PAPER

Research Creation and Materiality: Making with 3D Printing and Ultra-High-Performance Concrete

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Research creation opens opportunities to explore the evolving understanding of materiality in a world seemingly split between hand-craft and digital design and fabrication. This project explores 3D printing of ultra-high performance concrete through a series of material exercises in the creation of a chair to interrogate how materiality might be evolving.

INTRODUCTION

The goal of this research project is to engage in *research creation* to explore the ways that our relationship to materiality might be changing as our modes of design and fabrication move to become almost totally digital. Research creation is described by the Social Sciences and Humanities Research Council of Canada as "An approach to research that combines creative and academic research practices, and supports the development of knowledge and innovation through artistic expression, scholarly investigation, and experi mentation. The creation process is situated within the research activity and produces critically informed work in a variety of media (art forms). Research-creation cannot be limited to the interpretation or analysis of a creator's work, conventional works of technological development, or work that focuses on the creation of curricula."[1] By moving the research question *into* the unpredictable act of making, research creation allows practice to become a "question generating machine" (Rheinberger)[2] from which methods emerge out of the context and the apparatus, and create an object which in this case in a series of constructions made in a variety of ways using one material.

This project explores a material (Ultra High-Performance Concrete or UHPC) and a digital fabrication tool (3D printer) through a series of creative exercises that demand direct engagement with the materials and tools. The project aims to interrogate the idea that in our increasingly digital world, the quality of architectural design is at risk due to the isolation of the maker (architect) from the qualities of the materials we build with (materiality), all exacerbated by modern software.[3] Without retreating into nostalgic ideas of "hand-craft", this research creation project revealed the hybridity of design and fabrication, even in what seemed to be an intensely technologically-tooled process. The exercises required direct engagement with a new material (UHPC) and with new tools (both hand-tools and digital tools and softwares) and revealed the critical relationship between the qualitative aspects of material (sensed by the maker) and the technological processes as key factors in achieving a final design. The intimate and dynamic relationship between a digitally drawn line, a recipe modification and a robotic toolpath and the dryness of the air became entwined in a series of failures/discoveries.

In contrast to the utopic vision of autonomous digital fabrication, digitally-assisted fabrication (DAF)[4] is not removing the maker from the concept of materiality or craft, but rather expanding the idea it to encompass new avenues of exploration and design potential through *embodied knowledge* that operates across new media.

Donna Haraway proposes that situated and embodied knowledges, the kind of open experimentation of this project is critically an act of "making with" the other, which in this case is a new material, set of tools, and processes.[5] Architect and artist, Cynthia Hammond builds upon this to propose that the maker "deeply consider one's action, thinking it through in relation to the material and historical specificity of space, asking, in a sense those specificities to be one's collaborators, one's interlocutors in creative work."[6] This project contributes to the call by Hammond and Haraway to reveal knowledge as situated, social and sensuous; and to an epistemology entwined in *making with* in our accelerating age of digital workmanship.

METHODOLOGY

At the most fundamental level, concrete (and by extension UHPC) manipulation can be generally categorized by the following three techniques: 1) casting into a mould, 2) applying to an armature, and 3) carving a solid block. These basic techniques are used in the first phase of explorations in this project with varying consistencies of UHPC, a relatively new form of precisely tailored fibre-reinforced concrete that is manipulated using basic traditional concrete fabrication methods in order to get to know the material before introducing the complexities of digital tools and techniques.

