

Thinking and Making – Digital Craft Hybridity

By

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## Abstract

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Since the industrial revolution, handcraft and technology have created divergent paths for making. New forms of software and hardware have rapidly become accessible and attractive to the design profession for a few key reasons: efficiency, speed, and accuracy. This thesis offers a hybrid methodology - a dialectic set of exercises occupying the spaces between software, hardware, and analogue craft in order to understand the relationship between materials and techniques involved in the process of making, without retreating into a romantic nostalgia of "hand craft".

The thesis will question the design process to critically understand how new technologies are shaping the way in which we build our world. Is it appropriate, or even possible, to design using only software for a profession that ultimately deals with the physical world? How can hybrid processes bridge and entwine hand craft and digital technology? To examine these questions, this thesis will first propose a process of *thinking by making*. By engaging in this process, this thesis proposes that its final product be a chair, which aims to embody comprehensive thought in materiality, technique, technology, and craft in a design that engages the human body.

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## Introduction

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To be clear, this thesis does not wish to take a Ruskinian stance and propose a revolution against the use of technology in architectural design, which often is the case when the word *craft* is employed.<sup>1</sup> This thesis will embrace technology as a necessity, not only in its role within architecture, but in all aspects of the human experience with the world. In hopes to broaden and embody our experiences with technology, the thesis will apply a variety of new and old technologies in a hybrid fashion. In doing so, I will address issues of *material and technique comprehension* in both the profession as well as in pedagogy. Ultimately, it is about explicating the process of *thinking by making*. The “what” of this thesis is the designing and building of a full-scale chair. The chair in this case is analogous to architecture in that they both share programmatic and structural constraints, as well as create space for the human body. However, the scale of the chair provides a more manageable framework for testing these ideas in order to immerse oneself in the process of *making*. The “how” is deceptively simple: by 3D printing it.

This thesis involves the use of various software, hardware, and traditional tools at different points in the process. In this case, software is simply the tools being used on the computer, while hardware is what is typically known as digital fabrication tools. The process is a dialectic in that one tool informs the work of the other yet may also create contradictions. The tools are agents in a non-linear, forward-looping process of refinement<sup>2</sup> towards the final product – which of course is never “final”. The virtual tools involve Rhinoceros® by Robert McNeel & Associates, that will be used for general design, form finding, and representation. The Grasshopper® plugin is used to aid both in design, alleviate repetitive tasks, and to create custom

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1. Pye, *The Nature and Art of Workmanship*, 118. Pye offers a well written critique on Ruskin and his “On the Nature of Gothic”. He asserts that: “The deficiencies of the Arts and Crafts movement can only be understood if it is realized that it did not originate in ideas about workmanship at all. Indeed it never developed anything approaching a rational theory of workmanship, but merely a collection of prejudices which are still preventing useful thought to this day.”

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2. Marchand, *Craftwork as Problem Solving*, 117.

G-code for the 3D printer to interpret. Simplify3D® is then the final step in the pipeline that will quickly produce reliable G-code to run the many material and geometry tests as well as to preview any custom G-code.

Regarding hardware, the thesis will focus primarily on using a large format 3D printer by 3D Potter® (**Figure 1.0**) that is of adequate size to experiment with scales like a chair. The printer was acquired by the CSALT lab in the summer of 2020 and primarily functions as a clay printer but can also be used to print cementitious material. Despite many preconceived notions surrounding digital fabrication, *making* with these tools is far more involved than a single push of a button, which is why traditional tools still find use and why this form of *making* is undeniably hybrid.

The material of choice for the thesis is concrete. More specifically, Ultra High-Performance Concrete (UHPC), which was chosen alongside a Mitacs grant in association with the Canadian Precast/Prestressed Concrete Institute, a partnership initiated by Professor Sheryl Boyle. In a short and oversimplified definition, UHPC is a refined and highly specialized version of the traditional concrete variant. It is a delicate and precise mixture of new and traditional materials (**Table 1**) that functions to optimize the materials behaviour in both its fresh and cured state. The mix design is entirely unique to the intended application and methods of use. The additional materials, in comparison to traditional concrete, create an incredibly dense molecular structure in the cured material (**Figure 1.1**) which positively affects both the strength and durability of the product by removing voids in the matrix.<sup>3</sup> This results in a concrete that can be designed to be virtually impermeable to water and resistant to chemical attacks.<sup>4</sup>

Further detailed accounts of mix designs will be given in the chapters to come as they have varied widely depending on



**Figure 1.0** Building the 3D Printer in the CSALT lab.

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3. Park et al., "Early-Age Strength of Ultra-High Performance Concrete in Various Curing Conditions," 5538.

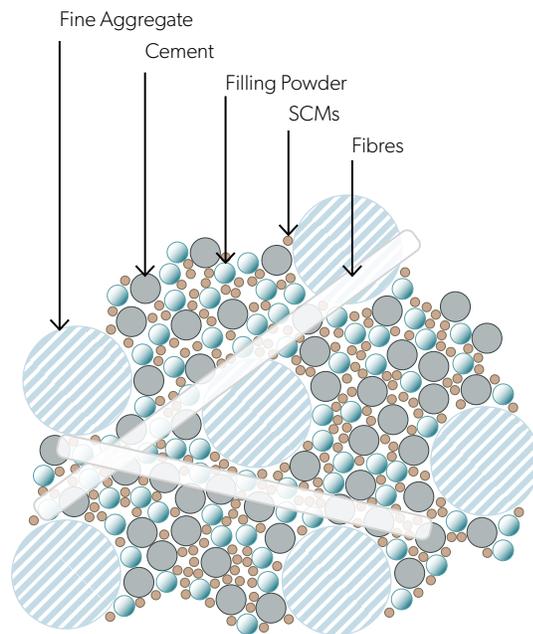
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4. Kosmatka, Kerkhoff, and Panarese, *Design and Control of Concrete Mixtures*, 299.

the materials available at the time. By introducing supplementary cementitious materials (SCMs) which are often found as byproducts of other industries, manufacturers of UHPC can displace the total amount of portland cement required in the mix. By reducing the amount of portland cement, we can help offset the dependence on a material whose production accounts for about 8% of total global CO<sub>2</sub> emissions.<sup>5</sup> In addition, the increased strength UHPC directly equates to being able to use less of it to achieve the same structural performance.

5. Rodgers, "Climate Change: The Massive CO<sub>2</sub> Emitter You May Not Know About."

This thesis uses the chair project to embody an understanding of hybrid fabrication techniques made up of software, hardware, and analogue tools. Before moving into case study examples, processes of making, and the products of making, it is important to establish the theoretical framework within which this research exists.



**Figure 1.1** *Diagram of the cured molecular structure of UHPC.*

**Table 1. UHPC Material Matrix Options**

<b>Ingredients<sup>1</sup></b>	
Binder	· Portland Cement
Supplementary Cementitious Material <sup>2</sup>	· Metakolin · Fly Ash · Silica Fume · Blast Furnace Slag
Aggregate	· Silica Sand (>#70 Mesh)
Fillers	· Silica Flour · Limestone Flour
Fibers	· Glass Fibers · Polypropylene Fibers · Steel Fibers
Admixtures	· Superplasticizers (High Range Water Reducers) · Accelerators/Retarders · Viscosity Modifying Agents · Air Entrainers
<b>Water</b>	

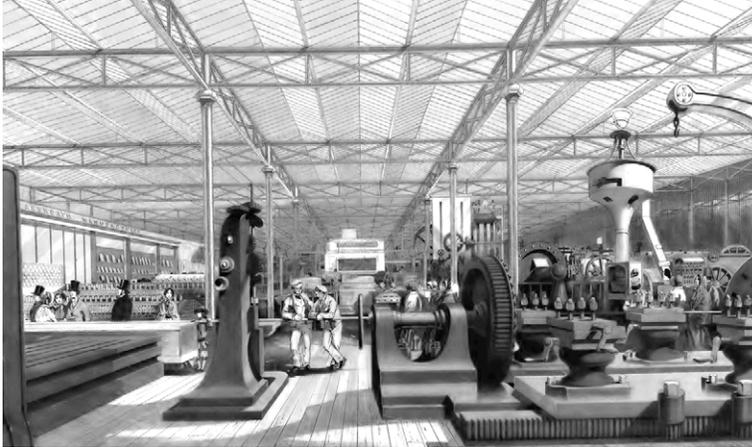
1. General categories from UHPC Solutions, "What is Ultra-High Performance Concrete (UHPC)?"

2. Term "supplementary" used because they behave similar to Portland Cement when hydrated. These are the four major kinds as outlined by Kosmatka, Kerkhoff, and Panarese, *Design and Control of Concrete Mixtures*, 57-61

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## CHAPTER 1.

### On Technology in Design



**Figure 1.2** *Plate from Dickinson's comprehensive pictures of the Great Exhibition of 1851. Moving Machinery.*

“It seems to me highly characteristic that the much discussed question of whether man should be “adjusted” to the machine or the machines should be adjusted to the nature of man never arose with respect to mere tools or instruments.”<sup>6</sup>

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HANNAH ARENDT, 1964

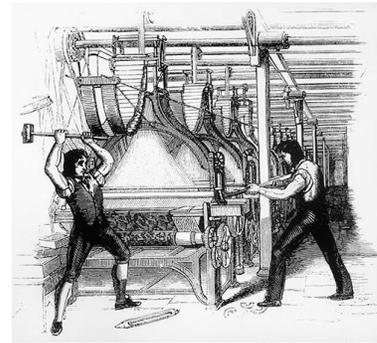
The discussion regarding technology and its impact is by no means considered to be revolutionary. Academics, thinkers and writers since the late 18<sup>th</sup> century have mulled over its social implications. In perhaps an over-simplified reduction, modern technology from its birth during the industrial revolution can be said to have provided speed and efficiency to how we make things (objects or information). This led to one part of society embracing new technology with open arms upon realizing the potential of its implications of capitalist exploitation. With the rise of modern technology also came the other part of society that was, to say the least, skeptical. A famous image comes to mind, of the English Luddites destroying the weaving machines that stole their craft from them circa 1812 (**Figure 1.3**). Likewise, the famous Arts and Crafts movement of William Morris inspired by the words of John Ruskin was seen as a revolution against growing capitalist culture in Europe.

Architecture, both pedagogical and professional, was part of this dialogue. The industrial revolution could be interpreted as the singularity that gave rise to architectural modernism, and therefore by extension, new technologies did in fact affect the *style* of architecture being produced. For example, pre-fabrication and the standardized unit became to architects another tool in the tool chest. But these technologies had yet to penetrate the studios of architects and designers to the pervasive level that we see with computer technology during the 21<sup>st</sup> century. Similarly, some architects and designers today harbour similar feelings towards the computer that the luddites had towards weaving machines. Like in 18<sup>th</sup> century society, there are designers that wish to wage a war on computer technology and then those that exploit the computer for many of the same reasons that the early capitalists did.

This thesis finds no issue with the use of computer software and the virtual realm of architecture, for it would be difficult to ignore the benefits that computer aided design (CAD) and

6.

Arendt, "Labour, Work, Action (1964)," 176.



**Figure 1.3** Luddites destroying weaving machinery.

building information modelling (BIM) bring to the practice. Strictly speaking in terms of architecture, the exploitation of the computer by architects does not constitute the same social crisis as the industrial revolution had created. What is of focus and importance for this work is the designer's growing *dependence* on software as a tool to the point where it can be argued that the software used for designing ultimately controls the result – despite any perceived agency the designer may think they hold. Today, it could be argued that modern *software* designers have the most control over what is designed and built.<sup>7</sup>

I believe that modern software is not as democratic a tool as the traditional tools of an architect once were. Pencil on paper, knife on basswood, or hot-wire through foam was, and still is, a human-technology (pencil, knife, hot-wire as technology) relationship that provides direct connection between mind, body and object. This is categorized by Don Ihde in his work "Technics and Praxis" as being an *embodied* relationship between the human and technology<sup>8</sup>. This is contrasted by the nature of modern software. Software stands in between the human mind-body and the articulated idea (object), and at times proves to be an obstacle in allowing a direct relationship to and from the idea. In other words, while software may lend itself to speed and efficiency of the production and representation, it can hinder the *quality*<sup>9</sup> of an idea because of a loss in the direct relationship between mind, body and object.<sup>10</sup> This could be attributed to the complexity of recent software development. Rather than the designer being preoccupied with resolving the idea through direct, uninterrupted engagement, the designer tends to lose focus by worrying about how to manipulate the software itself and not the idea. The growing complexity of software, combined with the number of software platforms today, seldom allows for clear and direct transfer of implicit knowledge of technique and material across different suites of software – such as, for example, the way in which one would

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7.

Ravenscroft, "Zaha Hadid Architects and Grimshaw among Architects to Criticise Autodesk's BIM Software." The article discusses a filed lawsuit against Autodesk by RIBA members in which the Architects are concerned over the rising costs of the software versus the total lack of development and constrain they feel they have within the software.

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8.

Ihde, *Technics and Praxis*, 11–13. He provides us with the example of chalk on a blackboard. Where we do not necessarily feel the chalk in the hand but rather experience the blackboard *through* the chalk – its roughness and its smoothness.

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9.

Pye, *The Nature and Art of Workmanship*, 50. Quality in these terms is borrowed from Pye's definition: where it is the clarity/resemblance of the thing presented/made to the original design intention in the mind of the designer.

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10.

Pallasmaa, *The Thinking Hand*, 97. The "distance between maker and object" was also observed by Pallasmaa, though he posits that the computer creates the distance while this thesis argues that it is software.

know to use a table-saw for a specific cut over a mitre-saw. Despite being different tools, their functions are fundamentally the same: to cut material, and thus basic techniques and knowledge are transferable.

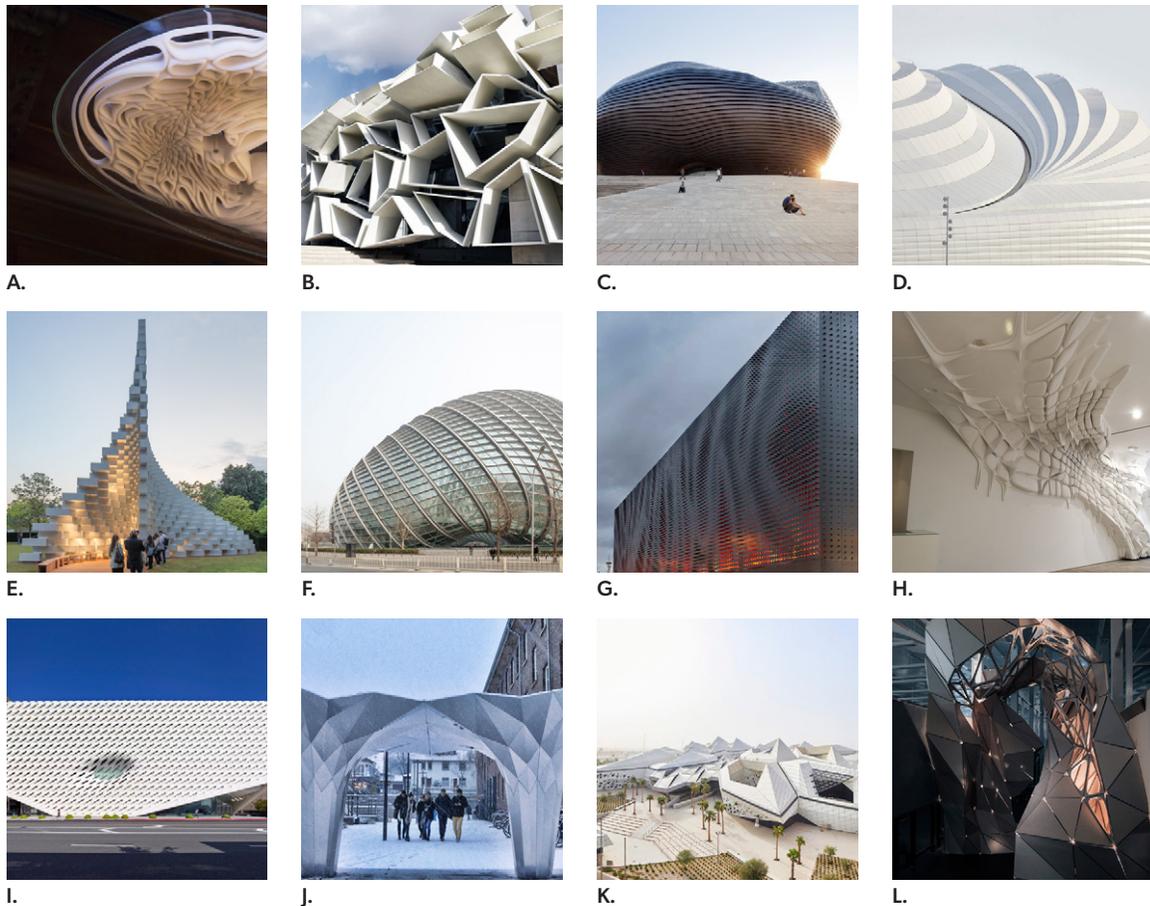
While this idea could turn to a discussion about software design, this thesis will examine a small set of case studies that together hint at the current state of design language (see **Figure 1.4**). Many of these examples are categorized as “parametric design,” meaning that the computer is tasked with resolving complex curvatures and repetitive yet slightly varying elements in ways that are in resonance with software. While designers working with craftspeople have been able to find unique methods and techniques to complete complex works involving significant labour, craft and risk prior to recent developments in software; parametricism can be considered the architectural language and style of the computer, which is close to entirely stripping the authorship or “makers mark” of the architect and craftspeople involved in a project. The architect now builds frameworks and empty parameters for the computer to iterate through. This is not to argue that parametricism constitutes a crisis *in* architecture, but again that the crisis lies in the architect’s personal dependence on the software that directly effects the *quality* of the idea. What are we to think of built work that is void of the understanding of material, technique, and craft due to the separation caused by software?

To reiterate, although this thesis is critical of parametricism as a design language, the argument is in the quality of design work.<sup>11</sup> How can architects better understand their tools (software, hardware, and traditional) in order to produce thoughtful and embodied work in a digital world? This thesis argues that the answer potentially lies within hybrid means of thinking, designing and making. To use a cliché: we should be wary of an architect whose only tool is software in the same way we would be of a carpenter whose only tool is a hammer.

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11.

Quality, again, as the resemblance of the thing built to the mental image the designer holds. If the designer allows the computer to dictate the language being used, then what of the designer’s agency?



**Figure 1.4** *Examples of contemporary parametricism.*  
**A.** Arturo Tedeschi et al. *HorizON* 3D printed lamp.  
**B.** Mehرداد Iravanian Architects. *Greenland Complex*.  
**C.** MAD Architects. *Ordos Art & City Museum*.  
**D.** Zaha Hadid Architects. *Al-Wakrah Stadium*.  
**E.** BIG Architects. *Serpentine Pavilion*.  
**F.** BIAD UFO. *Phoenix International Media Center*.  
**G.** Space Group. *Clarion Hotel and Congress Trondheim*.  
**H.** Zaha Hadid Architects. *Kartal Pendik Masterplan Installation*.  
**I.** Diller Scofidio + Renfro. *The Broad Museum*.  
**J.** Tal Freidman Workshop. *Oragami Pavilion*.  
**K.** Zaha Hadid Architects. *KAPSARC*.  
**L.** Larry Martine Studio. *Involution*.

