CONCRETE LATTICE
UNITIZED ARCHITECTURE OF ASSEMBLY

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ABSTRACT: *Concrete Lattice* seeks to challenge our normative association with concrete building construction by developing a lattice system of prefabricated units using Glass-Fiber Reinforced Concrete (GFRC) as the primary material. Lattice systems are porous, lightweight, and deployable; terms that are not typically associated with concrete structures. The design of parametric units rather than linear components, typical of lattice systems, highlights issues of assembly in precast building systems using integrated components. While design workflows and CNC fabrication aided in efficiently manufacturing the units, the assembly is post-tensioned during the construction process to limit the amount of scaffolding necessary. Our goal was to address the gap between design and production by exploring the development of complex lattice systems and using digital design tools to streamline the production of units to be deployed on site. The design of our *Concrete Lattice* through prototyping and fabrication highlights the value of design research for design studio learning.

The complexity demonstrated through this project argues for the use of computational design in both informing design decisions and managing the myriad contingencies involved in the production of a novel structure. Complexity in this respect addresses not only formal and experiential concerns, but also structural and manufacturing processes. Our *Concrete Lattice* makes explicit the role digital technology plays in the integration of design, engineering, and fabrication. While this discourse is not new, our design aims to take full advantage of lessons from precedents and offer a unique project uncharacteristic of what we have come to expect from concrete as a material.

KEYWORDS: concrete, lattice, digital fabrication, formwork design, computational design

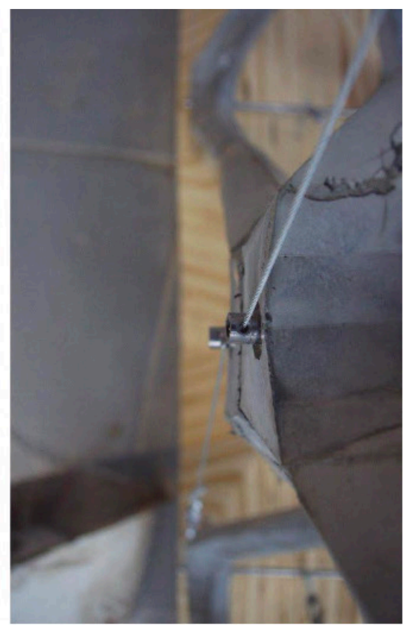


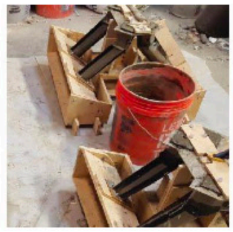
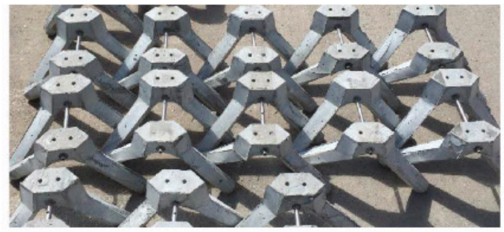
Figure 1-2: (left to right) Final installation of Concrete Lattice structure at Taubman College's Liberty Research Annex. Detail of integrated post-tensioning connection.

1.0 INTRODUCTION

This paper expands upon the work produced in the graduate thesis design studio led by Assistant Professor Tsz Yan Ng at the Taubman College of Architecture + Urban Planning, University of Michigan between 2015-2016. This course was jointly taught with Assistant Professor Wes McGee, whose seminar, Advanced Digital Fabrication, is linked with the thesis section to provide students the opportunity to fully explore novel techniques in digital fabrication.

As a yearlong, terminal-year design thesis course, the fall semester seminar is structured to provide the conceptual background for the development of disciplinary questions and the technical skills both in terms of computational design and in casting concrete. The exercises in the seminar introduce relevant historical and contemporary precedents as well as techniques for mold making through different design approaches. This includes “part to whole” assemblies, mix composition, techniques and processes for manipulation at various states of curing, and experimental processes previously prohibitive, but now possible through the use of Computer Numeric Control (CNC) fabrication techniques. The design studio in the winter term provides the opportunity for individual groups (in teams of two) to explore a trajectory of investigation involving design research, prototyping, and the production of a final design at full scale. As the title of the course suggests, issues of labor are investigated to address the inherent gap that exists in the industry for building in concrete – where the skilled intellectual labor of concrete mix development and formwork design is separate from the pure manual labor necessary to produce formwork for casting. This gap is reconsidered in light of new fabrication technologies, informing a more direct relationship between the various aspects of architectural production.

