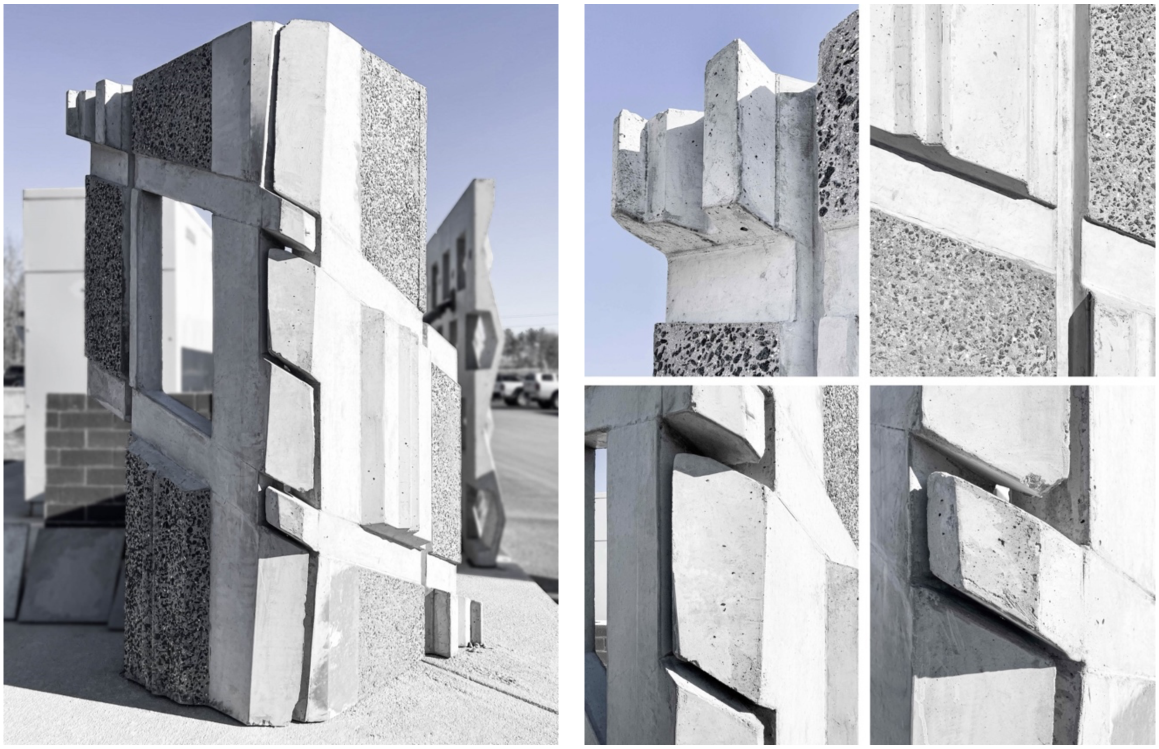


Figure 2: Final unique precast panels from single form at 90° corner and details of corner joint, extruded profiles, & sandblasted and revealed aggregate finishes.

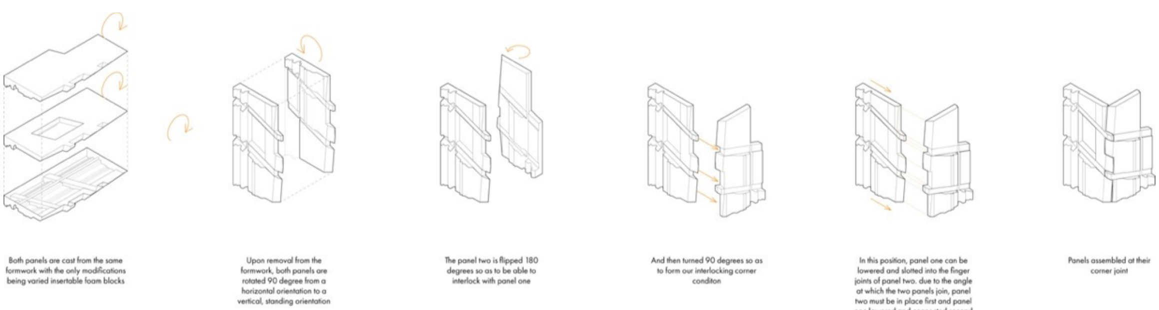
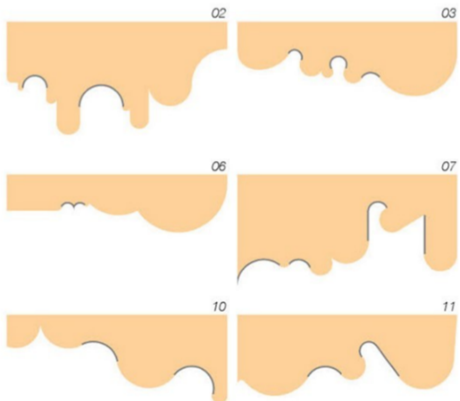


Figure 3: A step-by-step process of casting, removal, and joining the corner panels. This diagram helps to further illustrate the necessary rotation of each panel to ensure that the corner notches will properly interlock.