To address the question of *quality* in built work, of the designer's agency and their "maker's mark", I will elaborate on two issues that I believe would require architects, and most importantly students, to grasp in order to reach a meaningful conclusion. These two issues are 1) material comprehension, and 2) technique comprehension, caused by the separation between mind, body and object<sup>12</sup> in architectural design, exacerbated by the hegemony of modern software.

<sup>12</sup>.  
Object, product, the thing built.

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## 1.1.

### Issues of Material Comprehension

“The large issue here is that simulation can be a poor substitute for tactile experience.”<sup>13</sup>

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RICHARD SENNETT

Issues of material comprehension could be described as issues of being able to (or not able to) transfer *embodied* knowledge of a material, and our experience with it, into the virtual space of software. Walter Benjamin’s theory of aura proves to be useful to begin this section. The word ‘aura’ is used in Benjamin’s essay “The Work of Art in the Age of Mechanical Reproduction,” which he broadly refers to as being:

“... [an artwork’s] presence in time and space, its unique existence at the place where it happens to be.”<sup>14</sup>

By extension, the aura of physical materials may be at the heart of this matter. Does the designer truly understand the aura, the unique physical presence of a material, if the extent of their experience with the material is limited to manipulating an image rendered in a virtual three-dimensional model?

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13.

Sennett, *The Craftsman*, 43.

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14.

Benjamin, “The Work of Art in the Age of Mechanical Reproduction,” 169.

Richard Sennett observes that:

*“Drawing in bricks by hand, tedious though the process is, prompts the designer to think about their materiality, to engage with their solidity as against the blank, unmarked space on paper of a window.”<sup>15</sup>*

I would argue that Sennett’s exercise alone is an insufficient experience to constitute having an embodied understanding of materials and materiality. What of the student or designer that has never picked up a brick? Drawing them even by hand would prove to be a useless exercise – never mind that a single brick rarely makes up any experience we have in the world. Perhaps a more meaningful experience would be simply jumping up to take a seat on a low brick wall in a park and *feeling* the mass of brick. What of standing in a narrow alleyway lined with four-storey brick walls that had all their openings filled in – their sheer weight looming over you? And arguably the most important: what of the experience of *actually* laying a few courses of brick even if it was just part of a field trip to a local manufacturer? What is at stake here is the phenomenology of material and architecture, which will be examined shortly.

According to Sennett, the discussion of materiality began around the mid-18<sup>th</sup> century, and it has remained relevant to contemporary architectural discourse in works by architects like Steven Holl (**Figure 1.5**) and many others who hold materiality as a core principle.<sup>16</sup> Sennett identifies the origin of the discussion on materiality in Isaac Ware’s “The Complete Body of Architecture” published in 1756 as

*“...trying to make sense of naturalness, which is for him the proposition that a building ought to look on the outside like the materials of which it is internally made; this makes the building honest – and again, rough-hewn and irregular.”<sup>17</sup>*

15.

Sennett, *The Craftsman*, 41.



**Figure 1.5** *Museum of Ocean and Surf* by Steven Holl Architects + Solange Fabiao. 2011. Photo credit Iwan Baan

16.

Such as Peter Zumthor, whose work is referenced later. Juhani Pallasmaa is also a modern proponent of material consciousness and contributes to the discourse through his written works which are a primary reference in this work.

17.

Sennett, *The Craftsman*, 138.

Interestingly, he also identifies the anthropomorphizing of materials by craftsmen around the same time period. Brick masons of the early 18<sup>th</sup> century referred to the brick as “honest” or “warm,” and although Sennett mentions that why they did this remains inexplicable, he states:

*“its purpose is to heighten our consciousness of the materials themselves and in this way to think about their value.”<sup>18</sup>*

18.  
Sennett, 137.

While the brick is honest, Sennett brings our attention to its anti-thesis. Stucco – a material that one might label as a “fake” simulation of the real. But to the craftsmen involved intimately with the material, stucco shared similar anthropomorphic characteristics. It was considered the material of play, fantasy and freedom.<sup>19</sup> It allowed the craftsmen to experiment with their work and allowed them to impart their own “maker’s mark” on their work. As Sennett poetically concludes his section:

19.  
Sennett, 140.

*“The craftsman constructing an object that seems simple and honest is as thoughtful – might we say as cunning? – as the craftsman contriving a fantasy.”<sup>20</sup>*

20.  
Sennett, 142.

Although stucco is seldom used today by architects, there are contemporary materials that provide architects with the same sense of freedom that stucco workers had. However, these materials and their use are still deeply rooted in a context of material consciousness that contrasts (read: pits) naturalness (brick) with artificiality (stucco).<sup>21</sup> For example, the contemporary architect Juhani Pallasmaa writes of:

21.  
Sennett, 138. Sennett interestingly identifies issues surrounding artificiality as stemming from masons who “were beginning to be aware of, and feel engaged in, debates about the meaning of naturalness as opposed to the artifice – the great Enlightenment preoccupation about nature brought home to the proper use of a natural material.”

*“scaleless sheets of glass, enamelled metals and synthetic plastics – tend to present their unyielding surfaces to the eye without conveying their material essence or age.”<sup>22</sup>*

22.  
Pallasmaa, *The Eyes of the Skin*, 34.

Here Pallasmaa is extending Sennett’s observations of Isaac Ware by positing that these modern materials are not “honest” as they don’t convey their “essence or age”. This thesis argues that the issue does not reside in the material per se, but rather in the architect’s ability to manipulate the freedom

that the material provides. The lack of material essence that one might observe in the earlier examples of parametricism (**Figure 1.4**) could rather be said as a lack of ability on part of the architect to create a true fantasy in the same way stucco workers in the 18<sup>th</sup> century were able to. It would be unfair to assert that every architect is expected to have the same material understanding and consciousness as a craftsman, but it nevertheless would be a fair statement to say that there is much to be learned from each other.

This circles us back to the opening statements of this section. Contemporary designers rarely find themselves having embodied relationships with materials. As designers, there is much to be learned of the embodied knowledge within the materials that make up our “human artifice”<sup>23</sup> – to use Hannah Arendt’s words – whether it be brick, concrete, glass, drywall, wood, and so on. If designers and architects made a conscious effort to understand the aura of a material, then there would be a hope in transferring their embodied knowledge of the material into the digital realm. We could begin to see new ideas that effectively use materials to portray honesty, or the inverse, to create effective fantasies.

Part of advancing this consciousness of material involves the understanding of limitations. In quoting Constantin Brancusi, Pallasmaa notes:

*“You cannot make what you want to make, but what the material permits you to make. You cannot make out of marble what you would make out of wood, or out of wood what you would make out of stone...Each material has its own life, and one cannot without punishment destroy a living material to make a dumb senseless thing. That is, we must not try to make materials speak our language, we must go with them to the point where others will understand their language.”<sup>24</sup>*

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23.

Arendt, “Labour, Work, Action (1964),” 172. Arendt uses the word as “the world in distinction to nature...” in essence, the world in which humanity builds through action and speech.

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24.

Pallasmaa, *The Thinking Hand*, 55.

With modern software then, the novice and untrained mind and hand tends to contort and force material onto a formal expression they have conceived on the screen, which further drives apart their relationship with the material. Modern digital fabrication techniques in turn then permit this forcible appliqué of material on space because the designer cannot *feel* the material's resistance. If I accept Sennett's observation regarding the anthropomorphizing of materials, can a true understanding of a material's value still exist by simply forcing it onto the forms we design?

This is all not to say that there is a complete lack of understanding amongst all designers of today. There are architects who exhibit a deep understanding of the materials that they employ in their projects, such as Peter Zumthor (**Figure 1.6**). According to Zumthor, *form* is the final part of the design process that he concerns himself with, after he has considered the materiality and the emotional phenomena of being in a space.<sup>25</sup> In his personal account of his process, Zumthor states:

*"Quality architecture to me is when a building manages to move me."*<sup>26</sup>

He is directly speaking of the experiential and emotional phenomena we encounter we interact with our built environment. It is no coincidence that his effectiveness in eliciting emotional response in patrons has to do with his training as a cabinetmaker early in his career.<sup>27</sup> Therefore before he engaged with design at an architectural scale, he already had a profound understanding of the relationship between materiality and technique.



**Figure 1.6** Kolumba Museum by Peter Zumthor. 2007. Photo credit Jose Fernando Vazquez

25.

In *Atmospheres*, Zumthor provides several chapter titles that outline his design process as: body in architecture (the human body), material compatibility, the sound of a space, the temperature of a space, surrounding objects, composure and seduction, interior/exterior tension, levels of intimacy, and the light on things. The final element in his list is *a beautiful form*, which he states is only possible when the other requirements have been appropriately addressed.

26.

Zumthor, *Atmospheres*, 11.

27.

Zumthor, 76.

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## 1.2.

### Issues of Technique Comprehension

“Technique develops by a dialectic between the correct way to do something and a willingness to experiment through error.”<sup>28</sup>

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RICHARD SENNETT

In Don Ihde’s concept of *embodied relationships* between technology and humans, phenomenological discourse creates an *embodied* relationship where technology becomes an extension of our human experience in the world.<sup>29</sup> Sennett’s citation of Michael Polanyi provides an excellent example of this phenomena:

*“When we bring down the hammer we do not feel that its handle has struck our palm but that its head has struck the nail...I have a subsidiary awareness of the feeling in the palm of my hand which is merged into my focal awareness of my driving in the nail.”*<sup>30</sup>

Therefore, when we speak of technique and issues concerning technique, what is at heart is Ihde’s human-technology relationship, not simply an implication that technique exists only at the level of the human hand. This likening of technique to technology comes from their root in the Greek word *Techne*, “art or skill”<sup>31</sup> which Heidegger elaborated in his philosophy on technology.<sup>32</sup> What is of interest for this thesis is the definition of technique as *how* we use technology. Interest in *how* technology is used is not new and can be seen via 16<sup>th</sup> to 18<sup>th</sup> manuscripts that try to shed light on “hidden” knowledge, the type of knowledge generally attributed to people with high technical proficiency.

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28.

Sennett, *The Craftsman*, 160.

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29.

Ihde, *Technics and Praxis*, 8.

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30.

Sennett, *The Craftsman*, 174.

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31.

Merriam-Webster, “Techne.” What is important to note is the use of *art*, in that technique is not something reserved solely for craftsmen but permeates into intellectual realms such as art.

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32.

Ihde, *Technics and Praxis*, 128.

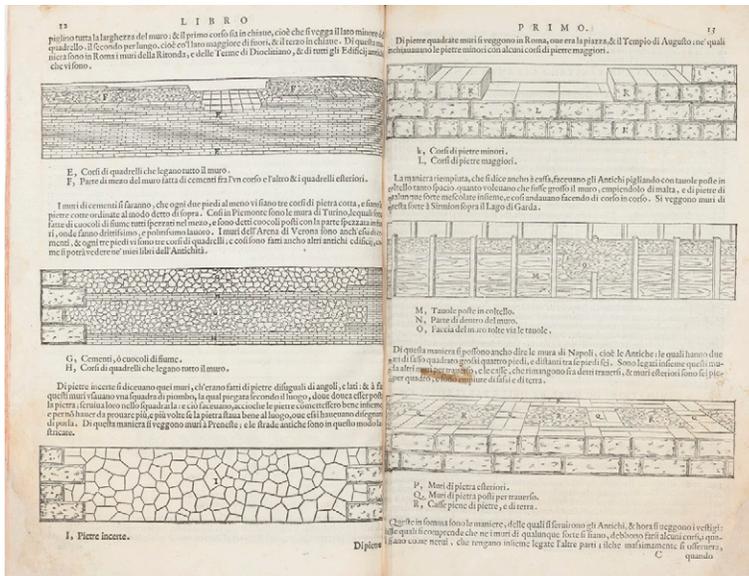


Figure 1.7 Plate from Andrea Palladio's *Four Books on Architecture*. 1570.

Figures 1.7 and Figure 1.8 are illustrated and translated versions of Vitruvius' "Ten Books on Architecture," where both Palladio and Perrault added their own illustrations to the written words of Vitruvius. The illustrations are a means to communicate that which words cannot with respect to *how*<sup>33</sup> the concrete walls should be built, which in Vitruvius, can be difficult to mentally grasp with words alone. Diderot's "Encyclopedie" (Figure 1.9) then tries to catalogue human-technology related knowledge through beautifully illustrated plates. What is of interest in Figure 1.9 is the inclusion of a single scene that shows the process of *how* work is being done. One can appreciate Palladio's, Perrault's and Diderot's effectiveness in trying to bring to light certain elements of "hidden" knowledge, which would otherwise require thousands of pages of words to convey.

Most of the discussion up to this point has dealt with simple technologies, such as a hammer or pencil, but they serve as relevant parallels to a conversation on computers, software, and digital fabrication. Understanding and explicating the techniques associated with these modern technologies is the focus of this thesis. In other words, *how* we use software and

33.

The *how* is in the using of technology to execute, for example, the building of concrete walls.

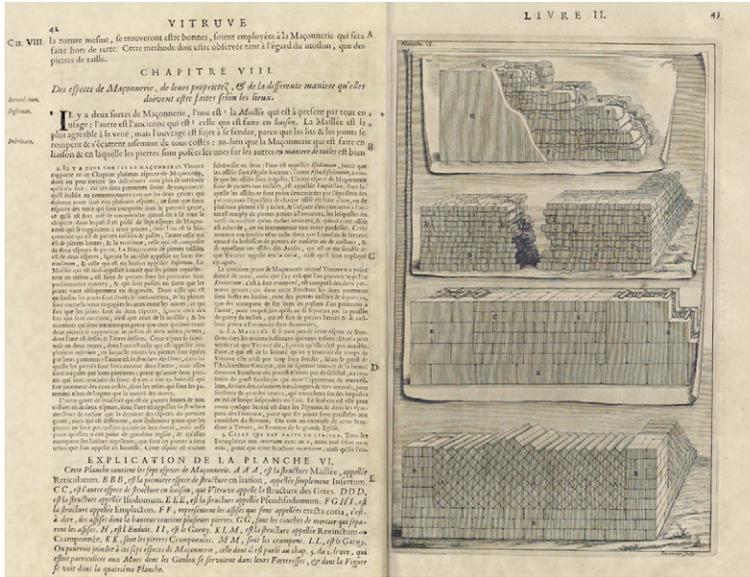


Figure 1.8 Plate from M. Perrault's French Translation of Vitruvius' Ten Books on Architecture, 1684.

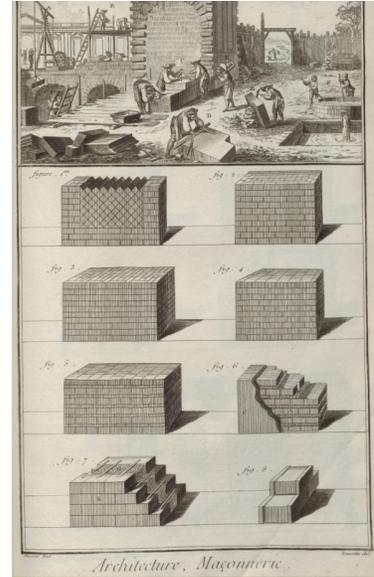


Figure 1.9 Plate from Diderot and D'Alembert's Encyclopedie, Architecture and Masonry, 1765.

new digital tools in the design process and in the making.

It is no secret that technology, even in its early forms, is substantially older than science.<sup>34</sup> For Ihde, the question of technology is an issue of social hierarchy and organization, where the science-technology distinctions produce the theory-practice distinction, in which those that *think* are of more importance than those that *do*. What Ihde brilliantly infers is that the theory-practice distinction can be reduced even further to the mind-body distinction by associating *theory* with the mind and *practice* with the body. He then proposes an inversion: if technology is considered the parent of science, then a hierarchy of body-mind is more appropriate. Pamela Smith in her work "The Body of the Artisan (2006)" shows through historic analysis that this proposal of a body-mind distinction is critical, when she unveils how the artisans and craftspeople during the Renaissance established the foundations for modern scientific inquiry.<sup>35</sup> It is this connection between technology and body that is of interest in her work and elaborated by Richard Sennett and Trevor H.J. Marchand. These authors focus less on philosophical discourse and more on social and cultural factors to

34. Ihde, "Introduction," xix. Ihde makes an interesting point when saying that there is a tendency for people to claim that modern science has produced our modern technology, and thus reduced technology to an "applied science."

35. Marchand, *Craftwork as Problem Solving*, 14.

reveal that knowledge produced by the body (hand) is of equal value to that produced by the mind.

This thesis uses Sennett's definition of a *craftsman* as:

*"one who has the desire to do a job well done for its own sake."*<sup>36</sup>

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36.  
Sennett, *The Craftsman*, 9.

Thus, a job well done involves high levels of technical understanding (technique) on part of the craftsman in order to execute it. Sennett notes that, to spectators, technique at times appears "soulless" or "mechanical" because of its association to industrial labour and routine as mindless tasks.<sup>37</sup> But for a highly trained craftsman, technique is anything but mindless and mechanical. Technique at this high level encompasses a profound connection between mind, body, tool (technology) and material (object) to the point where it *appears* mindless to observers, but in fact the craftsman is problem-solving in real-time. Marchand echoes the same sentiment when he writes:

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37.  
Sennett, 175.

*"The craftspeople presented in these case studies are thinking with tools, and actively engaged with materials, other actors, and the surrounding environment in their individual pursuits to settle problems, enhance skills, broaden knowledge, and construct social identities and professional status."*<sup>38</sup>

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38.  
Marchand, *Craftwork as Problem Solving*, 12.

Craftwork as its own realm of skill and knowledge remains an enigma to the rest of society. Sennett and Marchand both note that the secretive nature of craft lies in the fact that first, language is insufficient to accurately describe it<sup>39</sup> (and this thesis will show that at times, pictures, videos and drawings still fail), and second, that you can only learn by doing.<sup>40</sup> This gives rise to two categories of knowledge that Sennett describes as explicit and tacit knowledge.<sup>41</sup> The explicit is visible and easily identifiable – while the tacit is what he likens to "instinctive" knowledge that is engrained in our everyday experience of the world and therefore is so obvious that we do not think much about it. Tacit knowledge then could be said to be, within craftwork, as having a broad range of experiences with materials

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39.  
Sennett, *The Craftsman*, 95. He makes a humorous point when he says, "it [craftwork] is perhaps beyond human capacities to explain; it taxes the powers of the most professional writer to describe precisely how to tie a slipknot (and certainly is beyond mine)."

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40.  
Marchand, *Craftwork as Problem Solving*, 3–4.