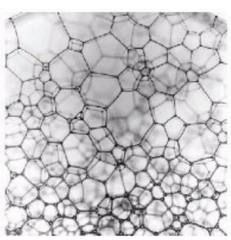


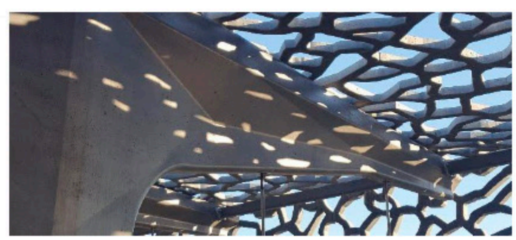



Figures 3-6: (left to right) Fabrication techniques explored for this project include CNC routing, robotic rod bending, waterjet cutting, ZUND cutting, jig manufacturing, and cast units of *Concrete Lattice*

1.1 Background
Many precedents served as inspiration for developing various aspects of *Concrete Lattice*. Extending from the work of Maciej Kaczynski in his 2013 project, *Crease, Fold, Pour* (Kaczynski, 2013); our use of Polyethylene Terephthalate Glycol-Modified (PETG) for formwork is similar with regard to how it utilizes folding for formal and structural potentials (Figure 04). Folding techniques highlight both formal aesthetics and structural performance of specific origami patterns. The work deviated from Kaczynski’s by moving away from a cast-in-place structure to working with a set of self-similar precast units as a comprehensive building system. The advantages of precast units include the possibility of disassembly/reassembly and the ability to install the project within a short period.

This project also takes cues from research in masonry compression-only systems explored by Philippe Block (Block & Ochsendorf, 2008) and from variable-volume systems such as *La Voûte de Lafevre* by Matter Design (Clifford & McGee, 2014). As precedents, these projects provided the framework to explore computational design processes where form is integrated with performance, optimized with material and structural considerations.



Figures 7-10: (left to right) Inspiration from spatial net structures, biomimetic geometries, and precedents of concrete lattice structures: *Crease, Fold, Pour* by Kaczynski (2013) and the MuCEM by Rudy Riccioti in Marseille, France (2013)

The geometric design of this lattice system explores a “part to whole” assembly derived from a diamond cellular structure. Algorithmic design techniques were explored concurrently with biomimetic precedents found in nature. The diamond cell can produce a few variations of the base geometry, from rhomboids to hexagonal struts, and these are typically found in spider webs, turtle shells, and microscopic structure of soap bubbles. A similar geometric study was performed in the exploration of the lattice system through spatial nets, which take cues from spider webs but evolve outside the symmetrical pattern (Figure 07). This research stems from the paper *Spatial Nets: The Computational and Material Study of Reticular Geometries*, which experiments with reconfigurable jigs to produce volumetric nets (Askarinejad & Chaaraoui, 2015). The theoretical principles presented in this project - of reconfiguration, slender materials, and space creation, were inspiration for the diamond lattice form with the adjustable jig as a necessary component for the casting process.

The use of concrete necessitates an understanding of compression-only systems. From the hanging chain models of Antoni Gaudi to the experiments and research of Frei Otto (Otto & Rasch, 1995), these principles have been tested and explored by architects seeking to extend the boundaries of the discipline to produce novel designs with optimized structural performance. As new software techniques have become available, we are now able to perform these tests digitally as simulated models. This project explored catenary logics using Kangaroo, a physics-based plug-in for Grasshopper, which informed the structural performance through interactive simulation and optimization of the variable units. While digital simulation is possible, many iterations of physical prototyping were still necessary to identify issues of material behavior of both PETG molding processes and GFRC casting.

2.0 PROCESS & FABRICATION

During the seminar phase, we began by collectively developing a base knowledge of material properties for concrete and casting techniques through different approaches of formwork design. These early experiments were performed alongside broader exposure to construction systems, which for this project, was focused on precast units that are typical to the building industry. Our goal for the design studio semester was to redefine the notion of the units, with a set of parameters that could produce manageable variations, be mass-produced, and deployed as a structural system. Additionally, as a team of two people, the scope of realizing the project within a short period after the prototyping and design phase was a challenge compared to more traditional design studios that does not require full-scale realization.

