Tall Wood, Thin Concrete: Digitally Drafting and Crafting in UHPC (Ultra High Performance Concrete) and Mass Timber

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This paper illustrates how a graduate design studio can seek out an innovative and comprehensive design process, while simultaneously addressing two current crises in the architectural profession: 1) A perceived disconnect between the abstraction of design education and the realities of practice; and, 2) The critically time sensitive imperative of transforming ecological practices in building materials and building energy consumption.

CONTEXT AND PREMISE

A NEED FOR URGENCY: In terms of environmental stewardship and climate change, the year 2030 has emerged as an important milestone in the discipline of architecture. Model pathways undertaken by organizations such as the Intergovernmental Panel on Climate Change in 2017 note that by 2030 global net anthropogenic CO_2 emissions have to decline by approximately 45% from the levels recorded in 2010, and continue forward reaching net zero by approximately 2050 to have limited or no overshoot of a global rise in temperature of 1.5°C.[1] 2030 is now ten years away, and an architectural project requires several years to complete, which means time is of the essence. Aside from the shear scalar issue of tackling this complex problem in the professional world, is the necessity to cultivate and instill an attitude of urgency and competency in the next generation of aspiring architects who are striving to make significant and lasting change in the built environment

A PERCEIVED DISCONNECT

> "If theory governs application, application also fosters theory, in a feedback loop that is continuous and progressive."
>
> —Paulo Belardi, *Why Architects Still Draw*

Architecture schools are not intended to be, nor positioned to be vocational schools, but once outside of the academic institution registered architects must assume full professional and social responsibility for a project. From the macro to the micro and back, architects must be synergistic thinkers, capable of taking seemingly incompatible or unrelated objectives and transforming them into holistic and inspirational works of architecture of the highest environmental standard. Simply put, architecture is demanding, asking and expecting a lot from architects. The premise here is that architectural education should do nothing less, and actively seek out this type of comprehensive synergistic process that students will confront outside the confines of the classroom. As such, this paper illustrates how a graduate design studio (called the Gateway Studio) can simultaneously address two current crises in the profession: A perceived disconnect between the abstraction of design education and the realities of practice; and the critically time sensitive imperative of transforming ecological practices in building materials and building energy consumption.

A catalyst for continuing this pedagogical research resurfaced in July of 2019 when Patrik Schumacher (Principal of the Pritzker prize winning architecture firm ZHA) enlisted social media to articulate a perceived crisis: "Architecture schools operate like art schools without any curriculum. Accordingly architectural education is detached from the profession and from societal realities [and] needs as expressed in real (public or private) client briefs…Students' portfolios after five years of studying might not include a single design that could meet minimal standards expected from a contemporary competition entry".[2] Critiques such as Schumacher's are not new to architectural education and surface in different forms and at different times in history. Likewise, architectural education has oscillated between an emphasis on pragmatic skill building and theoretical concepts throughout time reinforcing the duality of the architect as thinker or builder. Alberti set in motion the idea that "the art of building is dependent on a cultivated and educated way of thinking."[3] Alberti's idea is directed at understanding the way in which aspiring architects cultivate knowledge and expertise through an educational process. It also "exemplifies the contemporary view that architecture is about concepts and not about buildings, that architects should produce ideas rather than dealing with how these ideas can be realized."[4]