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41.  
Sennett, *The Craftsman*, 50.

and technology. . The craftsman’s ability to do good work for its own sake is predicated on a deep connection to their repository of tacit knowledge, for example, knowing exactly how much to shift your body weight to your dominant foot when preparing to make a cut at a saw so that the machine moves confidently through. A more contemporary example involving software could be knowing the precise timing of applied force/release in your two index fingers when masking images in Photoshop – trying not to fumble and forgetting which finger is responsible for which task.

Where does this leave us in the context of architectural discourse? Issues of technique comprehension return to the notion of the human-technology relationship. The speed and efficiency that makes software attractive in architectural design removes the embodied relationships between us, technology, the material, and the thing made. If an architect wishes to “do good work” (to become a *craftsman* of architecture) but only operates with software as the primary tool, then there are no opportunities to develop a range of *technique* or a tacit understanding of the processes that constitute the design and building of the material world. Not to say a craftsman of software has no place in architecture – in fact, it has become a necessity – but architecture as a polythetic profession, as craftwork is,<sup>42</sup> requires various experiences *with* technology. This is not referring to only simple technologies like the hammer, the pencil and the saw, but new digital tools like digital modelling software, 3D printers, laser cutters, and CNC machines. Software is just another tool in the tool chest.

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42.  
Marchand, *Craftwork as Problem Solving*,  
3.

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## 1.3.

### Case Studies

A select few case studies which have properties or demand inquiry pertinent to my thesis questions will now be explored below.



**Figure 1.10** *Manglar Chair by External Reference*

The use of a simulated texture on the chair shown in **Figure 1.10** and the intelligent placement of additional geometry to overcome inherent material limitations are two elements which are of interest to this thesis. The thinness of the extrusion is not interrupted by bulky post-reinforcing which is commendable. Likewise, the ability to imbed texture for increased haptic experience of the chair is something that my work in this thesis aims to further explore.



**Figure 1.11** *Private Commission by Philipp Aduatz*

**Figure 1.11** is an exemplary showcase of a formal typology which seems to be consistent across 3D printed concrete chairs. The simplicity of the form and its gentle curvature overcomes the material's inherent limitation of being able to achieve dramatic overhangs. In this case, the gradual overhang makes up the cupped seat. The addition of extra geometry in areas of higher stress also helps overcome the concrete's inability to perform in tension. The designers used these bulkier areas to imbed fiber-glass rods and carbon fiber textiles underneath the seat during the printing process which further helps the chair resist tensile forces.



**Figure 1.12** *Cloud Chair by Philipp Aduatz*

Despite the project shown in **Figure 1.12** not being digitally fabricated nor made of concrete, it somehow invokes a feeling of solidity and is suggestive of an organic digital language with the organic growth of the bubbles. The part is spray foam applied over a wooden armature. The successful portrayal of the fantasy that this piece manages to achieve is a goal that many digitally fabricated projects seek to achieve. The inability to distinguish the traces of a digital or hand tool is of interest to this project.



**Figure 1.13** *Oppo Betong by Blå Station*

**Figure 1.13** is evidently not 3D printed as the layering traces do not exist, but one could infer how digital fabrication technologies may have been used to create the molds that this chair would have been poured into – for example, the CNC milling of a two-part formwork as evident by the seam along the edges of the final product. What makes this project of interest is the perception of a softness in concrete, which is a characteristic that this research would like to explore in its own design process.



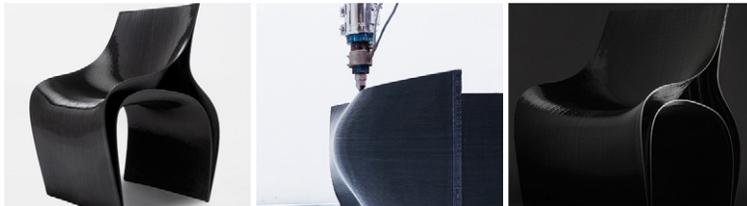
**Figure 1.14** *Mangrove Table by External Reference*

Although **Figure 1.14** not a chair, this project makes an interesting inversion of the method in which concrete would typically be printed. By simply printing the individual parts of the table upside-down on a bed, they remove the concern of achieving extreme overhangs. Manipulating orientations of geometries during the printing process is a technique that will be explored in this thesis.



**Figure 1.15** *P\_Ball by Emerging Objects*

A typology of small, individual pieces shown in **Figure 1.15** that are assembled to create the final object is also of interest to this work. The difficulties in these typologies exist in how they connect to one another. Concrete as a material and the low-resolution nature of the printing process may not allow directly imbedded connection points. Therefore, the way these parts are connected would need to involve some form of post-processing that brings the entire process back into the analogue realm.



**Figure 1.16** *Peeler by Nagami Design & Daniel Widrig*

**Figure 1.16** is an example of a chair that is closest to the scale and typology that this thesis will be able to explore, albeit printed in PETG plastic. The *Peeler* chair makes use of minimal material by printing a single perimeter which I find incredibly useful in trying to limit the weight of a printed concrete chair. The designers and makers poetically summarize their intentions as such:

*“The chair has been designed to satisfy both the ergonomic constraints of the human body, as well as the ergonomics of the robotic arm that prints it. Consisting of three undulating skin-like surfaces, Peeler emerges out of a convergence of human and machine requirements.”<sup>43</sup>*

**43.**  
Widrig, “Peeler, a Chair Designed by Daniel Widrig.”



**Figure 1.17** *Baoshan Pedestrian Bridge by Weiguo Xu, Yuan Gao, Chenwei Sun and Zhi Wang at Tsinghua University*

This project in **Figure 1.17** showcases a level of refinement as well as roughness that is associated with 3D printing concrete at larger scales. The individual parts are printed using a similar method as well as similar concrete mix to that which will be used in this thesis. One caveat is that this project utilizes a concrete pump to efficiently deliver the large amounts of concrete required (which is something this thesis will not be able to explore). The single-tube-extrusion method that this thesis is working with will present its own challenges as well as opportunities during fabrication.

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## 1.4.

### Process Overview

The designing and building stage of the chair is split into four phases which align with the colloquia presentations during the eight-month thesis. Below is the structure of the thesis.

#### **Phase 1: Traditional Crafting – Material and Technique Exploration**

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Phase 1 is a research phase as well as an opportunity to explore hands-on with UHPC and determine appropriate working techniques *for* the material. This phase creates an embodied relationship between myself, technique, and material before moving into the next formal design phase. This phase built upon my existing knowledge with the material and certain techniques, to determine if the techniques I already know are applicable, and to uncover the things I do not know.

#### **Phase 2: Hybrid Crafting – Concepts and Digital Explorations**

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Phase 2 began to address the question of the design of the chair by exploring potential conceptual departures. As indicated by the word “hybrid,” this phase assumes an adequate understanding of the embodied relationships established in Phase 1 and thus begins to incorporate digital techniques (both hardware and software) in combination with traditional analogue methods to work towards a hybrid way of working. Within this phase exists an exploratory sub-phase with the 3D printing machine and the UHPC to determine the correct recipe and consistency.

### **Phase 3: Half Scale Prototyping & Mix Design**

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Phase 3 began with three design proposals for prototypes of the chairs based on the conceptual departures from phase 2. The prototypes are sketched out and are built using the lessons learned from the first and second phases. At the end of this phase, the three prototypes will be synthesized into the design of the “final” prototype.

### **Phase 4: Full Scale Final Prototype**

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The final phase consisted of designing and working at full scale to create the final chair prototype. The word prototype is purposefully used because there is evidently aspects that can be improved on. The chair is a culmination of all the things learned from the processes and techniques from each of the previous phases, as well as the things learned from the material: its experiential qualities, performance qualities, and limitations.

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## **CHAPTER 2.**

### **Phase 1 – Traditional Crafting**

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## 2.1.

### Material, Technique, and Object

My goal in phase 1 was to understand UHPC as a material and the techniques involved. The focus of Phase 1 is making three “objects” that are made up of the characteristics outlined in **Table 2**. “Objects” in quotations is used purposefully to imply that they are solely objects, conceived with no function nor symbolic meaning. This is because I want to ensure that these explorations contain the least number of prejudices and assumptions that result from designing before understanding the material and processes. The explorations are therefore embodiments of *only* the relationship between technique and material. For this reason, only brief and crude sketches are completed initially to provide a point of departure. The thinking is done by the hands involved in making.

**Table 2.** Object, Material and Technique Matrix

	Object 1	Object 2	Object 3
Material Consistency	Fluid, mixed to optimal water-binder ratio to ensure adequate strength for stresses applied by connections.	More fluid, mixed with slightly higher water ratio to ensure good detail capture in the cast object.	Stiff, clay-like consistency in order to apply onto an armature.
Technique Exploration	Casting, multiple small repetitive elements with connections. Benefits from simple formwork for efficient reproduction.	Casting, single complex formwork. Higher complexity of making formwork is welcome if making only one.	Sculpting, good for complex volumes with undercuts, or situations where formwork would be too complex for reasonable execution.

It is important to emphasize that this phase is meant to be understood as a potential pedagogical and self-discovery tool. I cannot say that I am coming into this phase as a completely naïve actor, as I carry my own experiences and knowledge with me from working with concrete before at various scales. UHPC may be similar to traditional concrete, but not directly, and therefore I think that these explorations are justified in their value to the final outcome of this thesis. This phase in-fact challenges my already established knowledge of concrete as a material and forces me to begin to understand UHPC as a material that may be “like” concrete, but it is also something different. This phase lets me as the designer/maker fundamentally understand the material before working the material into an intended design.

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44.

Goss, *Concrete Handbook for Artists*, 13.

The three “objects” are a variation of the methodology used by Andrew Goss in “The Concrete Handbook for Artists,” where he identifies his methods most appropriate for working with concrete depending on its consistency. Goss identifies these fabrication techniques as: “1. *Casting into a mould*. 2. *Applying to an armature*. 3. *Carving a solid block*.”<sup>44</sup> I choose to ignore subtractive (carving) techniques of semi-cured UHPC because of the safety concerns involved with milling UHPC at the facilities, replacing it with two sub-methods of casting; the first being the casting of small, repetitive elements using simple formwork to later assemble; and the second, casting into a larger, more complex formwork that produces the final object with little post-processing required.

The language used in the analysis of each process is a personal account of the experience. This means that the descriptions and accounts are of *what* was learned and what is important for future phases, rather than serving as a how-to manual. 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.<sup>45</sup> 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.<sup>46</sup> What he learns of himself and his process is what this phase seeks to establish in this research, in hopes to move towards a comprehensive understanding of a design and making process.

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45.  
Marchand, *Craftwork as Problem Solving*,  
22.

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46.  
Marchand, 115–31.

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## 2.1.1.

### Thinking by Making – Object 1

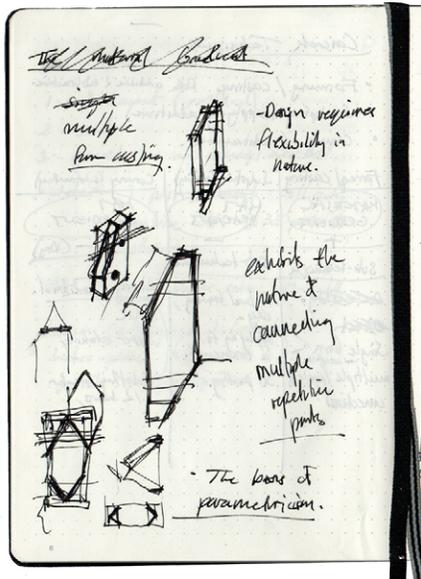
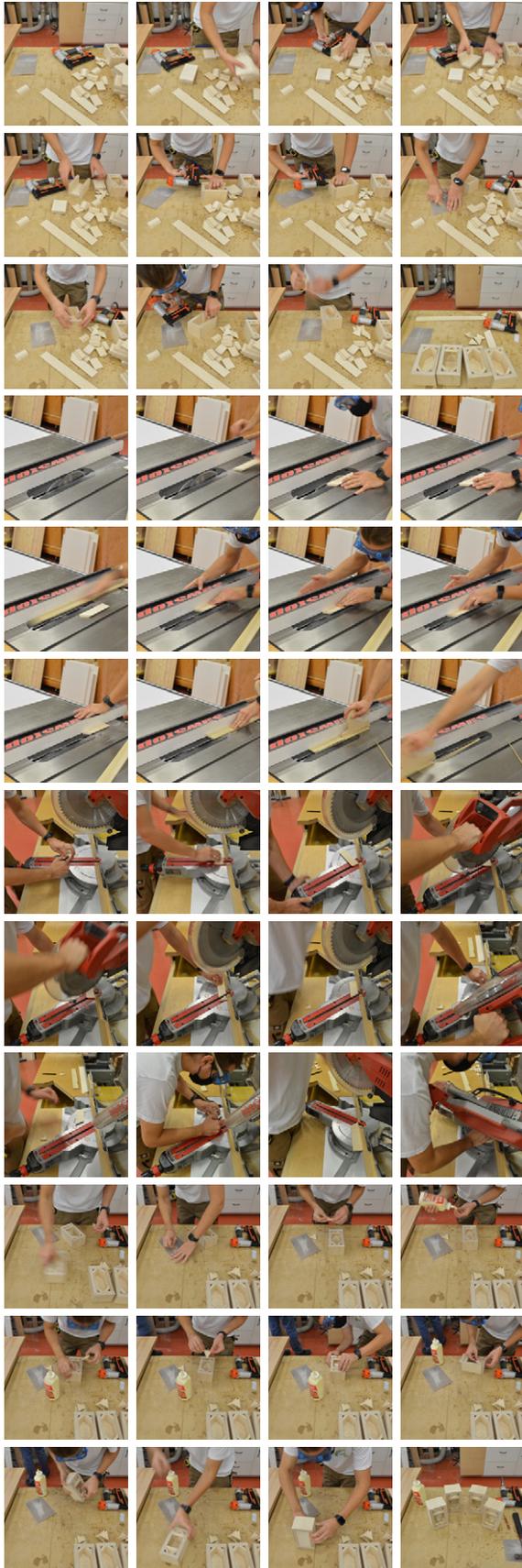


Figure 2.0 Initial sketch of object 1

#### Description

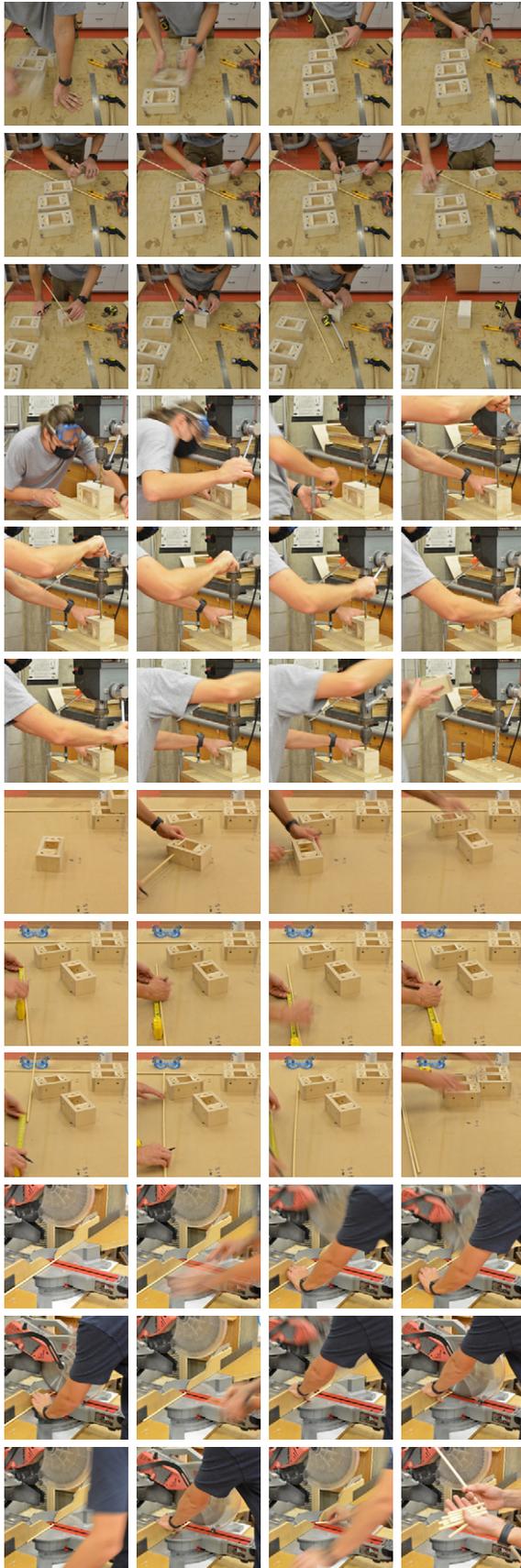
With object 1, I explored techniques associated with pre-casting small, repetitive elements which are then later connected in series. The focus of object 1 is simplicity in formwork. A simple formwork would allow for a quick assembly and disassembly, and the ability to cast as many elements as desired because of the ease in making them. The intention of this object was to have four identical parts that connect at shared points and therefore can pivot to any number of orientations. The type of connection used is a result of the process of making, rather than one that was planned. As will be shown, the process of making uncovers many issues that putting pencil to paper cannot anticipate.



**Account**

The materials I selected to make the formwork was a question of availability and durability. There were of course materials of lesser quality (durability) in the workshops' scrap bin, but I was drawn to the thickness of the Baltic birch plywood. Despite the formwork boxes being small and ultimately disposable, the half-inch thick plywood would provide adequate stability and strength when the time came to pour and vibrate the formworks full of UHPC – removing any risks of the formwork falling apart at the last minute. Additionally, I would have to worry less about ways to join the boxes using half-inch plywood versus something with a quarter-inch thickness, which in practice proves to be difficult to fasten with a pneumatic nail gun or to even handle with enough dexterity due to the thinness. Using another material like high-density foam would result in weak corner connections unless the time was taken to chemically bond them together – which I did not want to invest at this phase.

**Figure 2.1** *Object 1 process clips*



Using a material of such quality generally suggests working at higher degree of tolerance, even if it is just a formwork. I personally would find it unnerving to see rough joinery interrupting the plywood's grain. This suggests a certain relationship between the perceived quality of material and the level of *roughness*<sup>47</sup> one is willing to work at. This posed its own challenges, as I was not able to work as quickly as I would have liked. Mitering the corners, compound mitering the chamfers, and properly squaring the walls was time-consuming. It is important to note that engaging in these slower processes at the beginning is to limit inherent risks later, and to increase the apparent quality (quality in the craftsmanship and quality in the resemblance to the intended form) in the final casting. The inherent risk I was trying to eliminate in this instance was the UHPC leaking out of the formwork due to poor joinery. But time lost on a project can also be a risk that one would have to balance if there is not much of it.

47. Pye, *The Nature and Art of Workmanship*, 32–33. It is important to note Pye's definition of "rough workmanship" as not necessarily meaning bad workmanship. Roughness is approximation of the idealized form by the workman because: "he intends that it shall...because he has not the time to perfect the work, and finally, it may do so because he has not the knowledge, patience, or dexterity to perfect it." Therefore, when working with the birch plywood, I was not working in a rough fashion because it would seem disrespectful to the material at hand.