Figure 4: Screenshot images of a digital model were exchanged digitally, allowing team members to draw on top of the images and suggest new design potentials. These images specifically show the progression of the joint condition including diagonal notch, facet, and idea for faces.



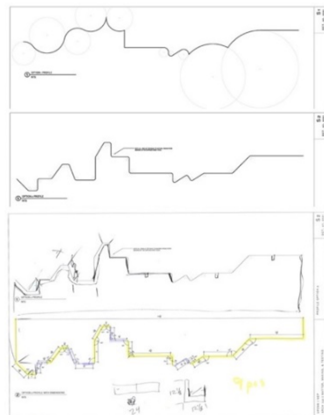


Figure 5 (left): The profile catalogue, left, highlights a selection of referenced profiles that were refined and modified for use on the panel façade.

Figure 6 (right): The shop drawings on the right show how these profiles were translated for our design and underwent a series of modifications to work with the constraints of casting with concrete.

2.3 Translating Digital Intent to Documentation for Physical Production

Initial translation between digital and physical production dealt primarily with the negative – that is, the formwork that needed to be produced in order for the two panels to be poured. This presented many challenges, not least the limit that each group received (2) 5'x10'x1/8" stainless steel sheets to be used to fabricate the formwork. The need for a waffle support grid was initially unknown, and as can be seen in fig. 7, accounts for approximately 50% of the total allowance of stainless-steel, however per conversations with project managers at Northeast Precast, it was clear that the grid, spaced at 12" increments, was necessary to support the weight of both the form placed within it and the subsequent 1,500 lbs of concrete poured into the form. Beyond material restrictions, the team also had to consider the simple nature of translating something from a 3-D model, and bring surfaces with no inherent thickness, into dimensional reality. The geometry was complex, with small ledges and other parts that were difficult to make thick. If the team had foreseen these difficulties while working on the design, it likely would have led to a different set of panels. One aspect of this that had been on our minds while designing was the need for slightly canted surfaces in order to prevent the panels from getting stuck in the form as it was being extracted. If we had been less prepared for this, it would have led to a lot of time spent later on remedying this potential problem.

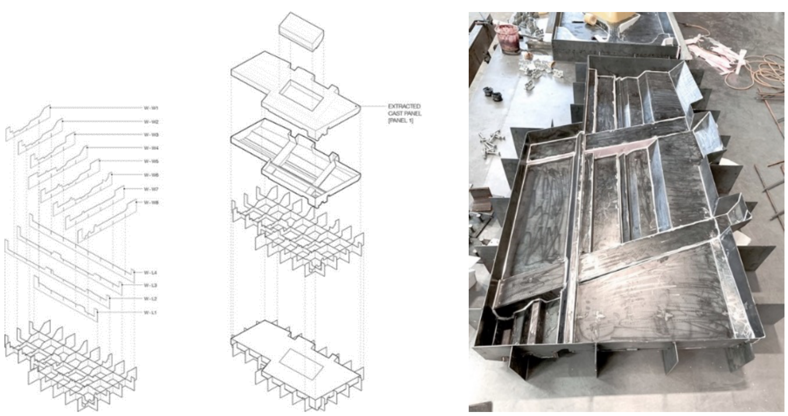


Figure 7: An exploded kit of parts breaks down the design elements, from the assembly of the waffle frame, to how the formwork sits within the waffle structure and where foam block outs are inserted. The finalized formwork was constructed from plasma-cut pieces of stainless steel, bent, and welded together. Seams were caulked for clean edge conditions.

The most satisfying part of the experience for the team, beside the reveal of the final concrete panels, was traveling to Northeast Precast to finish fabrication prior to pouring the concrete. Work at the plant involves assembling rebar lattices per shop drawings that had been prepared for the panels, as well as laying out rebar, CNC-foam block outs, pin anchors, embed plates and other various hardware required for the successful extraction and subsequent erection of the panels. The drawing phase that led up to this final fabrication and assembly day involved much back and forth between the student team and project managers at Northeast Precast to ensure everything was formatted and notated to their standards. Beyond preparation of the drawing files, teams were responsible for preparing fabrication files for the plasma cutter to cut the stainless-steel sheets as well as instructional files to digitally describe how each plasma cut piece had to be folded – including the location, degree, and direction of each fold. While tedious, it is clear that the preparation of these drawings and digital files were most responsible for successful execution of the fabrication and construction of the panels. As can be seen in figure 8, a clearly drawn and notated set of shop drawings made for easy work when the time came to physically lay out all the elements that went into the final concrete panels that are eventually hidden from view.