Over time the educational pendulum inevitably swings

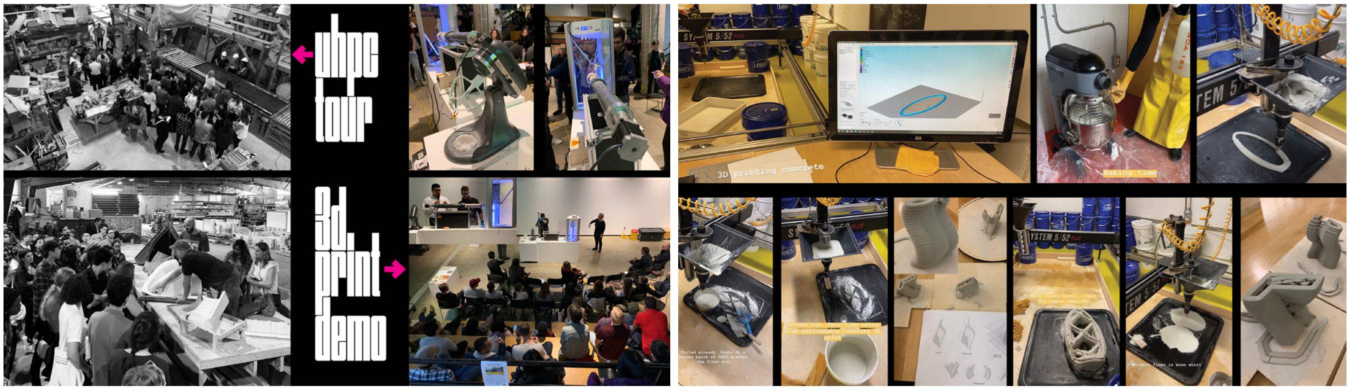

Figure 1. From left to right: Students attending the UHPC factory tour, the 3D concrete printing lecture and demonstration by industry partner Sika, and examples of student efforts to 3D print with UHPC in the materials lab at the architecture school. Image credit: Jerry Hacker with photographs of 3D UHPC printing provided courtesy of Brian Cheung (Gateway Studio student, 2019).

between unfettered exploration and pragmatic execution; however, architecture is a professional degree, and one of the goals is to prepare students for a potential life of practice. Presumably then, within these two poles lies an idealized pursuit, where the most imaginative architectural solution is married to an equally imaginative and probable excellence in execution. This is the foundation behind addressing perceived crisis one, while the probe for investigating crisis two (transforming a building's environmental footprint) involves interrogating materials, emerging fabrication techniques, and integrated building systems.

A SUPERIMPOSED MATERIAL FOCUS: In the architectural community there is a story of near legendary proportion whereby Norman Foster is giving a tour of the recently completed Sainsbury Centre for Visual Arts. The project, completed by Foster + Partners circa 1978, became emblematic of the emerging environmental movement gaining traction at the time, and exemplified a high-tech approach for cultural buildings. On the tour was another notable figure from architectural history: Buckminster Fuller. As recounted by Gellner in Architext, Fuller asked Foster a pointed question: How much does your building weigh? Gellner goes on to note:

> "What Fuller was driving at - something he drove at in nearly all his work - was the ideal of how to do the most with the least. His was a lifelong concern with energy and material efficiency, not only in the field of architecture, but also in engineering and design."[5]

The idea of weighing a building rings true for structural engineers because there is an immediate payback when a building's structure becomes lighter. For architects though material weight is slightly more elusive, although quantity plays a key role in understanding a building's embodied energy. Since embodied energy remains constant for the life of the building, and generally cannot be significantly reduced after the building is constructed, interrogating materials to understand how to do more with less can impact a building's environmental footprint. To paraphrase Mies van de Rohe, less is more (carbon offsetting).

TALL WOOD, THIN CONCRETE: Two materials beloved by architects, with potential for improved efficiency and emerging fabrication techniques, are concrete and wood. Pervasively consumed, concrete is routinely chosen for its durability, fire resistance, or aesthetic qualities. At times, such as in below grade applications, concrete is also a highly pragmatic material choice. Certain structures, like the Pantheon, have existed for thousands of years and are a testament to concrete's potential in terms of embodied energy and life cycle analysis. Because of concrete's pervasiveness though, cement, a critical component of concrete, is the second highest consumed and manufactured resource in the world and accounts for approximately 8% of world CO_2 emissions. Water, another essential ingredient of concrete, is generally deemed to be first.[6]

ULTRA HIGH PERFORMANCE CONCRETE (UHPC): Incremental advancements in concrete technology have resulted in high performance concretes, and in 1994 Ultra High Performance Concrete (UHPC) was introduced. UHPC uses fine and ultra fine powders, reinforcing fibers, super plasticizers and extremely low water to binder ratios to create a concrete with low porosity, high durability, self compactability, and with compressive strengths above 120MPa.[7] Materially, it is similar to conventional concrete, but the ingredients are proportioned to create a densely packed material.[8] The use of fibres makes it possible to 3D print the material, while improving desirable qualities such as elasticity (tensile resistance), reduced construction time, less material use, durability, corrosion and abrasion resistance, and impact protection. [9]

With this in mind, there is at least one important paradox with UHPC that was reviewed as part of a factory tour subsequently described within: It generally requires more cement than conventionally reinforced concrete, but less water and less volume of material. To this end, many research initiatives are underway to better understand the comprehensive life cycle analysis

Figure 2. Custom CNC milled cross laminated timber and UHPC acoustic panel. Image Credit: Provided courtesy of the author Laura Clark (Gateway Studio Student, Fall 2019).

and environmental impact of UHPC. Unfortunately, although this warrants further consideration, the depth of this issue cannot be explored within the extent of this paper. That said, considering potential water savings, volume reductions for lighter structural sections, increased service life and durability, reduced energy expended for on-site handling and transportation, and non-corrosion of traditional reinforcing bars, rather than abandoning the use of concrete altogether this exercise chooses to explore the potentials of UHPC as it relates to material efficiency and emerging fabrication techniques.