Figure 2.2 Object 1 process clips



Regardless of understanding, skill, or technical ability, working without a plan guarantees risks and leads to moments requiring improvisation, as David Gates also points out.<sup>48</sup> Improvisation can be considered the pinnacle of real-time problem solving. In this instance, the dowels that were intended to leave hollow connection points in the cast objects were in practice not able to be removed due to the friction against the UHPC. Perhaps a material that had a polished surface quality could have been pulled out with less effort and frustration. Instead, the dowels had to be drilled out and hacked away, which inevitably disturbed the still-curing UHPC. And finally, to my dismay, the hollow cores in the cast objects did not line up as I had intended in my mind's eye. I had to improvise. Since the hollow core was not a straight section between two parts, the only viable solution was to feed through something flexible. Luckily, there was some wire in the lab which was an acceptable solution, given the exploratory nature of this phase.

48. Marchand, *Craftwork as Problem Solving*, 119. "Improvising...entails responding to provisional and emergent conditions, and formulating strategies in that moment...A craftsman borrows from what they know as he or she interprets a situation and reforms it as needed in the moment-to-moment of the 'taskscape'. In this way, making becomes embedded in the idea, and the idea becomes imbedded in the making."

Figure 2.3 Object 1 process clips

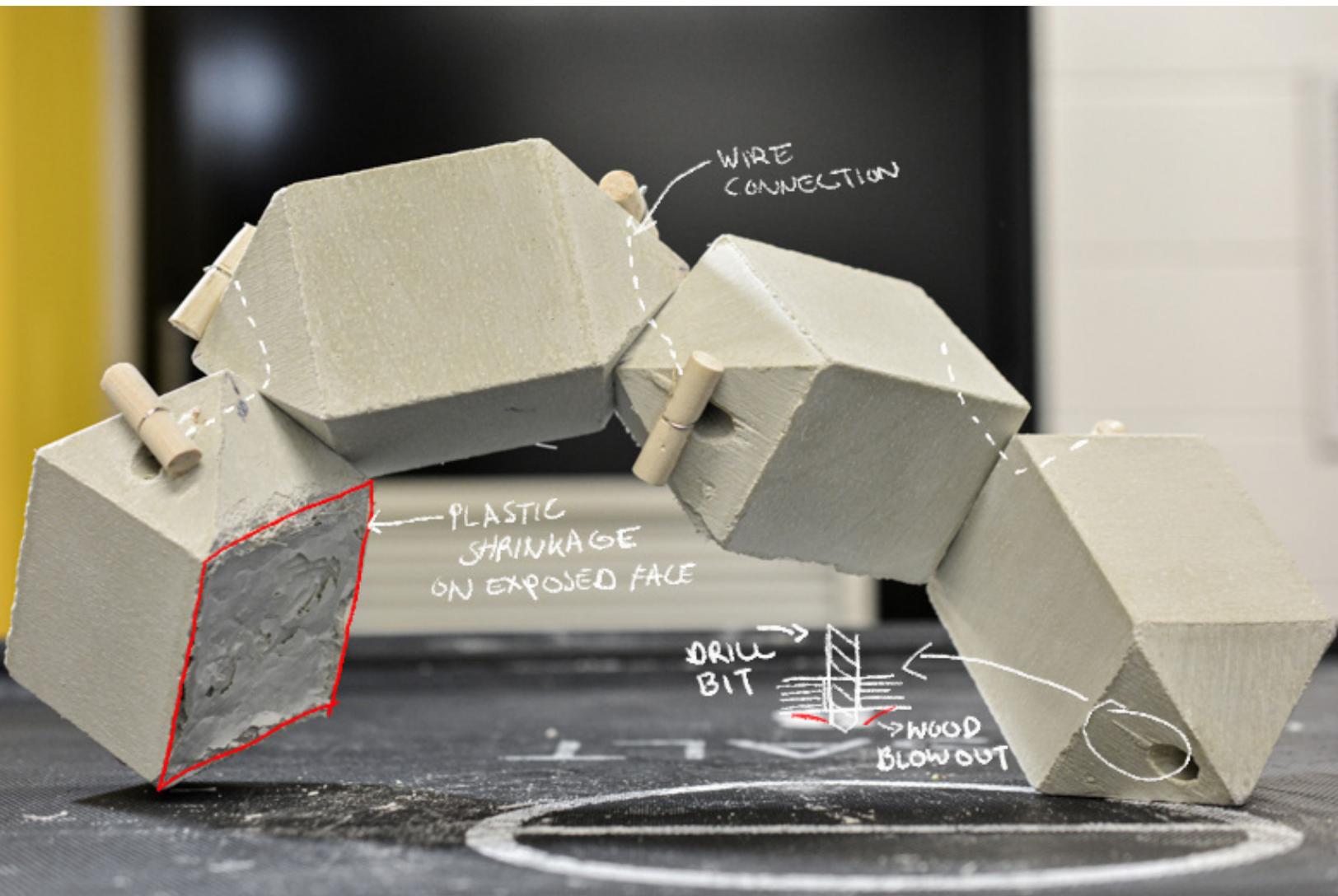


Figure 2.4 Object 1, assembled

## 2.1.2.

### Thinking by Making – Object 2

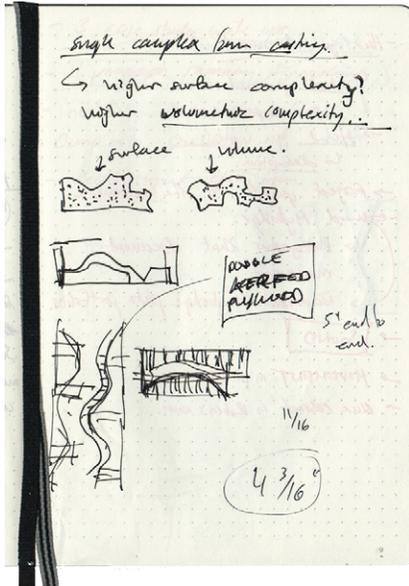
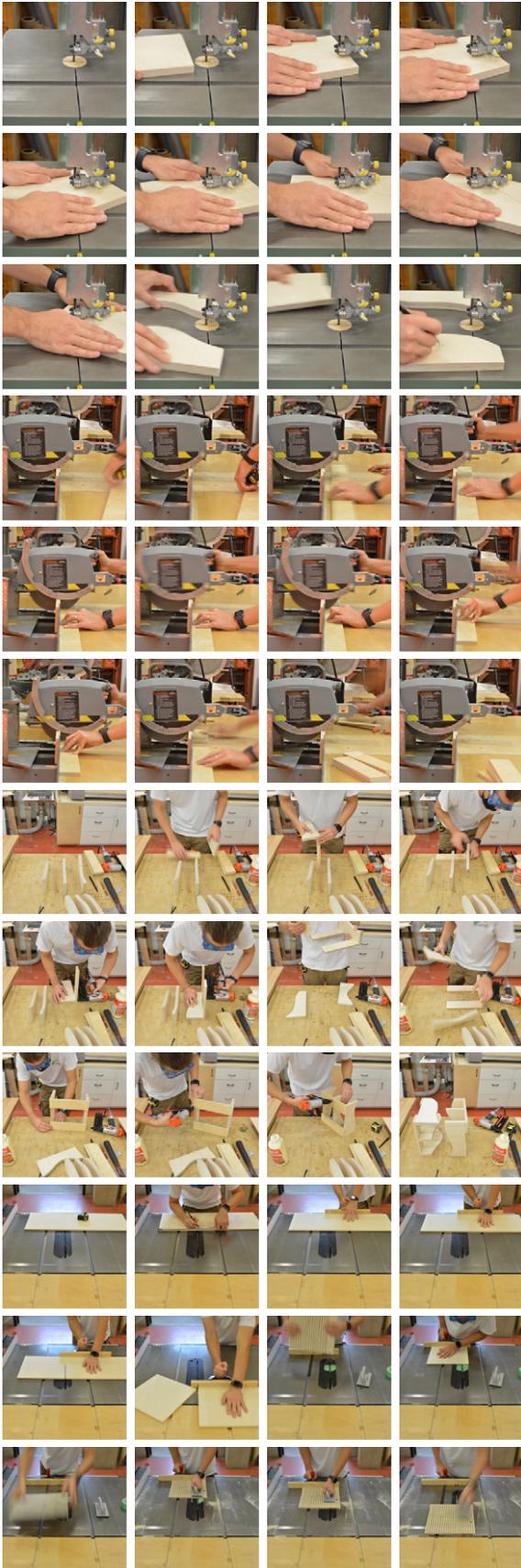


Figure 2.5 Initial sketch of object 2

#### Description

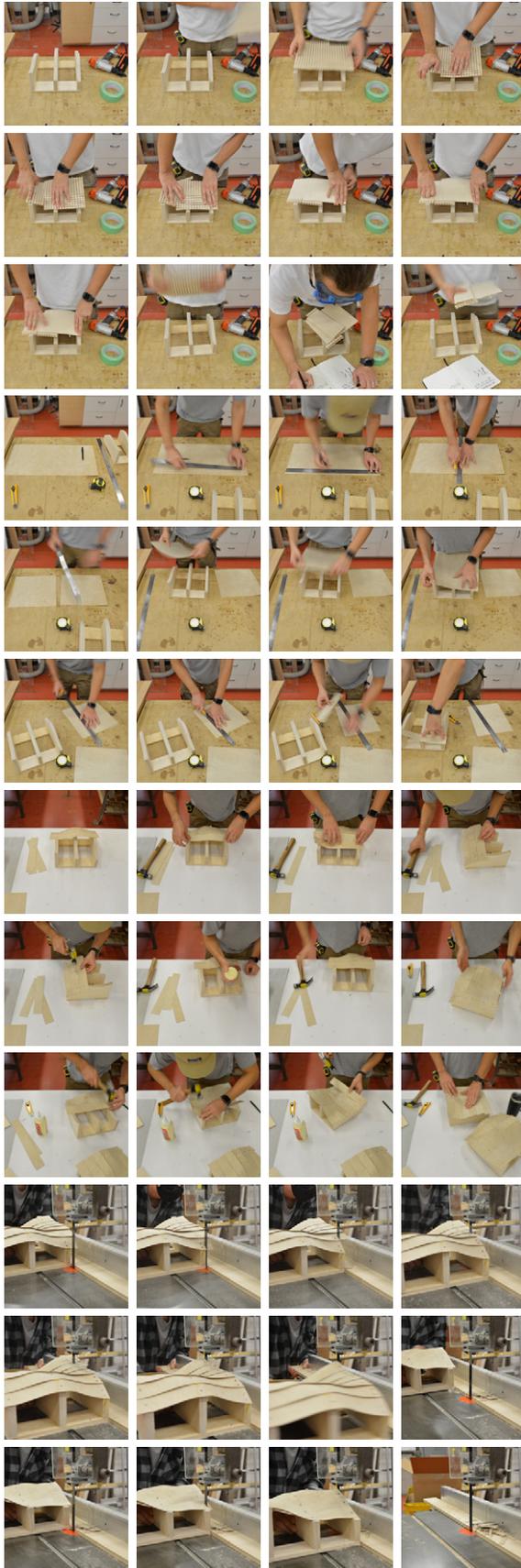
With object 2 I explored the other sub-technique of casting, which I earlier identified as using a slightly more complex formwork to make a singular form not requiring assembly. The primary challenge in this exploration was trying to create the curvature using the material readily available in the workshop. I did not want to just make a complex surface, but volume as well. I wanted to create something that would undulate, come together to create thin moments and resolve itself into something thicker at the base where it would stand. This exploration will show how working *against* material inherently brings elements of risk that are difficult to anticipate, even when equipped with a plan. The question of acceptable tolerances arises again.



## Account

I chose the material for the formwork for the same reasons as the previous exploration. Availability, durability, strength, and ability to handle efficiently and quickly. The outlier in this object being the surface curvature. A couple of techniques came to mind: steam bending a thin sheet of wood or kerf cutting a thicker piece of plywood to give it some flexibility. Knowing I was working at an acceptable level of roughness, I chose to ignore the steam bending route for it would be too much effort and time for the nature of this exploration. I began kerf cutting a square half-inch thick piece of plywood – this time low quality pine plywood since I was not entirely confident in what the result would be. Rob, the workshop technician, warned me that it probably would not work since I was dealing with extreme double curvatures. Regardless I felt it necessary to experience the failure, to feel in my own hands how the wood was resisting and what its limit was, and to then have the memory available to draw on in the future. Naturally, it did fail.

Figure 2.6 Object 2 process clips

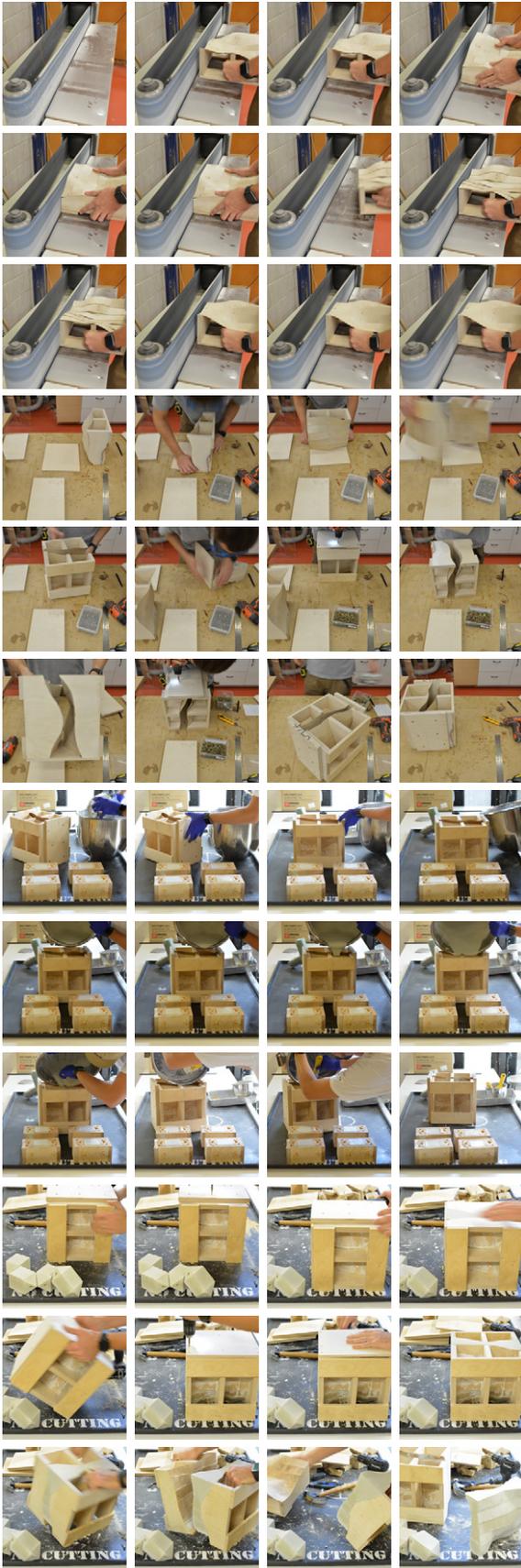


The workshop technicians suggested shingling strips of thin air-craft plywood across the curved sections of my formwork. I knew that this meant I had to concede to the idea of having a “smooth” surface on the cast object. But conceding is okay – it is inevitable when participating in what Pye calls the “workmanship of risk.”<sup>49</sup> The results of this kind of workmanship are often unknown, and to me the approximation of “smooth” was acceptable for this exploration. The process of assembly was simplified with this technique, and the material afforded its own variation upon the strict cut-out guide curves. It bulged and contorted in some areas where I could sense it was not comfortable being in. This required further improvisation, since the bulged strips left large gaps where UHPC would be free to escape. I remedied this with some latex caulking, and of course, if the formwork were meant to be its own stand-alone product for presentation, I would consider this unacceptable workmanship.

49.

Pye, *The Nature and Art of Workmanship*, 20. “The essential idea is that the quality of the result is continually at risk during the process of making...it depends on the judgement, dexterity, and care which the maker exercises as he works.”

Figure 2.7 Object 2 process clips



Learning from the first object, I chose instead to assemble this formwork with screws instead of pneumatic nails. This might seem obvious, but the first object was far too small of a size to comfortably, confidently, and time-efficiently use screws without risking rupture in the finished faces, resulting in unacceptable defects in the form. Object 2 provided enough space and thickness to be able to secure with screws, eliminating the need of excess prying force when unmoulding. This made the process a quick and painless task.

It was a happy coincidence that the surface quality of the aircraft plywood made unmoulding painless, unlike the pine dowels from earlier. The resulting UHPC surface, even though not entirely “smooth” as intended in my mind’s eye, was imprinted with the beautiful surface quality of the plywood; the fineness of the cement particles picking up on every variation in the grain and every slight change in direction. This was pleasant to see and perfectly acceptable.

**Figure 2.8** *Object 2 process clips*

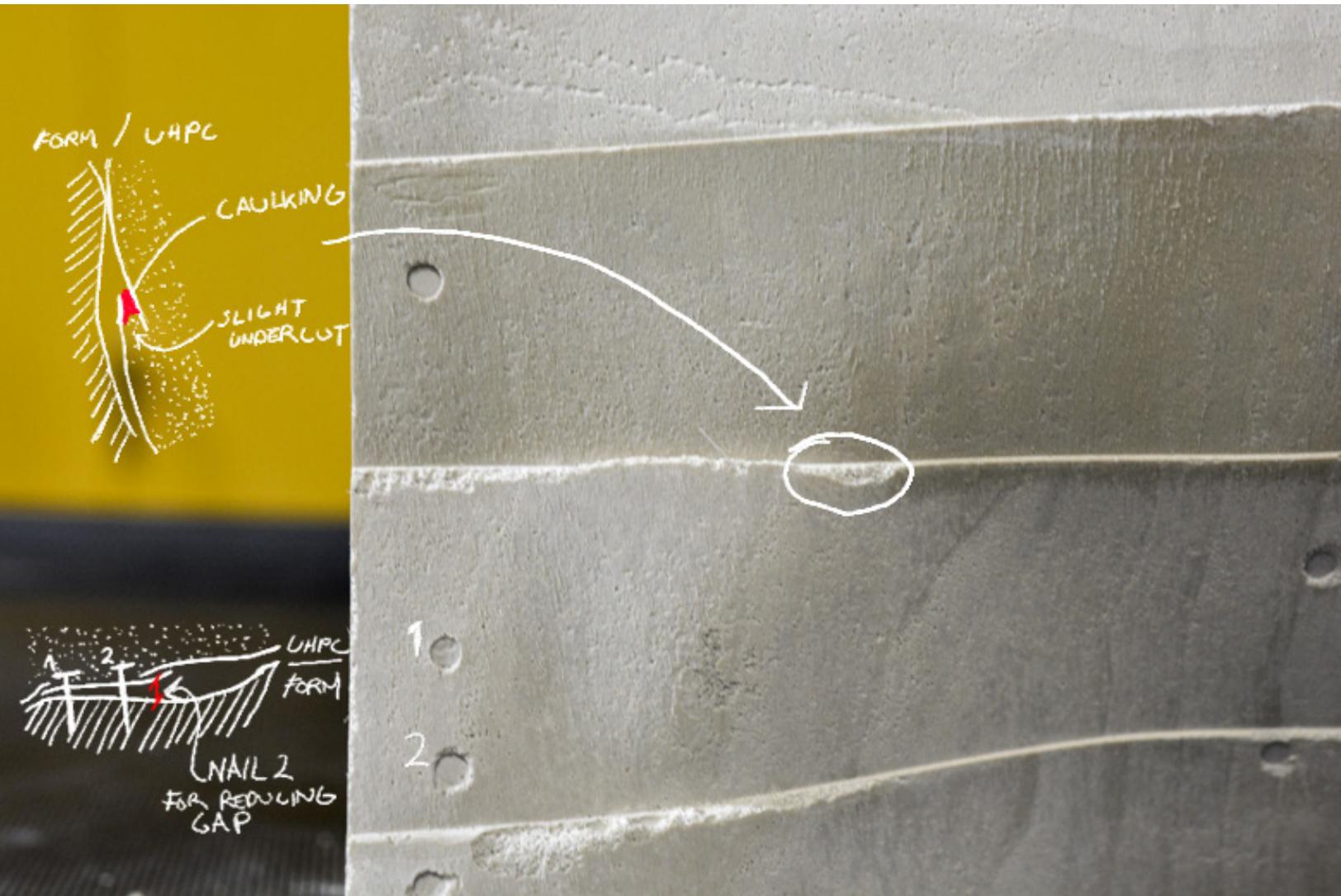


Figure 2.9 Object 2 detail

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### 2.1.3.