2.1 GFRC mix

There are four key ingredients in concrete: portland cement, aggregate, water, and air - the latter being a product of the chemical reaction between cement and water that also produces heat. In addition to a fine aggregate like sand, glass fibers of various lengths were introduced into our mix design for added strength and to resist cracking. Fiber reinforcement provided a critical advantage over steel for this project because of concerns for weight, workability, and cost. A polymer admixture was also used to reduce the water to cement ratio, enhance flow during casting, increase strength and bonding of the cement, and yield a smoother, non-porous cast surface. The ratio of these ingredients to one another is critical to ensure a smooth casting process and the desired resultant form.

2.2 Prototype testing

Fabrication and making were critical aspects of the ambitions for *Concrete Lattice*, thus prototyping at multiple stages of the design process charged us with identifying and solving problems as issues arise. The most significant component of the prototyping process beyond the concrete mix is the design and fabrication of the mold. We settled on PETG to have the most control over the lattice unit's form, and to build the formwork with an inexpensive material that could be cut using a two-dimensional CNC knife-cutter (ZUND) and folded into 3-dimensional molds. (Figure 11).

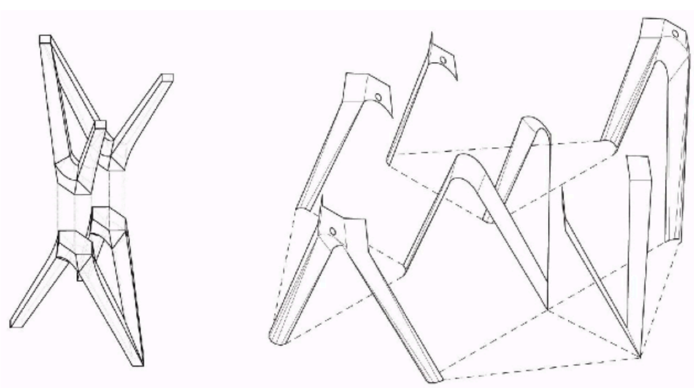


Figure 11: Lattice units split for casting with an assembly diagram for the PETG formwork parts

While the folding and assembly of these plastic parts helped structure critical moments in the mold, we were unable to limit inaccuracies due to flex of the PETG and cracking from the chemical reactions with the concrete mix. We devised an external adjustable jig to secure the formwork at critical connection points. The jig acted as a collar that provided additional stiffness to prevent the PETG flex caused by hydrostatic pressure of the concrete in its liquid state. The development of the formwork and the adjustable jig was informed by a series of prototypes, identifying the moments of failure and calibrating the formwork/jig design to address different challenges. As the design was refined, it was simultaneously adjusted in the overall lattice system with parameters that feed back to the computation process checking for feasibility of the lattice system, both structurally and in terms of fabrication. The adjustable jig evolved into a singular system capable of casting well over ten unique unit types (Figure 12). For the final lattice, we constructed six wooden jigs (enabling concurrency in production), cut from CNC routed plywood, and waterjet cut steel parts to secure the connection points on the ends of each unit. Within the singular jig system, steel collars, unique to each unit type, were used to accurately position the node at the top of the cast. In order to save time and material, the process was optimized to account for the various collar types needed in each casting session.