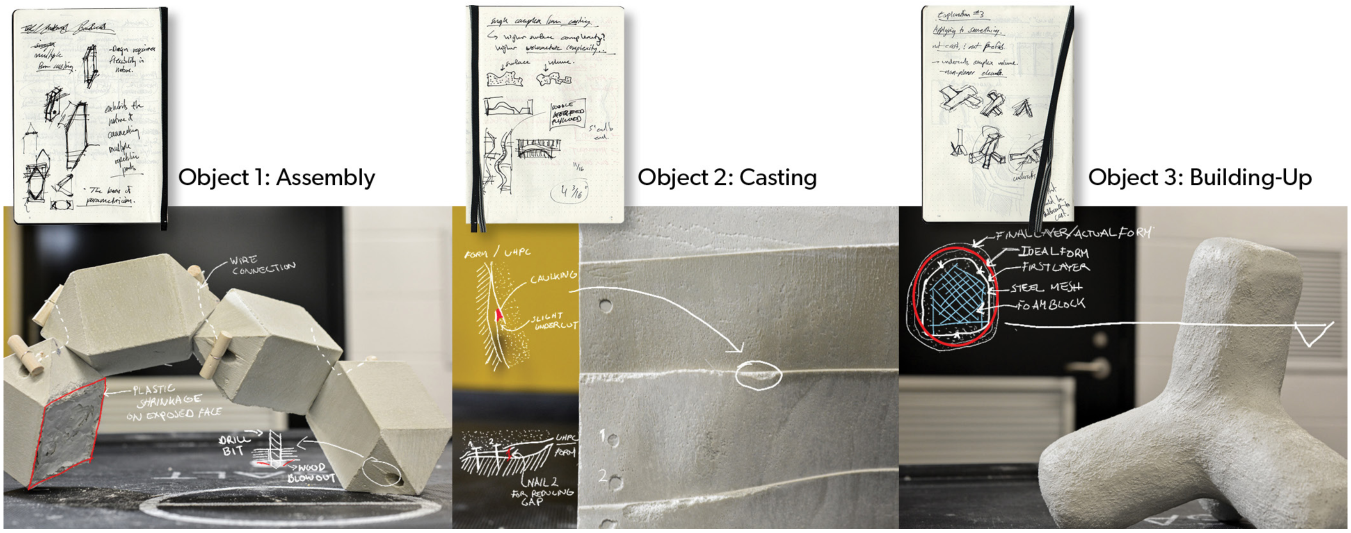

Figure 1. *UHPC object collections. Left to right: Object 1, 2 and 3*. Image by Sinan Husic

The second phase of this research project carries out digitally assisted hybrid exercises, utilizing the objects and basic techniques of the first phase to inform the products and newly introduced processes of the second phase.

The third phase is comprised of a more formal design process with a continuation of digitally-assisted fabrication techniques, where the products and failures from the previous phase serve as the foundation work to create half-scale prototypes of a chair, a synthesis test project that requires structural integrity, tacit contact with the body, and a design.

The fourth and final phase is devoted to the design and fabrication of a single full-scale chair which, for the purposes of this research project, is a repository of the knowledge gained from the process of designing and making with UHPC and new hybrid analogue/digital tools.

Each phase concludes with an independent analysis and reflection critical to the success of the proceeding phases. There indeed exists technical data which is important to the research project undoubtedly with respect to successfully handling UHPC as a material, but these facets of knowledge are not the subject of inquiry and fall outside the scope of this paper. Typically, each phase ends with a personal reflection by the author of *what* was learned and what is important for future phases, rather than serving as a how-to manual for the reader to follow. This method of analysis builds on the accounts of *making* found in Trevor H.J. Marchand's work, "Craftwork as Problem Solving". Chapter 6 of his book is dedicated to the work of David Gates, a trained cabinetmaker turned furniture designer and maker. Gates explores the effects on his products if he consciously chooses to create pieces using methods and techniques outside of his comfort zone. He notes that he seeks to limit the number of tools he uses in the process, to impose time restrictions on himself, to use only off-cut timber pieces, and to prohibit himself the use of drawing and measuring.[7] What he learns of himself and his process is primarily what this research seeks to reveal within the contemporary framework of digital tools, new materials and the maker.

PHASE 1: HANDS-ON UHPC

The first exercises attempted to establish a basic understanding of UHPC as a material on its own through familiarity with basic working techniques, without the use of digital design and fabrication tools. The products of this phase are referred to as "Objects" (Figure 1) and were conceived in a single, crude sketch as void of any symbolic meaning or functional purpose. This was important to the process as it established free experiment or "play" with materials and techniques as a critical mode of working without introducing the conceptual apparatus accompanying a typical design prompt. This work allowed the design and making process to unfold simultaneously rather than as two distinct elements in a "forward-looping process of refinement."[8]

The first phase highlighted the impact of free play and working within a loose framework (in this case from a simple crude sketch) as opposed to repeating patterns and structures of a discipline (i.e., working from a prescribed design) to achieve a kind of attunement with a material. Using a loose framework in the design/making process allows the author to emotionally accept mistakes and variations in the product, while practicing "real-time problem solving"[9] skills which is essential to the designer/maker.