## Thinking by Making – Object 3

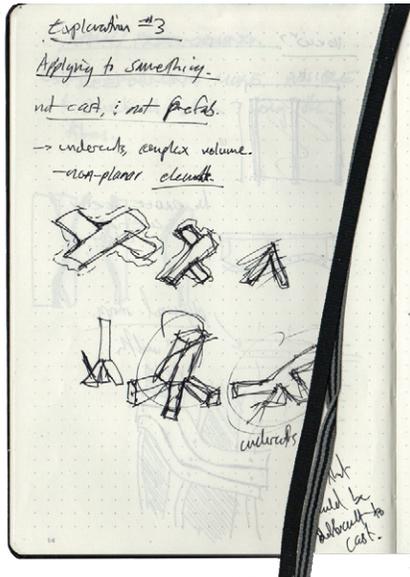
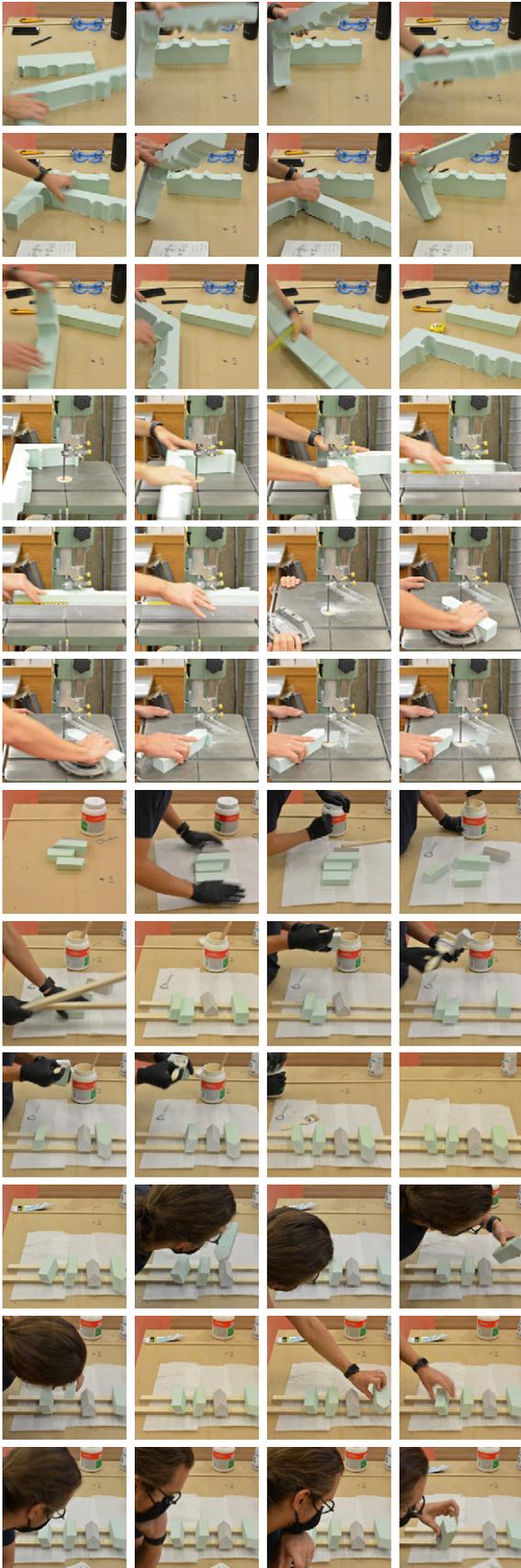


Figure 2.10 Initial sketch of object 2

### Description

With object 3 I explored the final technique of applying UHPC onto an armature. Applying UHPC in an additive manner allows the making of forms which would otherwise be difficult, if not impossible, to achieve with casting techniques. This can be seen by the design of the multiple undercuts in the object. The largest issue faced in this exploration was achieving the correct consistency of UHPC. If it is too stiff, the concrete would not be able to adhere to itself while being pressed onto the armature. If too loose, then gravity takes over. These explorations provided me with a better understanding of UHPC by feeling it in my hands. I learned in this early phase that the UHPC is incredibly sensitive to the chemicals in the wet ingredients.



## Account

The material selected for the armature of Object 3 was high-density foam which was also readily available in the workshops' scrap bin. In this case I was not particularly interested in continuing with the birch plywood for a couple reasons: 1) I knew the level of tolerance and accuracy required was far less than the previous explorations, since any mistakes would be covered up by the applied UHPC. 2) This design would require a large amount of plywood for the volume it occupied, which felt wasteful and uneconomical. The foam scraps were already roughly the same cross-sectional size, reducing the time and effort needed in the making process. Using the foam as the filler material and steel mesh to reinforce the applied UHPC is a technique that I borrow from Goss and his similar example.<sup>50</sup>

50.  
Goss, *Concrete Handbook for Artists*,  
65–74.

Figure 2.11 Object 3 process clips



Accepting early on that I would be working quickly and roughly meant I did not have to worry about the appearance of the internal joints and connections. I was able to do away with measuring almost entirely and relied on relative measurements and the “eyeballing” of angles. These same principles applied when I was wrapping the armature with the steel mesh. If the form was mostly covered and the curvatures were approximate to the envisioned form, then doing “good, regulated workmanship”<sup>51</sup> was not a concern just yet. The benefit to this technique of layering material means there is a gradual increase in quality of workmanship in each successive layer.

Once the armature was complete, I was able to continue this process of material layering with UHPC. The first pass of layering resulted in a rough, unappealing surface quality due to the stiffness in the UHPC, but the stiffness was necessary in order to successfully apply the material in bulk. The second layer then afforded the possibility to work with a looser consistency of UHPC, allowing the visible surface to be sculpted and polished in the way I had intended.

51. Pye, *The Nature and Art of Workmanship*, 52. Regulated workmanship in Pye’s definition is where “the achievement appears to correspond exactly with the idea.” This contrasts with “free” workmanship, where there a visible approximation between product and idea.

Figure 2.12 Object 3 process clips

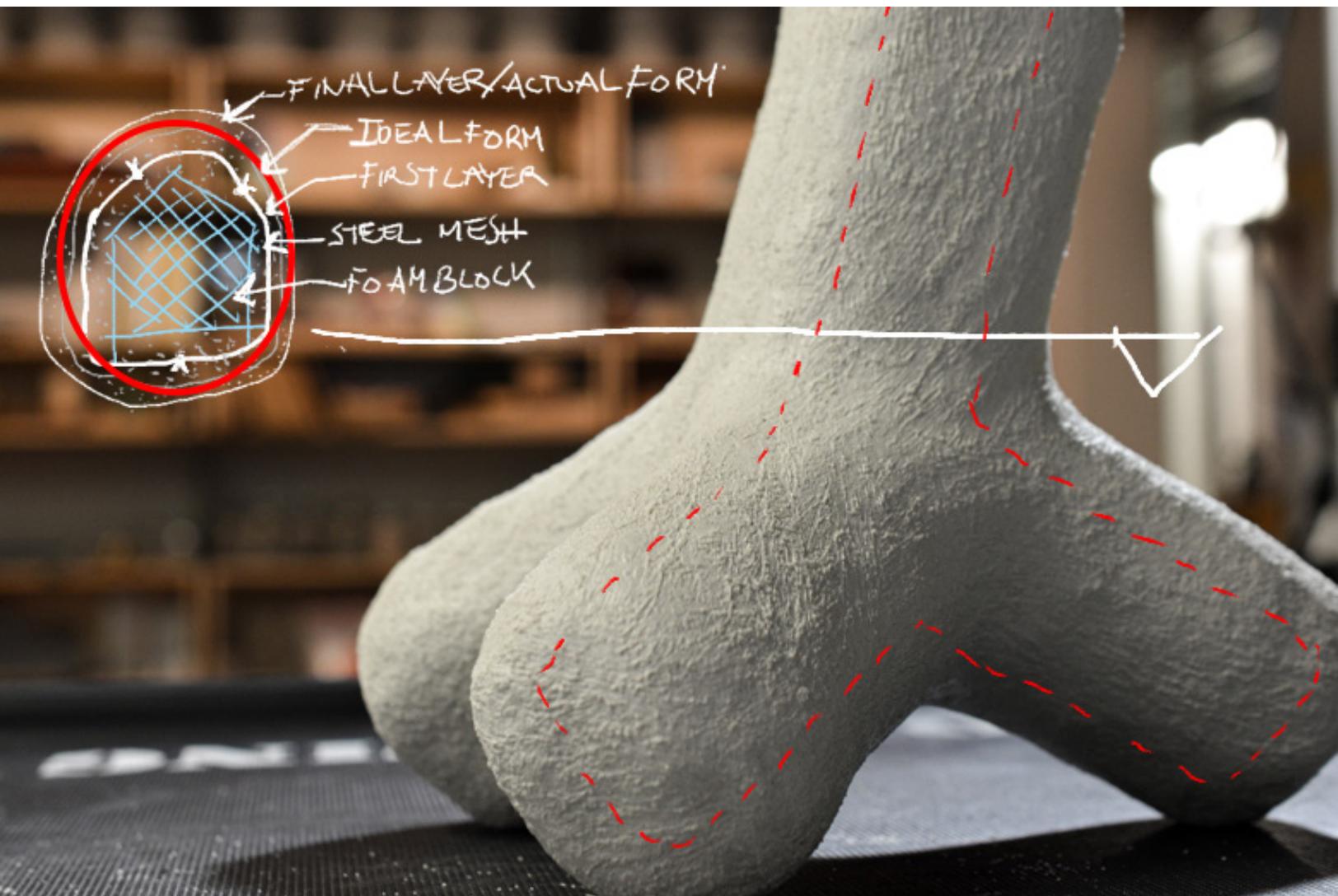


Figure 2.13 Object 3 detail

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## 2.2.

### Collections & Reflections

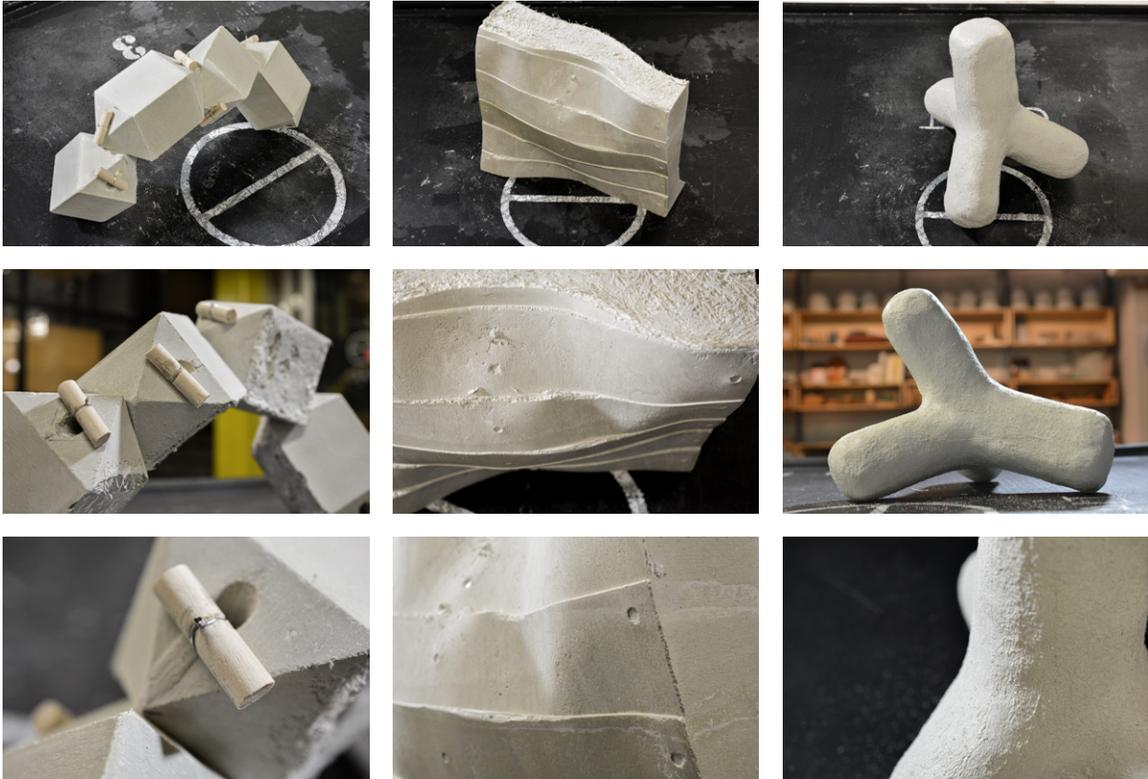


Figure 2.14 UHPC Object collections. Left to right: object 1, 2, and 3

There is a fine line to strike between time and effort invested in the *making* process and the resulting quality of the final product, both in terms of workmanship and resemblance to the intended idea i.e., the *design*. Speaking in strictly pragmatic terms, there is an optimal return on investment, where dwelling too long on an aspect may not produce any visible benefits in the work, while some seemingly insignificant decisions may become detrimental. For example, I did not need to sand all the plywood edges for the formworks since the machines left them in adequate condition. Conversely, the small additional nail I chose to put in the formwork of Object 2 sticks out like a sore thumb in the final product. These explorations resulted in a

lower threshold of quality than what I would normally consider acceptable, but it is important to understand that it was about the process and internalizing information *from* the material to inform processes later where I would want good quality workmanship to show.

I have learned that there is liberation in working within a framework, rather than working towards a prescribed design, but not to say prescribed designs do not have their advantages. It becomes easier to accept mistakes and variations working within a framework, in this case the crude departing sketch. In order to improve on the mistakes, they need to be *made* first, which may sound cliché but remains a reality for craftspeople. Only then the craftspeople can understand what other decisions could be made or changed to remedy them. This is the looping-forward process of thinking by making.



For example, there are many things I could improve on in the phase: the finish of the material at points where the UHPC is poured – the plastic shrinkage of the concrete leaves an undesirable surface quality. Using wood as a formwork for anything other than straight planes becomes difficult to control if the designer wants the most accurate representation of the idea. I could have capitalized on the mechanical properties of UHPC to explore ideas of *lightness*.

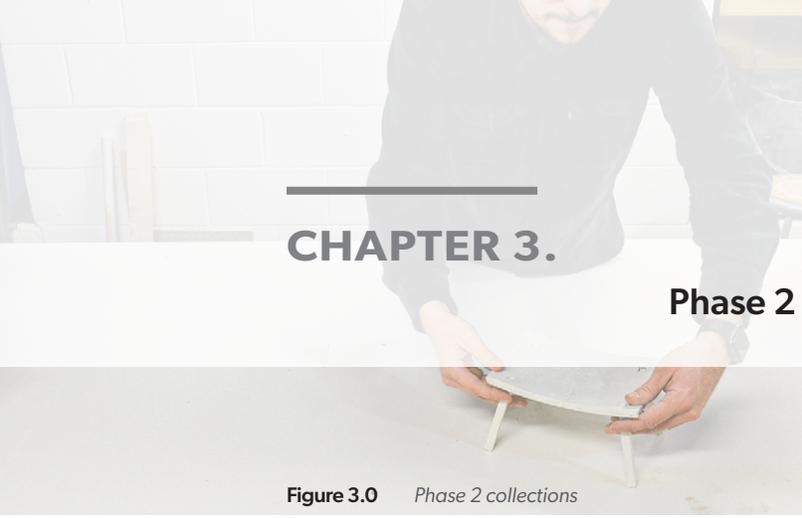
There are mistakes and variations, but there are also moments of failure, which is at the extreme end of the spectrum. This means that there is no product to show nor anything to potentially salvage. I had mentioned that mistakes and variations are instrumental in understanding what could have been done differently and failure is much the same, but additionally comes with feelings of frustration and then hopelessness that tends to cloud any clear judgement the craftsperson may have. Throughout this process I found failure to be a humbling occurrence once the clarity returns and I can critically assess the next steps. What failure means in terms of workmanship and to the process I engage in, is simply that at this juncture there is an insufficient understanding of the material and techniques for manipulating it. The only remedy is to learn more. Again, these kinds of failures are unpredictable and usually cannot be resolved through only drawing or thinking – but rather can only be addressed through making, again, without repeating the steps that brought the failure.

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## CHAPTER 3.

### Phase 2 – Hybrid Crafting

Figure 3.0 Phase 2 collections



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## 3.1.

### Material and Machine Experiments

It is imperative to conduct basic UHPC mixing explorations in order to determine the optimal ratios of raw material before moving into the making of the conceptual models. In other words, I need to continue to familiarize myself with the material and what its relationship is to the newly introduced technique of 3D printing. The general governing factors for 3D printing concrete are as follows:<sup>52</sup>

1. Workability. Traditionally known as *slump*. In the case of the CSALT printer, the mixture must be workable enough to manually load into the extrusion cartridges while simultaneously removing air pockets.
2. Extrudability. The ease with which the UHPC is deposited from the nozzle. If the mixture is too stiff, the extrusion motor fails to push it through the nozzle. If the mixture is too loose, then it does not satisfy the buildability requirement. Extrudability directly affects the surface finish of the printed part.
3. Open time. The mixture must not set within the cartridge before printing, nor during printing. While it must begin to set *immediately after* it has been deposited from the nozzle.
4. Buildability. The ability of the UHPC to develop enough initial strength to support subsequent layers above. As the printed part grows in height, the pressure exerted on the first printed layers compounds.