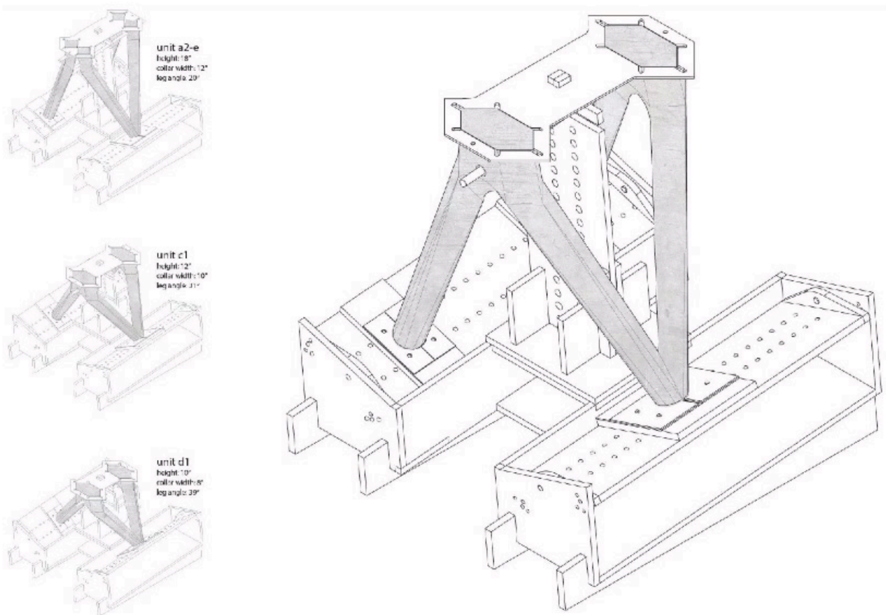


Figure 12: Axonometric of the PETG formwork in the reconfigurable jig system. Steel plates are at each node to ensure precise positioning of adjacent units.

2.3 Parametric design

In designing the units and their aggregation as an architectural system, we used the Rhinoceros modeling software and its parametric plug-in, Grasshopper, to develop a base unit with constraints in multiple dimensions. This parametric study allowed for precision in terms of aggregation and for the design of different combinations, creating varied typologies of spatial enclosures.

The individual unit inspired by biomimetic geometries is a cellular structure of a diamond lattice. For casting purposes, this diamond unit was split in half, creating compressive nodes at the ends of the linear elements where they meet. A steel collar fixes the position between the two ends along with other steel plates that hold the converging ends at the base of the jig. Node locations were controlled via the computational model to achieve a compression-only solution that would result in the least amount of shear stresses at the connection points.

The parameters of each unit were determined by its height, width between the joints, and the position of the legs at the base of the jig. The actual values were determined after a careful study using the Grasshopper plug-in, Kangaroo, which evaluated the desired curve of ten feet in height and ten feet in section. (Figure 13). Separate catenary curves were found for the inside and outside layers of the lattice geometry. These affect the individual unit parameters, adding a layer of complexity and asymmetry to the section of the half vault.

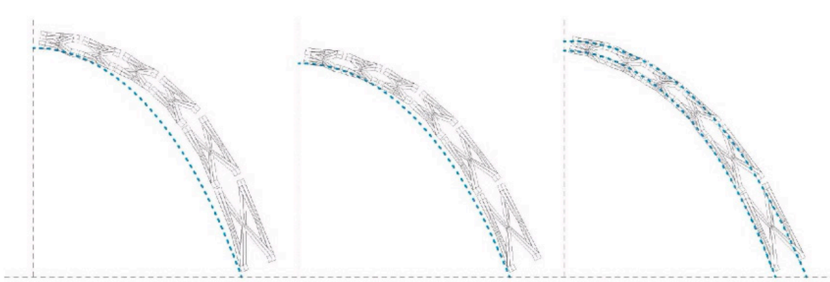


Figure 13: Structural studies of catenary curves using Kangaroo.

These studies show how the project's design was customized to find a compressive structural form within the dimensions of the exhibition site. Despite this complexity, the process was integrated through the Grasshopper code to output each unit's cut files for the formwork, bending curves for the interior rebar, and a 1:6 scale model for 3D printing.

2.4 Final construct

While the fabrication of parts and their corresponding labels were made efficient by the Grasshopper script, the PETG formwork assembly process was time consuming given the human labor involved. Similarly, during installation, labor in post-processing each unit and the final assembly of the 42-unit lattice construct (Figure 14) consumed more time than the casting schedule. The scaffolding used was a minimal set of dimensional lumber struts, one at each major node with a specially routed module to cradle at the joint. The process for post-tensioning each unit during assembly minimized risk of collapse, scaffolding costs, and labor - especially for disassembly and re-assembly of typical scaffold structures.