MASS TIMBER: Similarly, mass timber – large structural panels, posts, and beams glued under pressure or nailed together in perpendicular layers [10]– emerged in North America circa 1994. A renewable resource, mass timber is now a market accessible material with potential environmental benefits: It can sequester carbon during growth, can be lighter structurally compared to steel and concrete, can be designed for disassembly, and allows for more controlled off site work; however, like UHPC's nuances, mass timber's comprehensive environmental footprint must also consider logging practices, forestry management, transportation, adhesives, and the potential return of carbon to the environment at the end of its service life. Again, under the purview of this paper it is not possible to assess the comprehensive life cycle analysis of mass timber, and the studio exercise is focused on exploring material efficiency and emerging fabrication techniques.

PEDAGOGICAL EMPHASES

The exercise focuses on four main pedagogical strategies that are interrelated and cross over at times:

1) Context-Based Learning: The studio incorporated two major components where learning about materials occurred in an enriched context. To begin, students attended a full day field trip to a UHPC plant. During the trip students became intimately familiar with the process of taking a design from the drawing board and into physical production. Students engaged with the entire fabrication process including mold making, concrete science, and batch mixing and pouring. An industry partnership grant from the Canadian Precast Prestressed Concrete Institute allowed the studio to purchase factory UHPC kits for use in fabricating large scale details at the school of architecture. This direct factory experience was supplemented with a second live tutorial from an industry partner, Sika, explaining the intricacies of 3D printing with concrete. Taken together, students were able to see the inner workings and the evolution of the concrete industry first hand. Although our studio was not able to provide the same degree of engagement with factory tours and tutorials for mass timber, students deployed similar hands on learning exercises.

2) Empirical Learning: Following on the context-based learning, built into the syllabus of the studio was a dedicated portion of time where students were expected to examine a particular architectural detail in their project involving UHPC, mass timber or both. Students were expected to conceive, detail, and fabricate the detail ideally at a 1:1 scale. Building on the context based learning of the field trip, students were expected to use the UHPC kits to fabricate portions of their projects using emerging techniques such as 3D printing and CNC milling. During this experimental process, students also deployed more traditional analog techniques when working with the materials.

3) Deliberate and Distributed Practice: Another key component of the syllabus was the use of a defined set of drawing tasks that students performed multiple times in an attempt to hone their skills and performance in direct response to critical feedback and evaluations. Using a concept familiar to the professional discipline of architecture, students produced a 30-60-90% working drawing set (described further below). This provided students an opportunity to incrementally improve performance, while knowing the first iteration will have subsequent room for improvement throughout the exercise.

4) Calibrated and Coordinated Evaluation: Opposed to traditional studios that place a large emphasis on final

Figure 3. Fabricating large scale details as part of the empirical learning pedagogy designed for the course. Image credit: Jerry Hacker.

results and deliverables, or a large emphasis on the creative and imaginative efforts of the student, the exercise was evaluated as five equally weighted portions which were highly correlated to the objective of creating an iterative architectural proposition that strives for excellence in design, execution and environmental stewardship.

COURSE CRITERIA AND METHODOLOGY

To address the two aforementioned crises, a comprehensive design studio is used as a testing ground because it occupies a unique place in accredited schools of architecture. Programs routinely use comprehensive design studios to demonstrate student exposure to technical and systems integration requirements; however, two main issues often undermine the typical approach:

1) The process regularly devolves into a predominantly technically driven exercise at the expense of creative architectural invention; and,

2) These inevitable and critical pragmatic parts of architecture become over simplified, thereby diminishing their potential role as part of the architectural expression.

One major challenge is that architecture schools are not intended to be vocational schools and the notion of pragmatic execution requires a tempering with the creative process that accompanies contemporary studies in a relevant and progressively minded school of architecture. In direct response to this dilemma, a comprehensive studio was envisioned whereby students would be permitted to dream and imagine new possibilities for the way the world ought to be, without compromising the execution of the full range of pragmatic considerations (structure, mechanical, electrical, building envelope, detailing) and skill sets that an architect must one day possess, and that a competent and accredited professional degree in architecture must offer. In addition, given the urgency of the environmental crisis noted previously, exemplary environmental stewardship would necessarily be an integral part of any design proposal put forth. The following describes the components of the exercise that were developed to pursue excellence in design, execution and environmental stewardship, all the while experimenting with the efficient deployment of materials and emerging fabrication techniques.