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52.

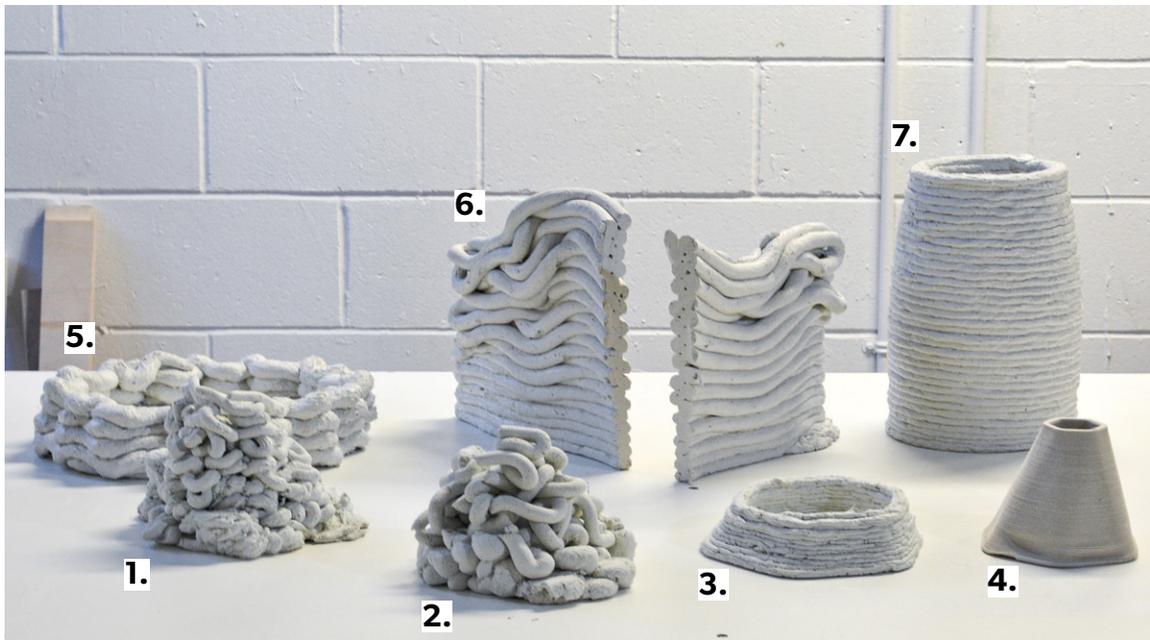
These general categories are as listed by Lediga and Kruger, "Optimizing Concrete Mix Design for Application in 3D Printing Technology for the Construction Industry," 4. The categories are common and used throughout literature involving 3D printing of concrete.

These factors have been encompassed in the word *rheology*,<sup>53</sup> which is the term used to remove any ambiguities around the general terms listed above. Rheology is empirical and is measured with precise instruments. For the scope of this thesis, the general terms as outlined above are sufficient.

53.

Tattersall and Banfill, *The Rheology of Fresh Concrete.*, 10. The definition is as follows: "the science of the deformation and flow of matter...it is concerned with relationships between stress, strain, rate of strain, and time."

The material used in this group of experiments is a prepackaged mix of white UHPC supplied by Spring Valley Corporation. The goal is to adjust the manufacturer's pre-determined mixing ratios to identify the optimal mix consistency which satisfy the rheological requirements above. After weighing the ingredients, it is assumed that the ratio between white portland cement (binder) and sand (aggregate) is 1 to 1. Due to the aggregate and binder being premixed, the only variable remaining is the wet ingredients, which is assumed to be a blend of water, high-range water reducers (superplasticizers), and a possible air-entraining admixture and/or accelerant. Since the binder is a white powder, it is safe to assume that granulated blast furnace slag is the supplementary cementitious material used because it is also white.



**Figure 3.1** Collection of 3D printed experiments. Summaries of each on following pages.

## Experiments 1 & 2

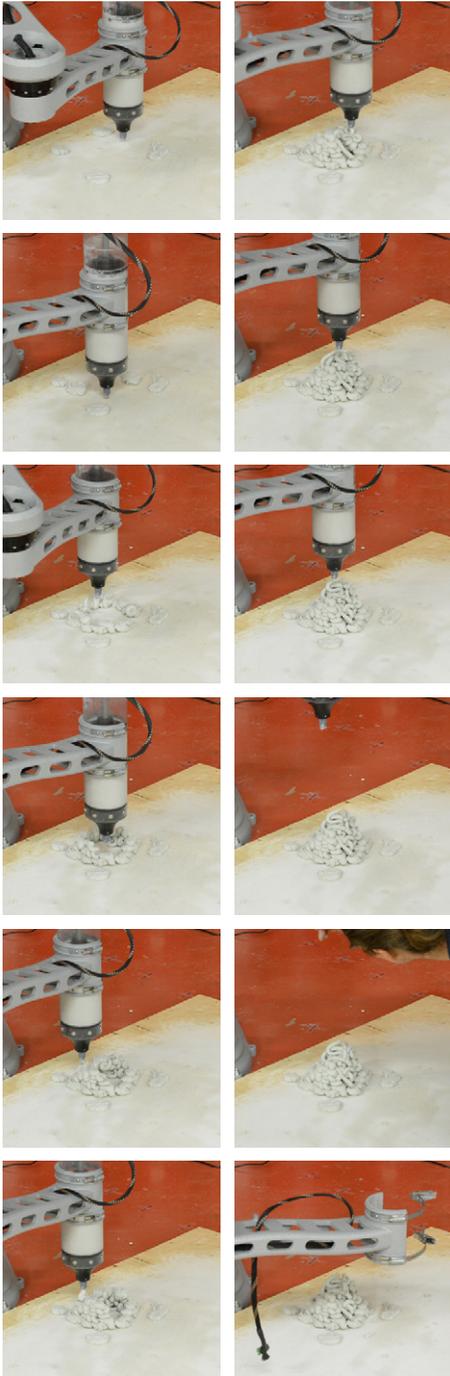


Figure 3.2 Time lapse of experiment 2

Table 3. Summary of Experiments 1 & 2

	Exp 1	Exp 2
<b>Mix Design</b>		
Dry Pre-mix	2.75 kg	2.75 kg
Wet Pre-mix	0.25 kg	0.325 kg
Fiber	-	0.010kg
Lime, NHL 3.5	-	-
Water	-	0.025 kg
<b>Machine</b>		
Nozzle Size	8mm	6mm
Layer Height	6mm	4mm
Print Speed	30mm/s	30mm/s

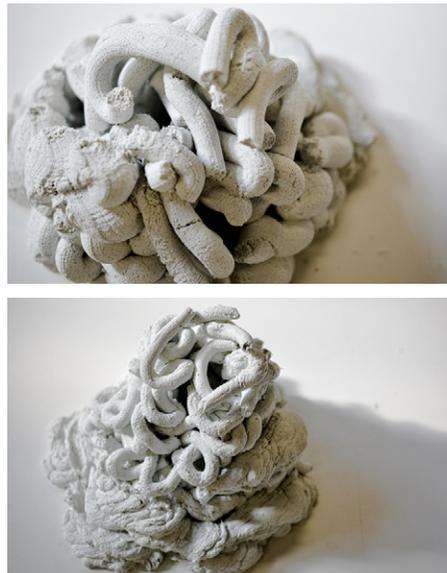
### Observations

Experiment 1: Extrusion not consistent, lack of plasticity. Potentially too stiff. Noticing significant drag in the cartridge and excess load on the motor.

Experiment 2: Inconsistent extrusion still an issue, despite more liquid in mix. Potentially too much friction inside of tube, to be remedied with a silicone lubricant.<sup>1</sup> Addition of Lime NHL 3.5 in future experiments will help create more paste, further reducing friction and increasing extrudability.

1. Use of silicone lubricant to reduce friction inside piston is noted in Chen et al., "The Effect of Viscosity-Modifying Admixture on the Extrudability of Limestone and Calcined Clay-Based Cementitious Material for Extrusion-Based 3D Concrete Printing."

Figure 3.3 Final photos of experiments 1 & 2



## Experiments 3 & 4

Figure 3.4 Time lapse of experiments 3 & 4



Table 4. Summary of Experiments 3 & 4

	Exp 3	Exp 4
<b>Mix Design</b>		
Dry Pre-mix	3.50 kg	-
Wet Pre-mix	0.455 kg	-
Fiber	0.010 kg	-
Lime, NHL 3.5	0.280 kg	-
Water	0.056 kg	-
<b>Machine</b>		
Nozzle Size	8mm	4mm
Layer Height	6mm	2mm
Print Speed	30mm/s	30mm/s

### Observations

Experiment 3: ideal workability, decent extrudability due to addition of lime. Promising buildability of layers. Fibers caused a blockage which in turn sheared the PLA nozzle. Recommend to increase nozzle size to reduce pressure in tube.

Experiment 4: printed in clay after experiment 3 as a sanity check. Ruling out possible motor failure after the clog occurred in experiment 3. Slight buckling in form suggests too drastic overhang in designed geometry.

Figure 3.5 Final photos of experiments 3 & 4

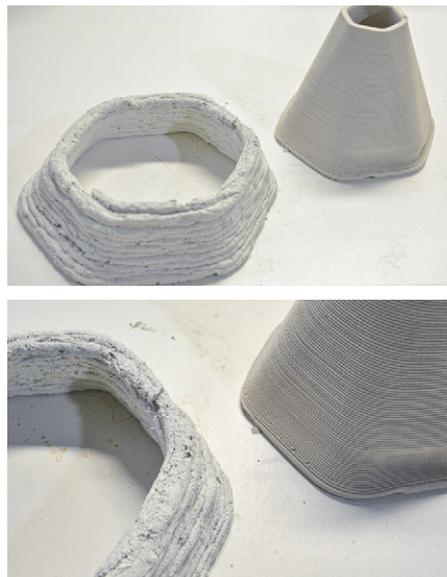
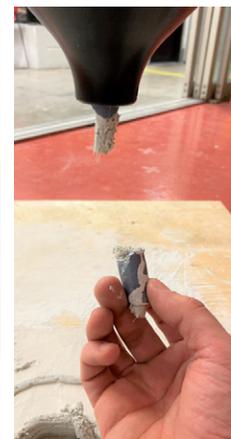


Figure 3.6 Sheared PLA nozzle



## Experiment 5



Figure 3.7 Time lapse of experiment 5

Table 5. Summary of Experiment 5

		Exp 5
<b>Mix Design</b>		
	Dry Pre-mix	5.00 kg
	Wet Pre-mix	0.650 kg
	Fiber	0.030 kg
	Lime, NHL 3.5	0.400 kg
	Water	0.085 kg
<b>Machine</b>		
	Nozzle Size <sup>1</sup>	15mm
	Layer Height <sup>2</sup>	16mm
	Print Speed	30mm/s
<b>Observations</b>		

The sharp edges of the geometry was a test to determine how the fibers affected surface quality of the printed part. It is determined that gradual changes in direction offer the best results in terms of surface quality as the fibers are less likely to protrude. Severe water bleeding in the mixture is noticed as the first layer slumps too much. Requires less water.

1. A custom milled PVC nozzle is used in this experiment. The extra length of the nozzle helps to create a better lubrication layer as the material is being deposited, resulting in a better surface quality and lessens the chances of filament tearing.
2. Layer height was incorrectly entered into the slicer software. The ideal ratio between nozzle size and layer height is determined to be in the range of 0.5-0.75.

Figure 3.8 Final photos of experiment 5



## Experiment 6



**Figure 3.9** Time lapse of experiment 6

**Table 6.** Summary of Experiment 6

		Exp 6
<b>Mix Design</b>		
	Dry Pre-mix	5.00 kg
	Wet Pre-mix	0.650 kg
	Fiber	0.020 kg
	Lime, NHL 3.5	0.400 kg
	Water	0.060 kg
<b>Machine</b>		
	Nozzle Size	15mm
	Layer Height	11.25 mm
	Print Speed	30mm/s

### Observations

Excellent extrudability. Layers began to compress under load suggesting the buildability of the mix was not yet optimal. The compression of layers results in a distance discrepancy as the part grows in height, as can be seen by the 'snaking' that occurs. Lowering layer height would decrease snaking as more extruded material is put into contact with the last deposited layer. Potential to experiment with retraction as the print nozzle moves upwards in Z direction. Retraction would be unnecessary if the object is printed in one continuous path, negating start and stop points. Less water bleeding occurring.



**Figure 3.10** Experiment 6 detail showing surface quality



**Figure 3.11** Informal strength test, 160 pounds loading.



**Figure 3.12** Cut object to assess layer adhesion

## Experiment 7

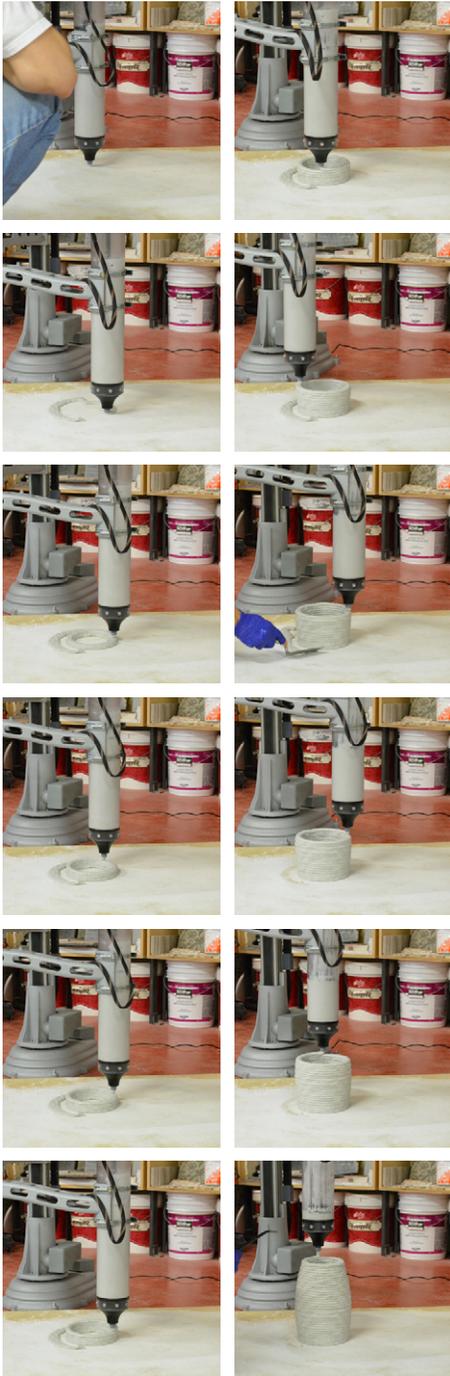


Figure 3.13 Time lapse of experiment 7

Table 7. Summary of Experiment 7

		Exp 7
<b>Mix Design</b>		
	Dry Pre-mix	5.00 kg
	Wet Pre-mix	0.650 kg
	Fiber	0.030 kg
	Lime, NHL 3.5	0.400 kg
	Water	0.050 kg
<b>Machine</b>		
	Nozzle Size <sup>1</sup>	~12.5 mm
	Layer Height	7 mm
	Print Speed	30mm/s
<b>Observations</b>		

Excellent extrudability and buildability to the mix. Still experiencing slight water bleeding in the first set of printed layers, this results in stiff material deposition at the top of the part. A potential remedy to this will be explored in Chapter 4. Pleased with surface quality, albeit slightly irregular due to the self-leveling nature of the mix and the short nozzle.

1. The nozzle size is given as a rough number. The nozzle was manually cut from a smaller nozzle, as the filament diameter of the 15mm nozzle was proportionally too large to the part being printed.