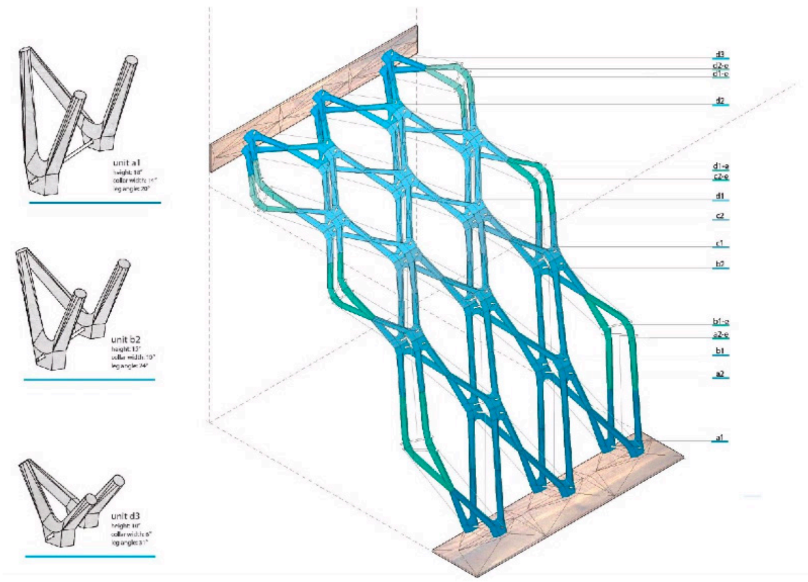


Figure 14: Axonometric view of the Concrete Lattice organized by unit type with examples of variations.

3.0 COMPLEXITY & CONTROL

Our *Concrete Lattice* demonstrates that complex geometry in precast systems can be fabricated, assembled, and managed efficiently during construction within a short amount of time. Moreover, the installation was never meant to be permanent. With this consideration in mind, the system had to account for the logistics of assembly and disassembly as part of the design criteria, adding another layer of complexity to the overall process. The issue of time limitation, while posed as a challenge, was an integrated pedagogical tool. Most design-build pedagogy emphasizes the full-scale construction while responsibility for the afterlife of the project, from maintenance to disassembly, falls on someone else. By inserting the criteria of the logistics of deconstruction, systematic thinking in the life-cycle process forced the project to be more comprehensive and innovative as an architectural system. This enabled the project to consider the role of adding intelligence to the building process as part of the design thinking. As such, this work highlights not only the importance of design research through making as a pedagogical framework for exploring innovative designs via computational tools, but also the integration of construction logic as a form of design thinking in any built work. In gaining control of this logic, it enables designers to command the building process more effectively rather than builders dictating and determining one's design based on conventional processes.

By implementing a systemic logic early on, this project advocates for parametric scripting programs in the design of complex architectural systems, especially those at the intersection of design and construction. An understanding of the capabilities inherent to the variable lattice system led to advanced development and increased the layers of complexity achievable in the project. In this respect, *Concrete Lattice* demonstrates a novel solution to concerns of experiential and formal value, and simultaneously strives to match the performance of standard structural and manufacturing processes.

3.1 Computational feedback

Concrete Lattice was developed through iterative development in Grasshopper, looking at typical lattice systems and applying them to surfaces. Early on, the use of catenary curves simulated in Kangaroo, allowed us to control loading due to gravity throughout the system. By breaking down the diamond lattice, we arrived at the structural cross unit, variable in multiple dimensions. Based on casting procedures, the lattice unit was split at the central node and a detailed script was designed for the precast unit. A separate code was also designed for the exploration of global forms when the units are aggregated, which led to the design of our final vault form. The process of prototyping enabled us to test the physical challenges that come with casting, which is much harder to predict with simulation software. As such, the feedback between prototyping and computational design informed many of the design decisions. With a high level of predictability, the design was optimized for structural performance while accounting for tolerances at critical moments to aid in the production of the final form.

3.2 Details and connections

Usually when one speaks about concrete architecture, it is reinforced concrete that is being referred to. For *Concrete Lattice*, despite the maximum use of glass fibers for reinforcement, two 3/8" rods had to be inserted to account for tensile strength along the linear extensions. Using an industrial robot, the rods were robotically bent and set in place inside the PETG formwork with tab connections to position the rebar at the proper depth. The bending system in use was developed as part of an ongoing trajectory of research at the University of Michigan (Pigram, et al, 2012).