DESIGN EXCELLENCE

Generally, architecture schools place a high degree of emphasis on the conceptual narrative of an architectural proposition. Inventive solutions, creative approaches to problem solving, and highly imaginative and often speculative pursuits are typical parts of the studio nomenclature. This studio exercise strives to define design excellence from the perspective of

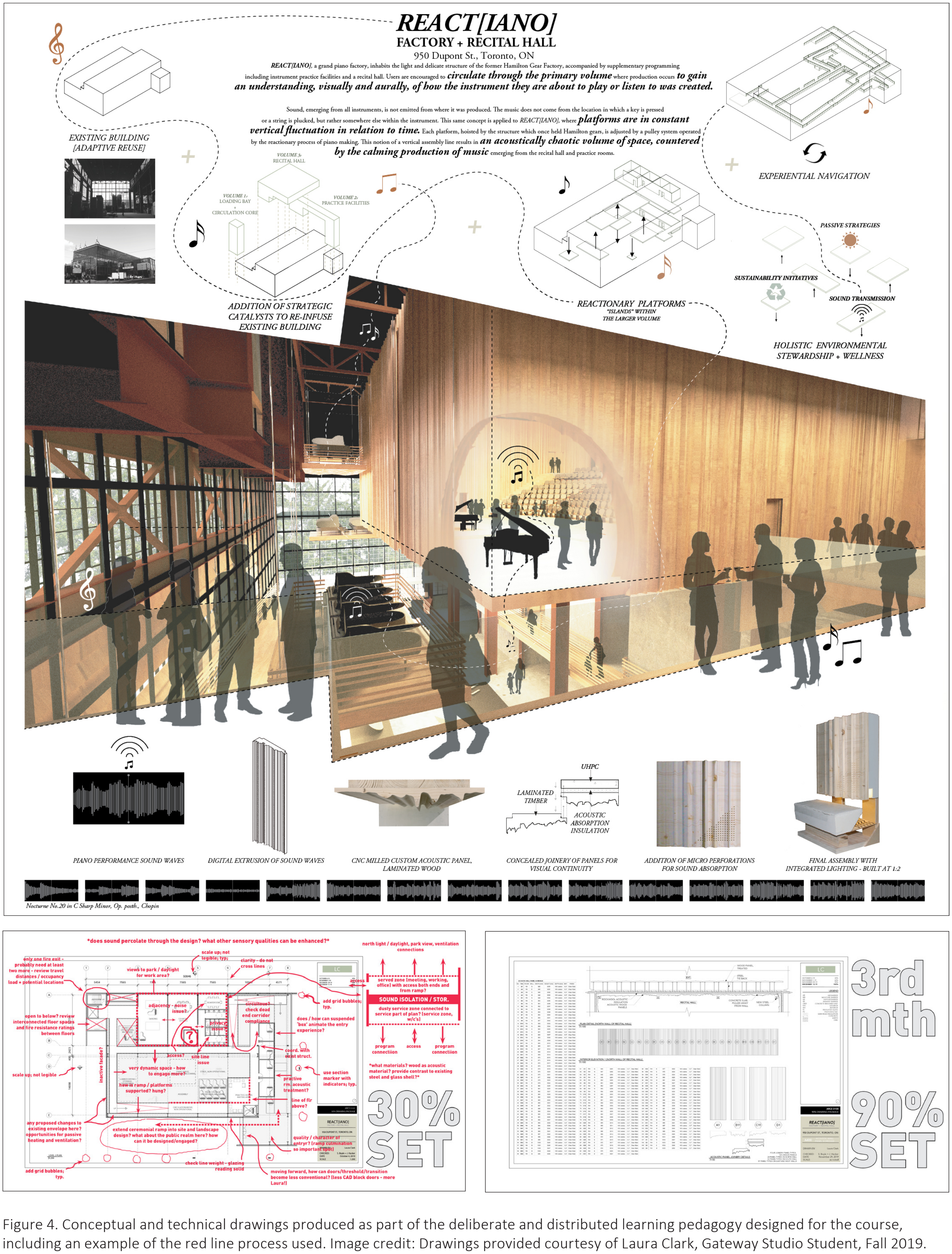

Figure 4. Conceptual and technical drawings produced as part of the deliberate and distributed learning pedagogy designed for the course, including an example of the red line process used. Image credit: Drawings provided courtesy of Laura Clark, Gateway Studio Student, Fall 2019.

creatively resolving the interdependence between a highly disparate set of seemingly competing interests into an elegant whole where the sum is greater than it's individually conceived parts.