PHASE 2: HYBRID CRAFTING

The objects of the first phase provided building blocks and material knowledge for early chair concepts in this phase. The designs of this phase remain as records of the process and serve as frameworks for later iterations - slowly becoming more precise as the process of this research unfolds. Each concept model daten für die formel:

abstand des punktes P vom fenster	a = 5,1 m
länge des fensters	m = 10,2 ,,
abstand des oberen fensterrandes von der tischfläche	f = 2,4 ,,
,, ,, unteren ,, ,, ,, ,,	f′ = —.— ,,
beleuchtungsstärke des fensters	b = 100,0 ftcdl.

$$Ep = 50\left[tg^{-1}\left(\frac{10,2}{5,1}\right) - \frac{5,1}{\sqrt{5,1^2+2,4^2}}\cdot tg^{-1}\left(\frac{10,2}{5,1^2+2,4^2}\right)\right] = 486,0\ lx,$$

$$Ep' = 50\left[tg^{-1}\left(\frac{10,2}{5,1}\right) - tg^{-1}\left(\frac{10,2}{5,1^2}\right)\right] = 435,0\ lx,$$

beleuchtungsstärke im punkte P = Ep − Ep′ = 41,0 lx
(12 hefner-lux ′lx′ = l footcandle).

Figure 2. *Hybrid conceptual models for potential chairs. From left to right: concept 1 (cast), 2 (cast + 3D print hybrid), and 3 (3D printed).* Image by Sinan Husic

(Figure 2) is thematically related to its respective "object" from the previous phase. Through hybrid craft, understood here as design and fabrication using analogue technologies with digital ones, the second phase sets out to attempt to use digital technologies to create design opportunities or solutions where difficulties occurred in the first phase. This use of the digital illuminates the question of *resolution* in fabricating an *accurate* approximation of an idea(design).[10] In this sense, the selective use of digital tools allowed for more precise and efficient approximation of a particular idea through the making process with less risk of failure in fabrication. The question of precision in processes does however reveal a new more granular concept of failure (a faulty toolpath as it relates to material consistency for example) which itself become manifest in the objects created. An example of this can be found in the following phase in the discussion of time and material efficiencies.

The introduction of 3D printing technology to the process reveals the need to carefully consider the rheology of *freshly mixed* UHPC as a material, which in the previous phase was much less of an issue. A precise balance between workability, extrudability, buildability, and open time must be struck to ensure success in the print. As such, the designer/maker must seemingly shift gears to a far more empirical mode of thinking while the importance of remaining attentive to the *feel of the material* becomes even more important; to know when and how to correct the rheology of the freshly mixed material before beginning the printing sequence.

PHASE 3: HALF-SCALE PROTOTYPING

The third phase of this project begins to address issues of ergonomics as well as solving a plethora of new technical and material-related hurdles associated with the three larger half-scale prototypes (Figure 3), namely the substantial increase of weight the designer/maker must manage during the fabrication process. Gravity, it seems, is still present in digital design and fabrication, despite what the computer screen might imply. And so, hybridity remains critical during the process to stay attuned to the material and the processes and discover ways to reduce risk of an unsuccessful product or poor workmanship. A hybrid workflow allowed the senses to engage and determine when it was more efficient to use one technology over another to save time, material or labour.

For example, the "simple" geometries of the legs in Prototype 1 (Figure 4) proved to be more difficult and time consuming to fabricate using digital technologies (such as a CNC Router) when factors such as set up time and file preparation, assembly, and potential misalignments are taken into consideration. Therefore, it was a more efficient use of material and time to use traditional shop-tools to fabricate certain elements of the formwork with measurements from a 3D model, assuming the designer/maker has established a comfortable level of skill to work in this manner. This allows for errors made to be quickly corrected locally and in real-time rather than risking having to re-start the whole process had it been executed with digital fabrication tools.