An additional steel component was needed and became both an integrated part of the cast and a major node of connection in the assembled design. A ¼" black steel pipe was buried below the cast line of the split unit and was used to connect to its pairing unit, forming the cross geometry. The pipe was pre-drilled to receive the connecting elements for the post-tensioning system. The tensioning cables were integrated into the lattice design by running parallel to the legs; two on the outside at the single leg and one cable down the center of the split legs, producing another layer of asymmetry in the overall design (Figure 15). While cable turnbuckles provide a method for adjustments during assembly, they also proved useful for disassembly. These component parts were neither an afterthought nor a reason to deviate from the catenary form, but simply about efficiencies in cost and time.

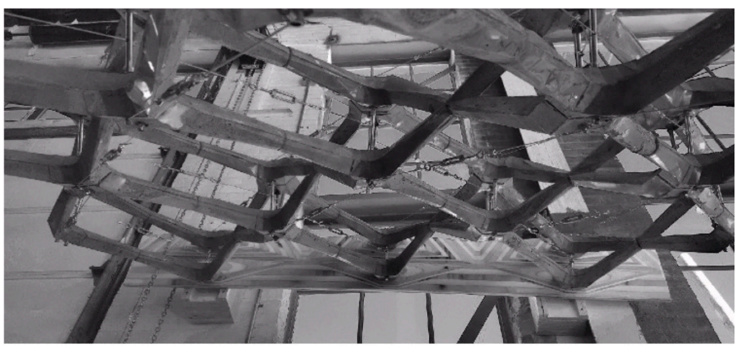


Figure 15: Image looking up below the lattice structure highlighting the compression-only connection at the wall and the network of post-tensioning cables.

3.3 Aggregation logic

This project imagines a broad range of variations and possibilities for how our innovative lattice system could enclose space. As mentioned, the parametric code of the basic diamond lattice could be adjusted to create units that when aggregated, produce diverse spatial forms (Figure 16). These typologies include spiral arrangements, thicket, vault, and branch logic. In the final vault design, slight adjustments had to be made to accommodate restrictions inherent in the unit, specifically in the length of legs and the width of the collar node. As the driving force for the vault design, the catenary curve was carefully studied and the vault iterated digitally to match multiple guiding curves. Nonetheless, small deviations from the perfect curve were necessary based on the parameters of the unit.

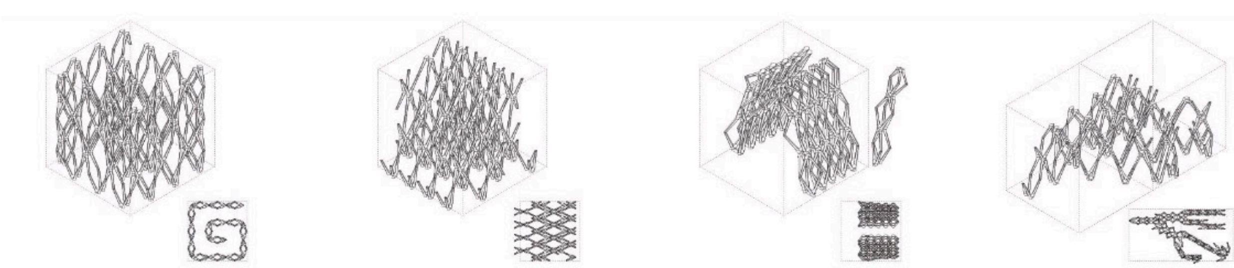


Figure 16: Typologies based on unit aggregation with spatial considerations. Left to right: spiral, thicket, vault, and branch.

4.0 FURTHER INVESTIGATIONS

While the unit serves as a model for the scalar versions of itself to proliferate, the parameters of each unit also determine how it can aggregate. The particularities of each context will affect the spatial design, and therefore the unit. Three contextual situations were considered in the design variations study; a high alpine refuge, a shelter in an open field, and an urban pavilion. Additionally, sensors could be integrated between the units to provide direct feedback and adjustments between the compression and the tensioning system. When one area loosens, other parts of that system or its connected counterpart could respond to changes automatically. To enclose the full vault structure, a layer of folded skin could be added to provide shelter, responsive to lighting and weather conditions (Figure 17).