PROGRAM, RESILIENCE, TECTONICS: In order to pursue this mandate, the exercise requires students to simultaneously confront three interdependent ideas throughout their decision making process: program, resilience and tectonics. By operating under this premise students cultivate the skill to harmonize competing interests, rather than emphasizing certain considerations at the expense of others.

DESIGN COMPETITION: In response to Schumacher's critique of student architectural portfolios not being comprehensive enough, part of the deliverables are structured around a design competition. Each year the American Institute of Architect's (AIA) Committee on the Environment, in conjunction with the Association of Collegiate Schools of Architecture, run a design competition that also focuses on exemplary environmental stewardship. The competition challenges "students to submit projects that use a thoroughly integrated approach to architecture, natural systems, and technology to provide architectural solutions that protect and enhance the environment. The competition recognizes ten exceptional studio projects that demonstrate designs moving towards carbon-neutral operation through creative and innovative integration of design strategies such as daylighting, passive heating and cooling, materials, water, energy generation, and sustainable systems."[11] To culminate the studio, students recalibrate their work into four graphic panels suitable for entry and review by an anonymous jury of architects and design professionals.

By structuring the studio around a design competition a secondary purpose is made possible: The competition serves as another type of gatekeeper in a conversation around quality in architecture. Although the competition is not a mandatory part of the course work, the final deliverables for the studio are modeled on the same requirements as the competition to encourage students to enter with minimal additional effort.

EXCELLENCE IN EXECUTION AND ENVIRONMENTAL STEWARDSHIP

ADAPTIVE RE-USE: In order to further embed the environmental aspirations for the project, the studio provides two adaptive re-use sites for students to engage. Studies, such as the one undertaken by the Preservation Green Lab have shown that "Building reuse almost always yields fewer environmental impacts than new construction when comparing buildings of similar size and functionality".[12] Opting for adaptive re-use sites lends itself to additional layers that need to be addressed and incorporated into any design response: For example, a heritage position must be developed to respect and infuse the existing buildings with a new life. Further, a response to building performance must be developed because at nearly 100 years old, the existing buildings were constructed under significantly less stringent performance requirements.

In this instance two diametrically opposed buildings are offered as potential sites of investigation, both of which incorporate the use of conventionally reinforced concrete, and one of which incorporates an early version of nail laminated timber – in other words, the same two materials that are being investigated in the studio, albeit from a contemporary perspective. One building is a formally heavy slip-form cast-in-place concrete shell with a wood post and beam interior currently used as an antiques store, while the second building is an old gear manufacturing comprised of an expansive steel structure and single pane curtain wall glazing and a heavy duty concrete raft slab on grade.

PROGRAM: A workshop is chosen as the program because of the myriad of competing design challenges it presents to students. For example, workshops introduce competing architectural agendas such as wet and dry areas, loud and quiet areas, varying issues of indoor air quality, or disparate processes of design and fabrication. Beyond this, the specific program for the workshop is left open to help students learn the process of developing a comprehensive program for a building, a skill that often crops up when owner groups hire architects for a project without a definite idea of the project program. These diverse requirements must therefore be addressed and orchestrated into a holistic solution.

ADVANCED BUILDING SYSTEMS (ABS): During the comprehensive studio, students are also enrolled in an independent course titled Advanced Building Systems that has been specifically developed to work in tandem with the studio exercise. The Gateway Studio project, happening concurrently, acts as the design vehicle for the Advanced Building Systems course, creating a coordinated outlet for the investigations. ABS has two main ambitions: One is to see systems design, such as mechanical, electrical or structural, not as a separate part of architectural design, but as another tool architects have at their disposal to help reinforce the conceptual clarity of the architecture; and the second is to give conceptual weight to detailing in buildings by focusing on experiential and oft marginalized sensory qualities. Accordingly, students use their Gateway Studio projects to go problem seeking first, and then answer the uncovered design questions with appropriate passive and active technologies.

ABS also foregrounds three main ways of reducing a building's environmental footprint: Embodied and operational carbon, renewable energy, and other non-related CO_2 items such as water consumption and treatment. Through a series of assignments connected to the Gateway Studio, students must work toward a solution that is pragmatic, robust, beautiful and ambitious in terms of environmental stewardship.