For example, with respect to efficiencies of time, an improperly marked and cut simple piece of flat stock used for formwork can be quickly re-marked and re-cut using a combination of miter saw and table saw and require no special preparation to use. In contrast, an improperly drawn piece of formwork that is sent to a CNC machine would need to be re-drawn, stripped of parts already cut, re-processed, re-communicated, and then

Figure 3. *Half-scale prototypes, from left to right: Prototype 1 (cast), 2 (cast + 3D print hybrid) and 3 (3D printed).* Image by Sinan Husic

re-cut by the machine, which moves far slower than pushing material through a saw. In terms of material efficiencies, designers typically place all parts to be cut on the CNC with a small buffer of material space between parts on the sheet in hopes to make "efficient" use of a material. These spaces compound and create a lace-like off-cut piece of flat stock that is rendered unusable should a small amount of material be needed later in the process. By contrast, waste generated by a table saw (if the geometries are simple enough) can easily be cut again, with the only waste being the width of the saw blade.

Conversely, elements of the prototype that were incredibly difficult to replicate manually, such as the curved top connection parts on the legs (of the first prototype) and the seat, are easily fabricated using the CNC machine. In this case, the difficulty is not necessarily in the skill required to replicate the curvatures of the design using traditional tools, but rather in the amount of preparation time and number of custom fabricated jigs required to successfully produce the part with acceptable accuracy and workmanship, which in this case proves to be an inefficient use of a time and material.

PHASE 4: "FINAL" PROTOTYPE

The final prototype (Figure 5) is the result of a hybrid use technologies and the design is a synthesis of all the lessons learned in the previous phases to create a successful process for the fabrication of the chair. It is of course not true that the first print attempt of the final chair was successful, since each iteration creates and exposes further technical hurdles and material particularities that must be adjusted when moving from half-scale to the full-scale fabrication. During this phase, one of the attempts at printing the chair resulted in a collapse despite all variables remaining constant. Therefore, further improvisation and iteration was required even in this final phase of the research project, separating this exploratory process from the repeatability of scientific experimentation and firmly placing it within the inquisitive space of research creation. The final prototype incorporates elements of assembly, casting, and 3D printing using an in-house concrete recipe designed in the previous phase which proved to be compatible with the cementitious 3D-printing system in the lab.

The most important new aspects considered during the design of the final prototype were overall dimensions (to fit with the human body) and weight (the chair will need to be moved from place to place). The previous phase had revealed that the digital tool itself has limits to its articulation, and that if the dimensions,