Figure 3.14 Final photos of experiment 7

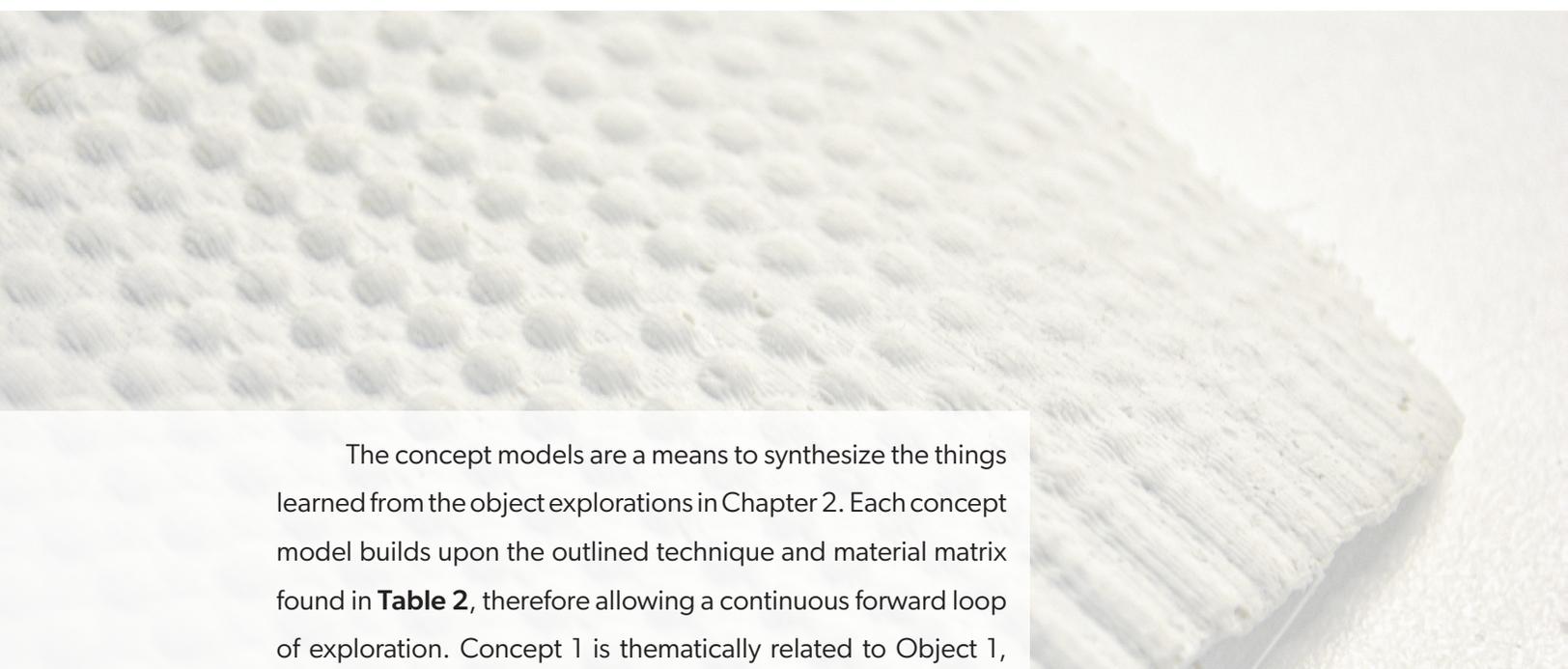




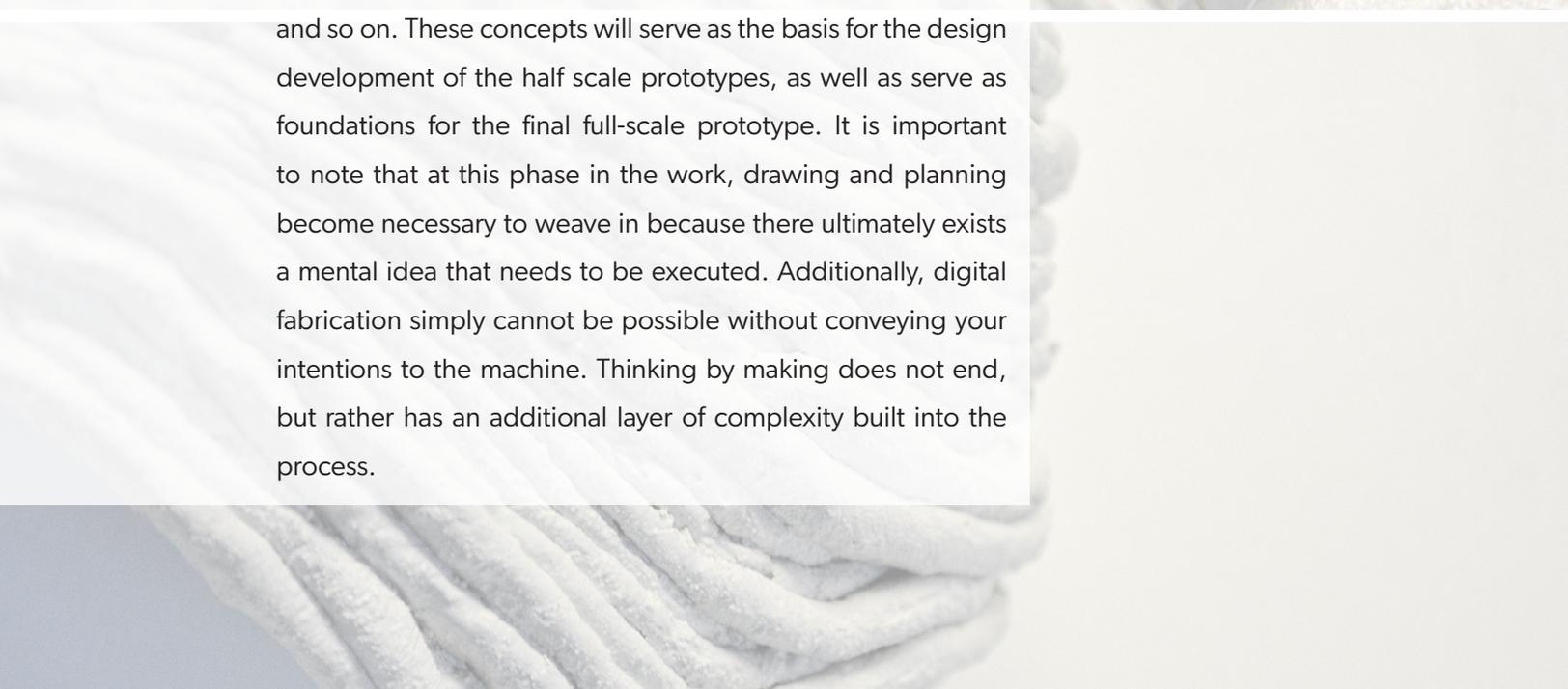
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## 3.2.

### Conceptual Models – Material and Technique Synthesis



The concept models are a means to synthesize the things learned from the object explorations in Chapter 2. Each concept model builds upon the outlined technique and material matrix found in **Table 2**, therefore allowing a continuous forward loop of exploration. Concept 1 is thematically related to Object 1, and so on. These concepts will serve as the basis for the design development of the half scale prototypes, as well as serve as foundations for the final full-scale prototype. It is important to note that at this phase in the work, drawing and planning become necessary to weave in because there ultimately exists a mental idea that needs to be executed. Additionally, digital fabrication simply cannot be possible without conveying your intentions to the machine. Thinking by making does not end, but rather has an additional layer of complexity built into the process.



### 3.2.1.

#### Concept 1

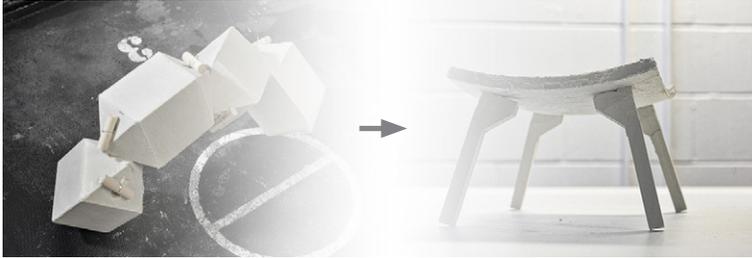


Figure 3.15 Parent-child relationship between Object 1 & Concept 1



Figure 3.16 Assembly of Concept 1

Concept 1 folds in the previously explored technique of *assembly*. There are five individually cast components that make up the conceptual 'seat' and 'legs' of this concept model. The assembly of the seat and legs looks to address the issues of *lightness* that were previously not explored adequately. The gentle curvature of the seat is deliberate as if to conform to the human body, while the legs were conceptualized to be complementary to the seat as thin, indiscrete elements that rely on bearing to transfer loads from the seat. The thinness of these elements is possible because of the mechanical properties of UHPC as a material, as was shown in Experiment 6. Bearing as a type of connection is used to simplify and rationalize the previous issues experienced when trying to connect cast elements together.

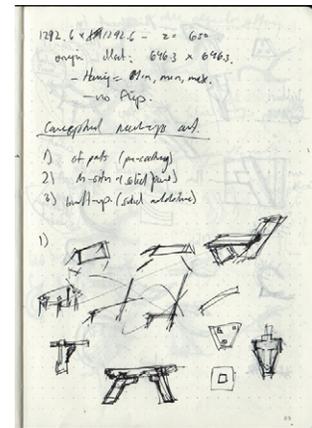
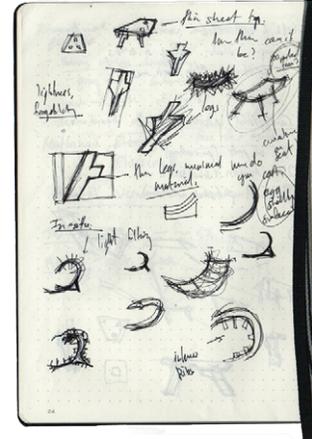
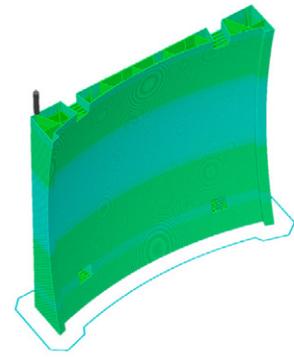
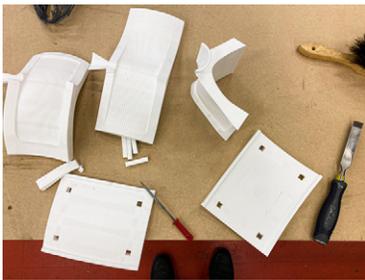


Figure 3.17 Concept 1 sketches

The formwork for the legs is manually cut out of plywood while the egg-shell seat formwork is 3D printed with PLA plastic. The use of these making techniques is determined by economies of effort, time and the *risk* involved in the making process. Essentially, trying to create a delicately curved formwork that is accurate to the intended design using traditional making techniques would be time consuming and difficult to approximate, regardless of material selection or technical skill (but not impossible of course). On the other hand, the legs are far quicker to measure, cut, and assemble with traditional techniques than could be 3D printed. There is an appropriate time and place for each tool to be used.



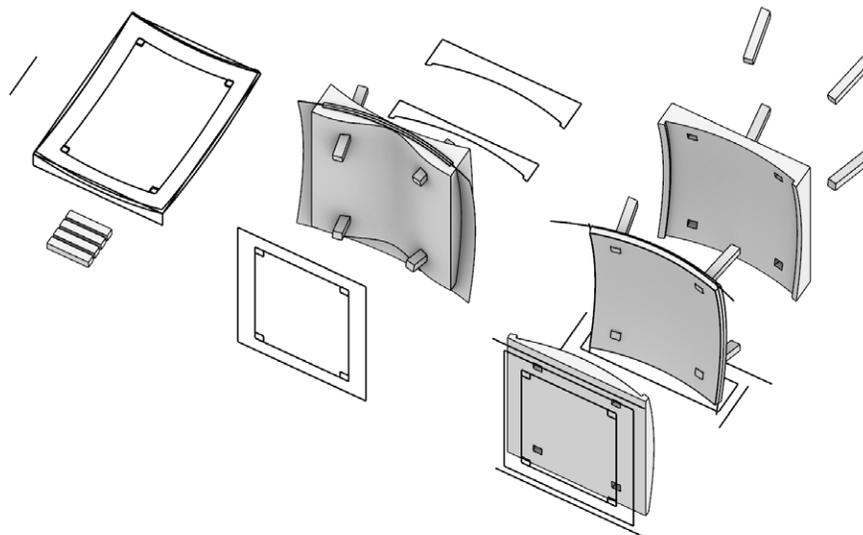
**Figure 3.18** Simplify3D slicer preview of how the printer will span over the designed openings. The form is printed as a single outline with a minimal amount of infill to reduce material usage, but remain rigid to hold the UHPC



**Figure 3.19** Cleaning up surface defects from the 3D printing process

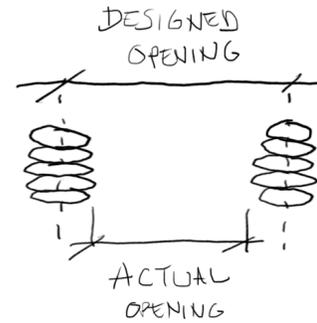


**Figure 3.20** Complete formworks for Concept 1



**Figure 3.21** Digitally planning the formwork for the seat, as well as establishing the size of the openings that receive the legs

Issues of tolerance, fragility and scale of material are found in this exploration. The connection between seat and leg is not at first realized due to the crossing of digital and analogue methods of making. For example, the thing made by hand results in slightly larger legs, while the diameter of the 3D printed filament results in openings that are slightly too small (**Figure 3.22**). In the spirit of improvisation and another indication of the hybrid nature of making, the legs are then (crudely) ground down with a hand-held angle grinder to an approximate size that would fit. Naturally, the vibration from grinding and the thinness of the legs exacerbates the fragility of the UHPC. Fragility is also an issue during the unmoulding of the parts. The 3D printed PLA formwork has a ribbed texture that is a by-product of the layer printing process, which the UHPC latches onto with considerable strength. Unmoulding the form results in the part cracking in two places but is luckily held in place by the embedded fibres. Fragility in this case is thought to be a result of the inability of the UHPC to scale down passed a certain threshold. Despite UHPC having strong mechanical properties, the 8mm thick seat and legs simply do not have *enough* material to effectively make use of those properties.



**Figure 3.22** Planned versus actual opening in 3D printed parts



**Figure 3.23** Ribbed texture in final cast and resultant seam. Note the burn marks from the grinder on the leg



**Figure 3.24** Seat detail highlighting cracks & join conditions



**Figure 3.25** Concept model 1, assembled

### 3.2.2.

#### Concept 2

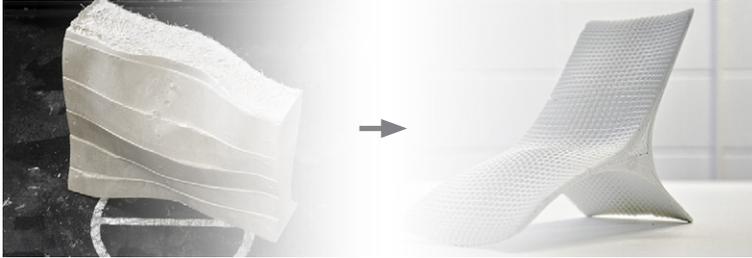


Figure 3.26 Parent-child relationship between Object 2 & Concept 2

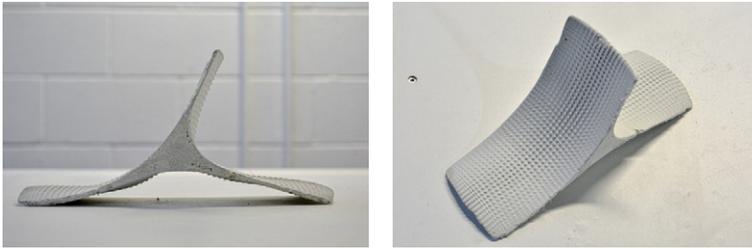


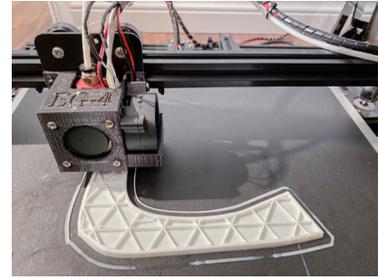
Figure 3.27 Photos of Concept model 2



Figure 3.28 Concept 2 sketches

The second concept model concerns itself with the question of casting complex surfaces and volumes. The intention with this concept model is to experiment with elements of texture that increase the haptic experience with the conceptual chair. The ability of UHPC to capture such fine surface texture in the formwork was observed in Object 2 in the previous chapter, and therefore is considered as an avenue for exploration. For this reason, the texture of the chair is designed as a studded gradient across the seat, to determine what the fall-off of resolution is. In addition to texture, the formal gestures of this conceptual chair imply a variety of uses depending on orientation. After briefly sketching the idea, the digital model is sculpted using the SubD tools in Rhinoceros® which allows for a single, smooth, curvature continuous geometry that is not interrupted at any point.

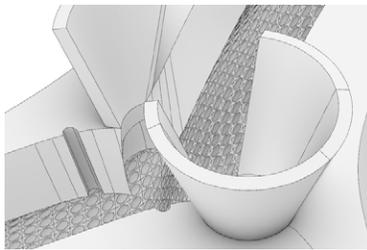
The making of this concept model turns to 3D printing with PLA plastic because the complexity of form would be impossible to realize via analogue methods, particularly at this small scale. To successfully un mould the part with minimal disturbance, the formwork is rationalized as a three-part mould, cut along the edges to minimize contact area between UHPC and formwork. Resolving the issue of casting a single, curvature continuous surface is paramount. It was previously observed in Object 1 and 2 that the point where the UHPC is poured from results in an unappealing surface due to shrinkage. To overcome this issue, the formwork is printed with a raised funnel opening and a couple of vent holes, which allows the UHPC to fill the top curved edge of the formwork. After unmoulding the object, the extra bit of concrete is simply ground off with an angle grinder. A fully 3D printed part still relies on moments of analogue intervention, as the formworks must also be manually filed and sanded to ensure a proper seal.



**Figure 3.29** *Printing of PLA formwork*



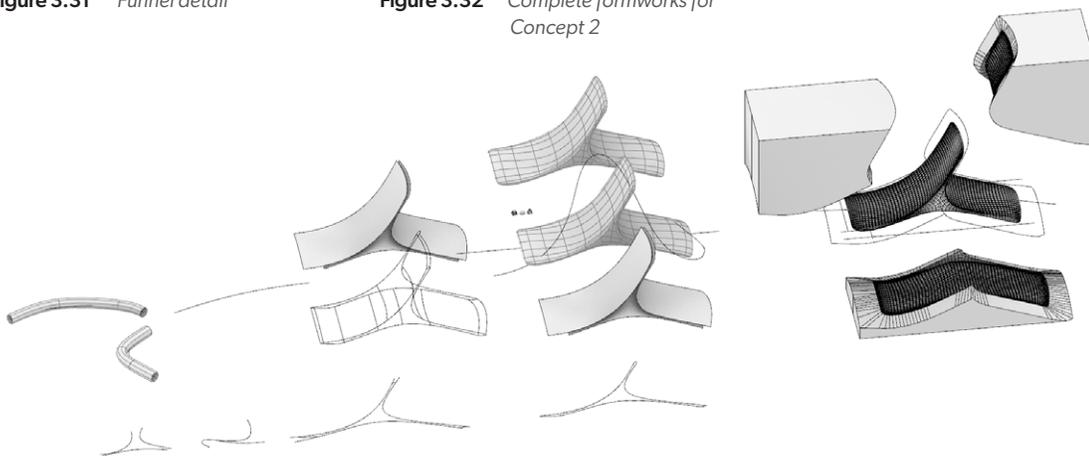
**Figure 3.30** *Filing edges of formworks for proper fitment*



**Figure 3.31** *Funnel detail*

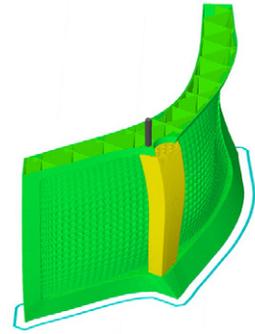


**Figure 3.32** *Complete formworks for Concept 2*

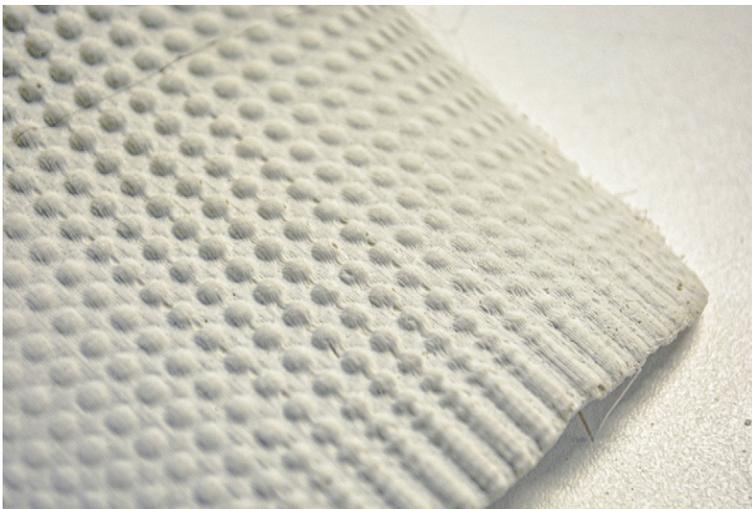


**Figure 3.33** *Digital iterations of Concept 2, and extracting the negative for formwork*

Issues of fragility and scale of material arise once again. Like the egg-shell seat of the previous concept model, the UHPC adheres to the formwork and makes for difficult unmoulding – the imbedded texture most likely being the culprit as it increases surface area. Two substantial cracks in the part occurred during unmoulding which could have been avoided had it been designed with more thickness in the material – another example of the UHPC being unable to preform optimally when scaled down. Nevertheless, this process helps to identify the limits of thinness in material.