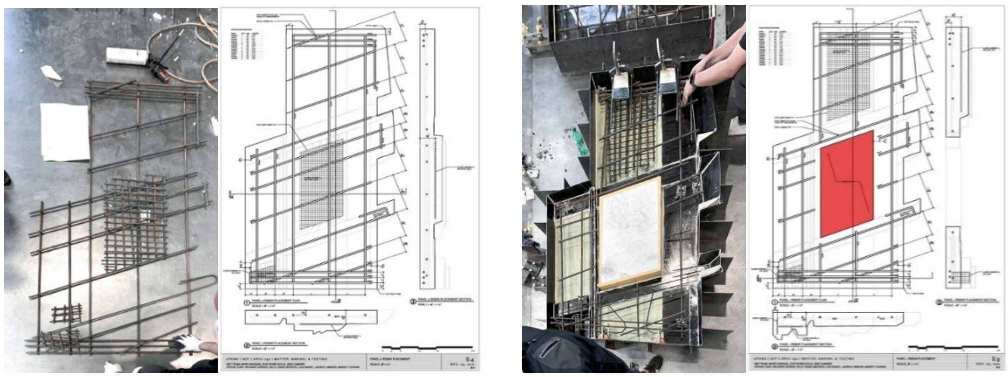


Figure 8: Shop drawings proved integral to the fabrication process. Physical assembly and orientation of rebar were nearly identical to shop drawings, as well as placement of foam block outs, pin anchors, and applied retardants.

2.4 Possibilities for Individual Panel Variation and Architectural Implementation

The formwork that was fabricated for the two panels slightly constrained the total number of unique panel options that student designs allowed for given the allowable stainless-steel sheet use from Northeast Precast. Had more material been allotted, the formwork fabricated could be used to create an immense number of unique panels given that there are 9 zones of the panel that can take 3 forms – extruded profile, flat, or void (fig. 9). Each zone may be partially or fully blocked off with theoretically re-usable stainless-steel pieces, which in our fabrication process was accomplished with CNC-milled expanded polystyrene (EPS) foam due to the constraint on the amount of stainless-steel sheet we could use. Beyond this, for the profiled and flat options, each could either be sandblasted or aggregate finished, increasing variability even more.

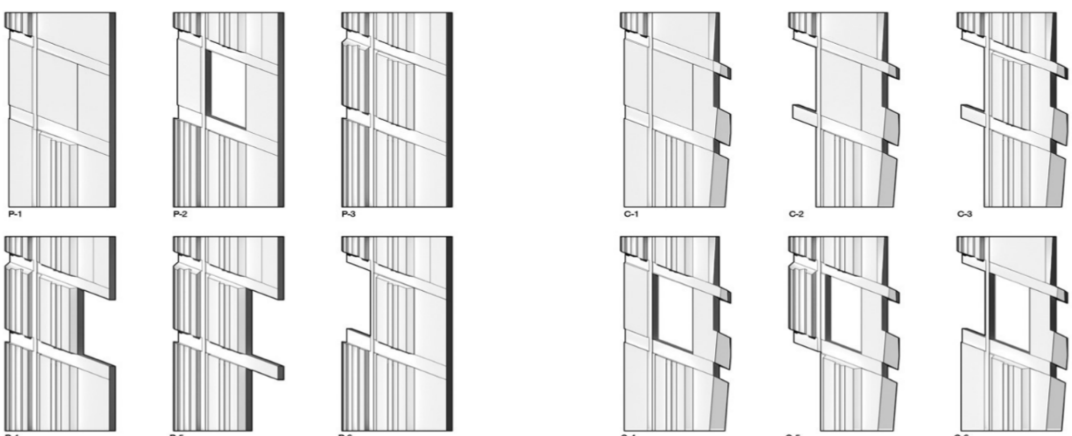


Figure 9: The specific multi zone-based design of the panel façade was a critical component to producing design variability. These zones offer the potential for both flat and articulated faces, as well as openings for fenestration and corner conditions, offering greater architectural interest.

Throughout the project, the team imagined and worked to design these panels such that there would be variation when applied as façade panels. The variation in panels allows for different types of openings to occur in the building allowing for natural light, and creates a highly expressive, and while static, constantly shifting façade due to its play on light. The extruded profiles cast deep shadows that alter its expression throughout the day. It should be noted that for the duration of the course the panels were consistently thought to be the size they were fabricated (4'x8'), but there is of course possibility for a scaling of these panels to a much larger dimension, as we saw first-hand being produced at Northeast Precast. These panels could be increased in size and possibly used on much larger buildings with interesting architectural effect.

3. CONCLUSION

The seminar has proven that collaboration with material and fabrication companies, like Northeast Precast, provides opportunities unparalleled to those typically available in a solely educational setting. Most important is the ability to translate, at scale, something designed digitally to something physical. To successfully translate from digital to physical, the project demanded that we adhere to schedule, material budgets, and required constant back-and-forth communication and collaboration with our project managers at Northeast Precast. Producing these panels continues to be an immensely rewarding experience for both students and the precast company, and the lessons learned by each will certainly carry forward as they further engage the profession and find opportunities to bring material, and precast, solutions into their work.