Underlying all of the systems work in ABS is the premise that passive design strategies must be the foundation, and only where absolutely necessary supplemented with active design strategies. As such, students must create arguments for how the systems in their buildings are integral to environmental stewardship and their architectural idea, as well as developing additional drawings such as reflected ceiling plans, structural diagrams, and mechanical and electrical distribution.

30, 60, 90: Another critical component of the exercise is modeling the course deliverables around the office practice of iterative, sequentially delivered red-lined working drawings. Since the semester is essentially three months in duration, a tripartite division provides a way to support the pedagogical goal of deliberate and distributed practice. By the end of the first month, students are required to understand the site, develop three conceptual options, select one and submit a 30% working drawing set comprised of seven essential sheets of drawings, laid out on title blocks, and organized according to the conventions of architectural production. Following the submission, the drawing sets are red lined and returned to the students with feedback to be interpreted and addressed.

The process is then repeated, and at the end of the second month a 60% submission is made. The number of drawing sheets is expanded to include additional information, such as elevation and sectional information, and the red line process is repeated again. At the end of the third month students submit a 90% working drawing set that includes a wide range of technical drawings an architect would be responsible for producing, including detailed plans, sections, interior and exterior elevations, schedules and large scale details of key areas of the project

HANDS ON FABRICATION: Between the 60% and 90% phase of the project the exercise incorporates a week long intensive charrette requiring students to first design an important project detail involving UHPC and/or mass timber and then proceed to construct the detail ideally at a scale of 1:1. For any details involving UHPC students are highly encouraged to experiment with the potentials of 3D printing, but in all instances students must make extensive use of the fabrication shops in the school which include, but are not necessarily limited to CNC machines, kilns, carpentry and metal fabrication, and laser cutting.

RESULTS AND CONCLUSIONS

Although largely anecdotal at this time, the exercise generated a number of important results. From a pedagogical point of view, the context-based learning initiatives proved highly valuable when transferring into the hands-on, empirical learning process of craft and making. By providing the students with a basis for understanding the fabrication methods and the formal potentials of UHPC at the factory, students were able to move into the physical construction stage of the exercise with a degree of confidence as to what might be achievable. The challenge was in transferring the knowledge gained by watching experts into a personal hands-on experience of detailing and making. This process was akin to watching a chef cook, and then further inventing and cooking a new recipe from that experience. The difference here is the recipe was an architectural detail and the cooking was the transformation of the detail into a physical, tangible reality.

In addition, the advanced fabrication technique of 3D printing in UHPC appeared relatively straight forward in the hands of the experienced trades and product developers; however, when it came time for students to replicate these results a gap became apparent. Trial and error quickly became the modus operandi as students grappled with learning how to mix the UHPC appropriately, understand set times, material consistency and a host of other unforeseen conditions that only arise during the act of physically building a detail.

Many students were also undertaking this type of comprehensive design process for the first time. The empirical learning process, whereby knowledge becomes rooted in first hand experience, offered an opportunity to augment the traditional drawing and detailing process of architecture by asking students to be stewards of their own creations. As students work towards completing their degrees, and potentially enter practice, the exercise offered a window into the transference process that inevitably occurs between the architect (as the orchestrator and designer of instructions) and the constructor (tasked with physically manifesting the architect's intentions). As is the case in any learning process, the results were varied in the degree of resolution obtained, but the value of any failed experiment was inherently embedded in the exercises of thinking through making.

Another important result of an early iteration of the studio was a winning entry in the anonymous peer reviewed competition made by one of the students. Although competitions are not a perfect metric by which to measure a design's worth, a competition does offer a type of third party review and validation that is often absent from a traditional studio where a professor is solely responsible for evaluating the student's success in meeting the identified metrics. Having an independent, peer reviewed selection of a project from this process highlights the value of a rigorous investigation into design concept, material potential, and execution as important components that contribute to creating a thoughtful, comprehensive, and innovative architectural proposition.

Finally, one important qualitative metric that underlined the value of this exercise was student effort and enthusiasm. Architects are no doubt generalists, but there are also a lot of very specific skills an architect needs to develop, including excellence in design and execution. From the professors' perspectives, the student effort displayed throughout the studio to learn both of these demanding skill sets appeared to be a testament to the desire to want to learn all facets of the architectural process, and not just the conceptual foundations. Retroactively following the studio, students have also expressed gratitude for the level of rigor, detail and diversity of thinking demanded by the course, as well as the experience of drafting and then crafting in UHPC and mass timber.

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