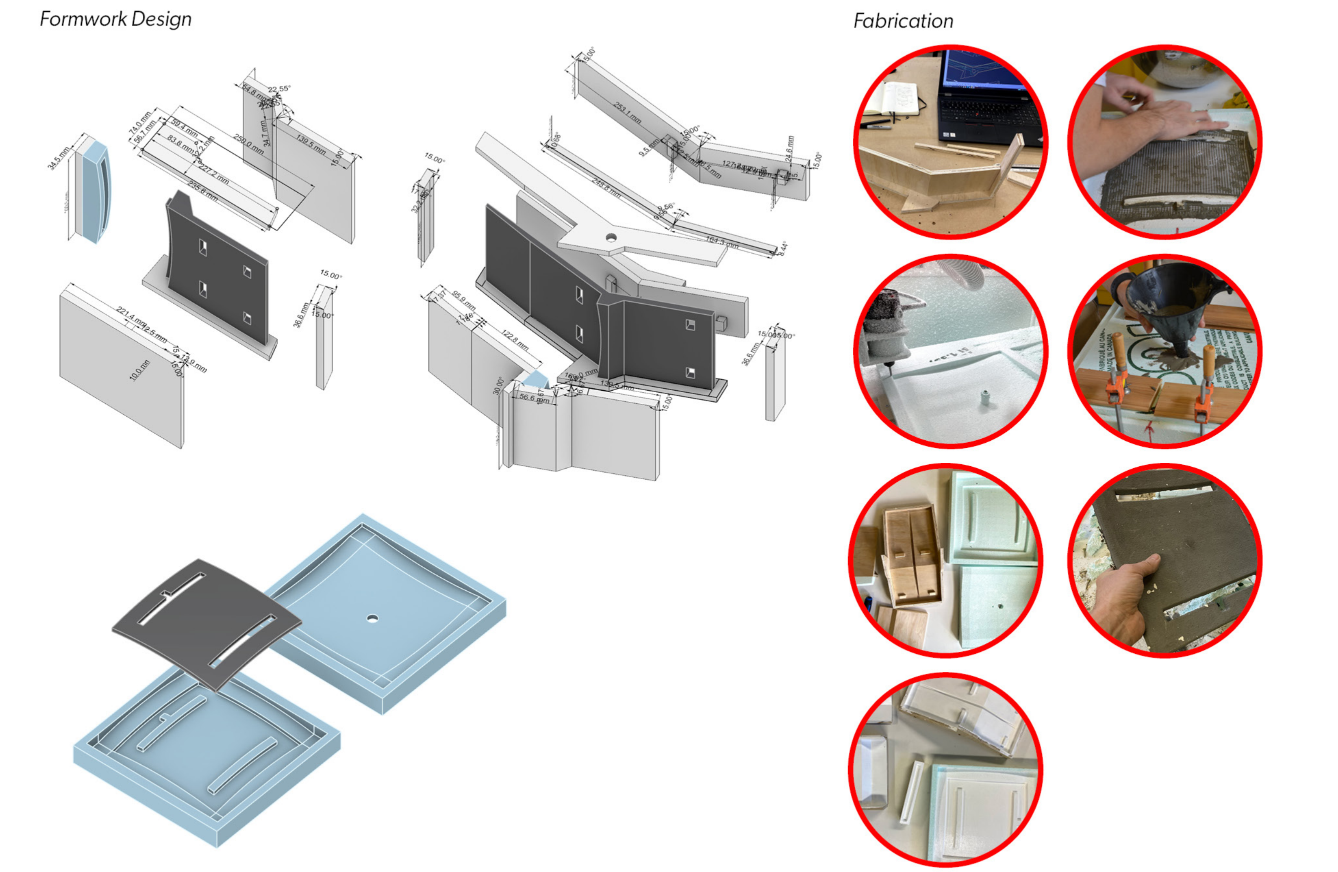

Figure 4. *Prototype 1 of Phase 3 formwork details.* Image by Sinan Husic

proportions, and toolpaths of movement were not optimized the robot arm would crash into itself. Secondly, the half-scale chairs brought to light the considerable weight of the final product. Cement, even UHPC, is heavy. Therefore, by optimizing the size and proportions of the chair, the total amount of filament being printed was considered which in turn greatly influenced the weight of the final product, and its ability to be moved around. For example, had Prototype 3 of Phase 3 been printed at full scale, it would weigh approximately 99 kilograms while the optimized final prototype of phase 4 was reduced to 68 kilograms using simple design alterations.

The chair was designed to be printed in two parts which were then cast together. This modular approach was determined based on the compounded relationship between the labour of mixing UHPC (a timed and complicated affair), the amount of material that can be loaded in the printer tubes at once, the workable time of the setting concrete in combination with the size of the printer nozzle, and finally the constant labour of mixing, cleaning, loading printing tubes and on-the-fly corrections of the print to prevent failure. This concert of activity determined that the chair would be printed in two parts and allowed a single half to be printed within a reasonable time-frame of 8 hours. The process undoubtedly highlighted the hybrid nature of 3D printing UHPC, as it is certainly not as simple as the press of a button as some might think.

CONCLUSION

We began this paper by discussing how our relationship to materiality might be changing as our modes of design and fabrication move towards a seemingly total digital process. By engaging in research creation, the process allowed design to emerge from working with materials and activities situated in our contemporary condition between hand-craft and digital fabrication. A feel for an unknown material was developed first using methods developed for traditional concrete which then informed ways of working with new digital fabrication processes of 3D printing. Unlike other forms of digitally-assisted craft which begin with digital cutting and are hand-finished, this project begins with the hand-work of mixing which was then finished digitally with the 3D printer in the printing process, and then further finished by hand. Research creation allowed for ideas to merge with materiality in processes, including digital ones alongside manual ones in a hybrid process that has the potential to not only move form, but to move the processes of design and fabrication into new territory.

Figure 5. *Final chair prototype images*. Image by Sinan Husic

ENDNOTES

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