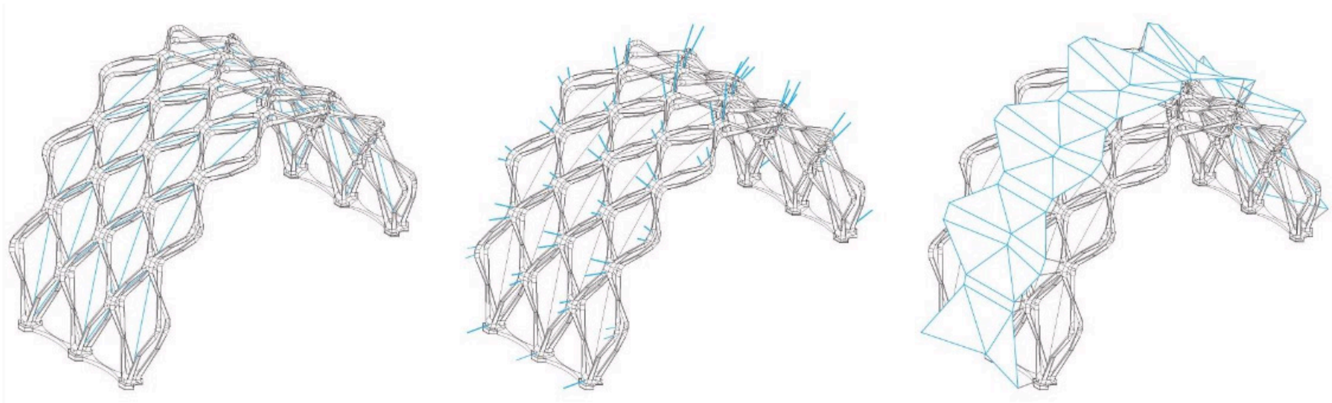


Figure 17: Axonometric diagrams of the lattice system assembled as a full vault with layers of componentry: from post-tensioning to flexible skin.

Any built work must negotiate social, economic, and natural environments by engaging the opportunities and constraints inherent in its context. As traditional building systems are designed and manufactured, contextual and environmental conditions are often accounted for in materials used, the building's orientation, or specialized weather barrier systems. *Concrete Lattice* imagines the entire form and make-up of the system adapting as necessary, and projects a future reality for building systems that can respond more readily to their environments.

5.0 CONCLUSION

> *It is this lack of mediation between design and production that is being reformulated with integrated digital design and fabrication processes: drawings and models are no longer used to represent design 'intent'; rather, they are used to communicate precise information on how to fabricate and with which material.*
> -Scott Marble, "Imaging Risk," 2010

The experience of participating in a design studio that includes research and fabrication, provided an opportunity to learn not only how to close the gap between two divorced aspects of architectural production – that of design and construction – but to also do so in an integrative manner. In architecture, specialized computational tools and software have been developed by many practices - such as Gehry Technologies and SHoP - to link design directly with the production of architecture (the construction and building of) as a seamless process. In doing so, the architect gains better control of the outcome by closing the loop between design and fabrication. Closing this gap in the building construction process offers not only the opportunity for the architect to experiment with more innovative designs outside the constraints of industry standards, but also simultaneously reduces construction costs by allowing for a more efficient fabrication process. These workflows between design and fabrication are gaining traction in how we practice as architects. Firms such as Diller, Sciofidio + Renfro (for Broad Museum, Los Angeles), Snohetta (for SF MOMA façade, San Francisco), and Rudy Riccioti (for MuCEM, Marseille) have already employed such processes in their projects. While smaller in scope, the thesis studio's pedagogical framework exposes this integrative process for architectural production by allowing the students to explore the full range of processes involved for this type of production.

By promoting this methodology for innovation in the building industry, *Concrete Lattice* advances our notion of precast units - with a set of parameters that produce manageable variations - that can be mass-produced, and deployed as a structural system. This project and the thesis studio at large also highlight the benefits of fabrication and technology for emerging designers at the academy. Exposure to advanced digital tools and workflows has helped to enhance architectural education and promote experimental designs among graduates seeking work that deviates from the traditional path.

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