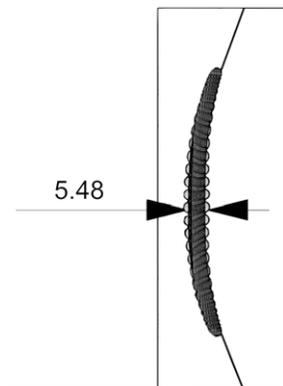
**Figure 3.34** Slicer preview, with custom support structure to enable the printing of overhang



**Figure 3.35** Fracture during unmoulding



**Figure 3.37** Photos of Concept 2



**Figure 3.36** Section through thin portion of formwork

### 3.2.3.

### Concept 3

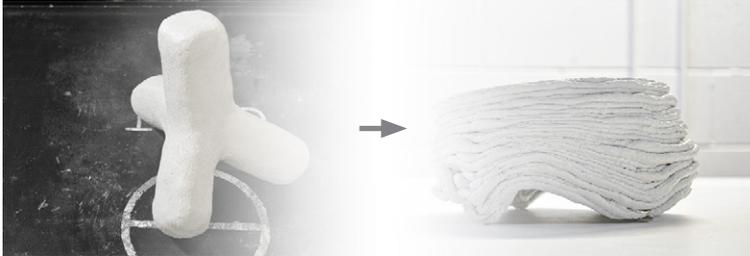


Figure 3.38 Parent-child relationship between Object 3 & Concept 3



Figure 3.39 Photo of Concept 3

The final conceptual exploration continues the idea of “building up” that was explored in Object 3. Instead of being built up manually, this conceptual model is 3D printed in its entirety. The intention of this concept model is for the “legs” of the chair to be *grown* out of the seat when printed up-side down. From what was observed in the previous experiments in Chapter 3.1, it is imperative to accomplish this using a single continuous helical tool path, without interruption. Interrupting the flow of material causes excessive build up of UHPC where it is not wanted in the print because of the residual pressure in the cartridge.

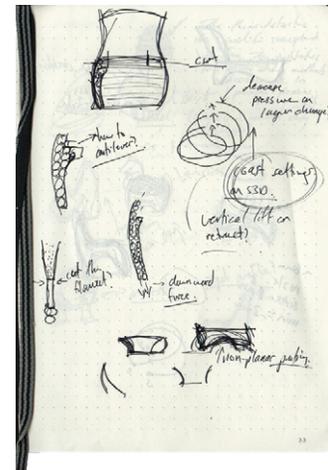
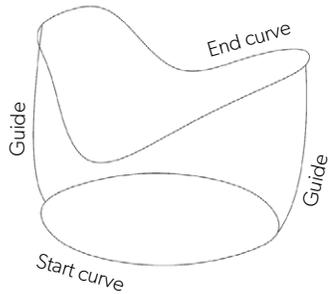
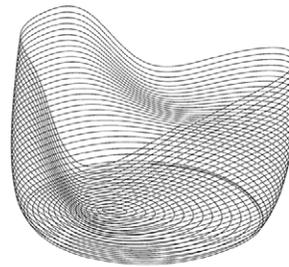


Figure 3.40 Sketches of Concept 3

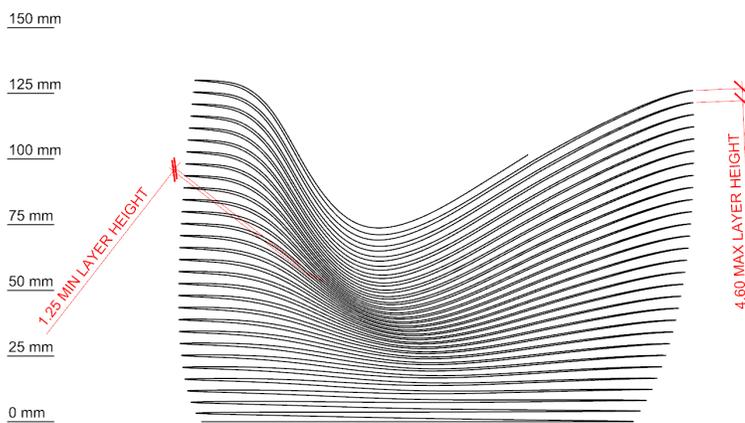
The solution to a single continuous helical tool path that allows for non-planar growth is in using the Grasshopper® plugin to generate a custom toolpath that can be sent to the 3D printer for interpretation. What is of interest in this exploration is the question of designing a toolpath and not the object directly. This means that the designer needs to design and predict the movements of the robot. Where the starts and ends of toolpath lines are, as well as the order they are drawn in, and the locations of any seams, become important factors that cannot be ignored when designing custom toolpaths.



**Figure 3.41** Geometry framework



**Figure 3.42** Resulting continuous, non-planar helix

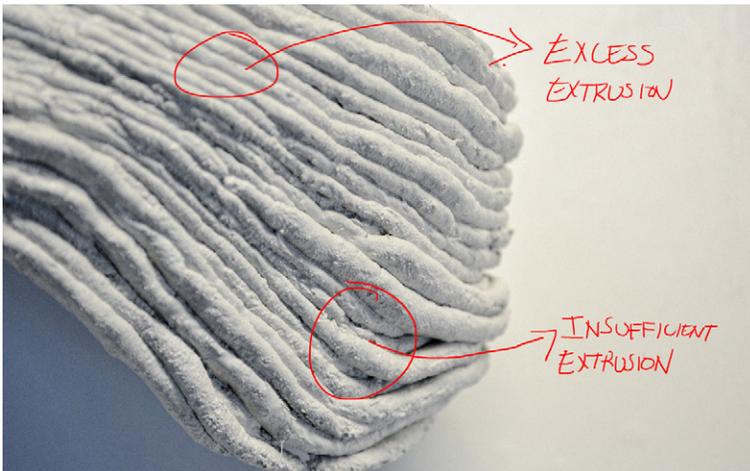


**Figure 3.43** Designed min and max layer heights, as a function of nozzle size. The max layer height cannot exceed 75% of the nozzle size.



**Figure 3.44** 3D printing timelapse

Further issues are encountered during the printing of this concept model. Unlike the previous two, fragility is not one because there is no unmoulding process which disturbs the UHPC. Instead, the issues here are centered around questions of optimization in mix design, layer height (the change in layer height), nozzle size, and geometry curvature. The presented concept model is only the second iteration, which is better in quality from the first. But it is evident there is still much optimization to be made. It is difficult to determine the culprit because it can be any permutation of the factors listed above. Further experiments and explorations will be conducted in the following chapter to seek the optimal combination of values.



**Figure 3.45** Detail of printed layers highlighting issues with extrusion rates of material

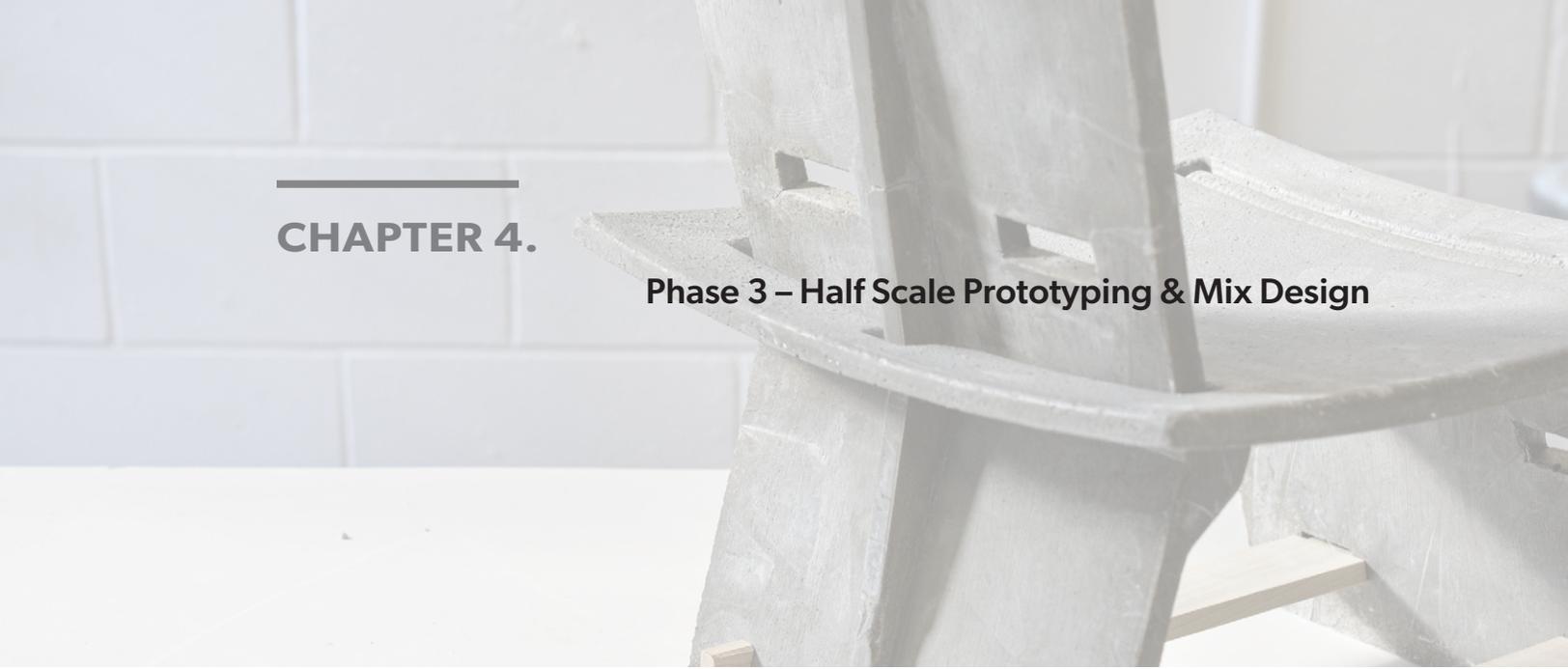


**Figure 3.46** Interior detail highlighting incorrect start/end point orientations

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**CHAPTER 4.**

**Phase 3 – Half Scale Prototyping & Mix Design**



**Figure 4.0** *Completed half scale prototypes*

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## 4.1.

### Overview

The third phase of this thesis moves towards more precise designs that relate to the human form via the making of half-scale prototypes. These processes will clarify the direction that is to be taken for the manufacture of the final chair. The lessons learned from the making processes of Chapter 2 and 3 are in some form or another encompassed in this phase as each design has its root in the earlier explorations. Like the previous chapter, Object 1 is thematically related to Concept 1 which is related to Prototype 1, and so on. As the work grows, the learned experience of the material and of appropriate techniques trickles upwards and will ultimately culminate in the last chapter.

Working at a half-scale when prototyping a chair has its advantages and disadvantages. The primary issue in this phase is grasping ergonomics, as the half-scale does not directly translate to how the full-scale would feel when sitting. But it does start to provide clues about *how* the making processes *could* be approached, as the half-scale is of an adequate size that similar<sup>54</sup> techniques and materials can be applicable to the manufacture of the full-scale chair. The issue of scale in material persists nevertheless, as it is difficult to predict if the UHPC will be structurally successful at the full scale when relying on observations from the half-scale.

An in-house UHPC mix design that does not rely on proprietary recipes is also found in this chapter (**Table 8**). With raw materials supplied to the CSALT lab by Sika Canada, Merkley Supply, and Poraver North America, this chapter experiments with various permutations of recipes to arrive at a successful UHPC mix that is compatible with the lab's 3D printer.

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54.

"Similar" but not directly applicable. It would be naïve to say, for example, that the exact same formwork design simply scaled up could be used to contain double the amount of UHPC. It inherently requires reconsideration.

## 4.1.1.

### Prototype 1 – Assembly



Figure 4.1 *Genealogy, Object 1 to Concept 1 to Prototype*

This prototype follows Concept 1, which explores ideas of assembling pre-cast elements. To briefly address the design, as a point of departure, the chair is loosely modelled on the proportions of the Emeco Navy Chair (Figure 4.2). The seat height is lowered slightly because of the way the connections were beginning to reveal themselves through the design process. Lowering the center of gravity puts less strain on the wedged mortise & tenon joints and is more pleasing proportionally – reminiscent of traditional Japanese chairs.

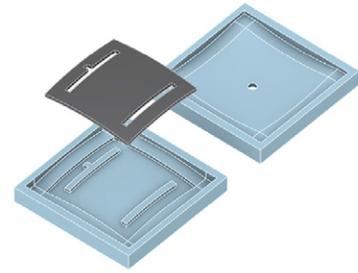
Learning from Concept 1, which had several shortcomings in the design of the legs, namely lateral stability, Prototype 1 resolves the issues by consolidating the four legs into two and incorporating the backrest into the hind leg. The two legs are then joined together with cross bars which resolves issues of lateral stability. The connection between the seat and legs is still a simple bearing type, but with tolerances considered more carefully and more surface area provided for load transfer. The design process of this prototype embodies everything learned of form making and casting from the previous explorations. The geometry of each element is carefully considered in relation to how the formwork is built, to ensure that they can be successfully cast without the risk of failure during un moulding or usage.



Figure 4.2 *Influence and result*



Conversely, the egg-shell seat and the curved portions of the legs still contain far too much risk in making if pursued via traditional methods. At the half scale, the subtlety in the double curvature of the seat is amplified. This combined with the presence of high-tolerance connection points, requires the precision of the CNC mill to manufacture as close as possible to the design intention. The cross bars and wedges are cut out of wood because of the issue of material scale had they been cast in UHPC. The concern is not if the UHPC could perform in tension, but rather that the overt thinness of the UHPC at the half-scale would bring issues of fragility which were previously observed in the other casting explorations. I am confident that the cross bar would function appropriately if cast in UHPC at full-scale.



**Figure 4.6** CNC profiles for seat formwork



**Figure 4.7** Before and after formwork preparation. Painted with high-gloss latex paint and sprayed with PTFE mould release



**Figure 4.8** CNC milling seat formwork

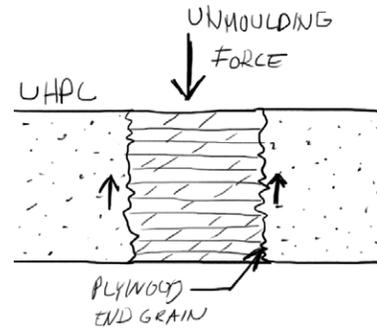


**Figure 4.9** Embedding fiberglass mesh into bottom face of seat for additional reinforcement



**Figure 4.10** Seat casting process

The un moulding of the parts is far more successful in this prototype than what was experienced in Concept 1, because the proper procedures were put in place to remedy the issues experienced before. Again, it would not have been possible to predict those issues before simply through drawing; the making of Object 1 and Concept 1 had to take place in order to think through the problems. This is not to say that it was a flawless process as there are still a couple technical issues that need further thinking through. Namely the trapped air bubbles in the cast seat, and the difficult removal of the plywood within cast openings of the legs. It is observed that the end grain of the plywood, even when painted over and sprayed with form release, still has rough texture that makes in-plane removal virtually impossible without damage (**Figure 4.11**).



**Figure 4.11** Diagram of un moulding parts with exposed plywood end grain



**Figure 4.12** Back side of cast seat, with air bubbles that could not escape



**Figure 4.14** Un moulding seat



**Figure 4.13** Un moulding hind leg







## 4.1.2.

### Prototype 2 – Casting



Figure 4.15 *Genealogy, Object 2 to Concept 2 to Prototype 2*

Prototype 2 addresses the technique of casting complex surfaces, following the previous explorations. The design is effectively a development of Concept 2, as the concept has many interesting traits that I wanted to continue exploring. The aspect of this prototype which the concept did not address appropriately is the location of the seat. The seat is therefore raised off the ground and sculpted further in relation to the human body. The various types of uses are still incorporated in the design – the chair, the podium, and the leaning position. After the appropriate profile was found, a series of contours that relate to the human form are drawn which define the final surfaces of the chair.

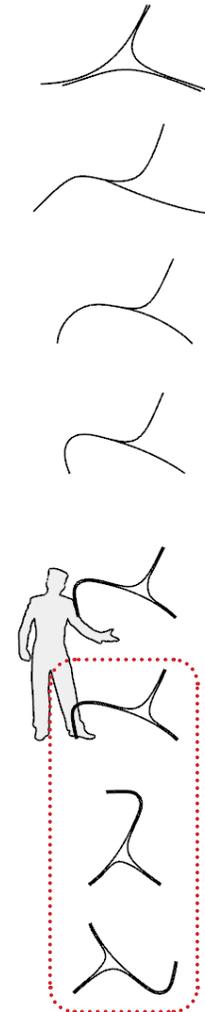
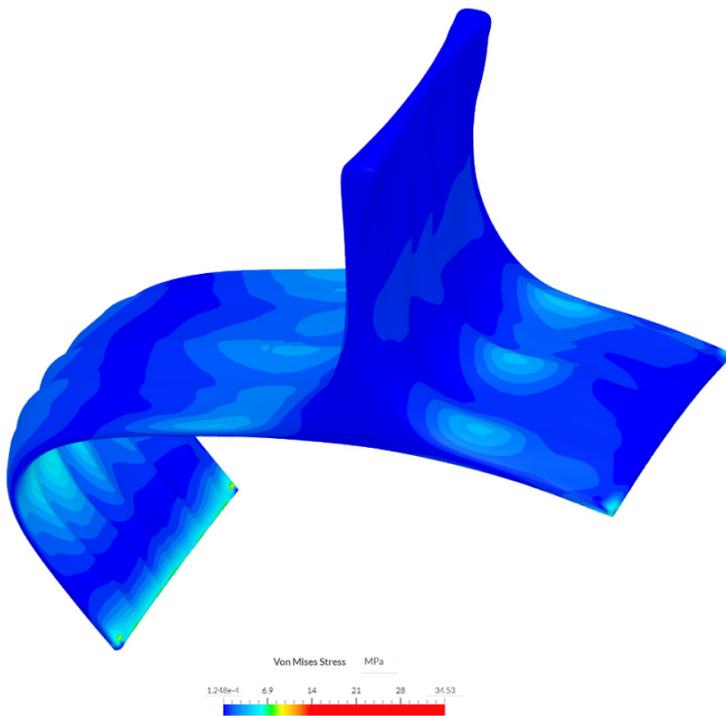


Figure 4.16 *Prototype development*

The formwork is 3D printed with clay because the complexities inherent in the geometry would be incredibly difficult to approximate otherwise; the size of the prototype also lends itself well to using the large-format 3D printer. The clay is unable to produce fine, high-resolution surface texture like the PLA printer when the thickness of extrusion required for adequate strength is estimated around 5mm. For this reason, the surface texture imbedded in the chair is a gradual wave pattern, with very few sharp changes in the Z-direction to avoid drastic overhangs and unsupported extrusions.

Finite element analysis is also conducted on the proposed design to determine if the thinness of the design at full-scale is possible, and to see how the ribbed surface texture affects the strength. It is shown in **Figure 4.18** that the UHPC, when loaded with 3000N (approximately 300kg) of force on the seat, does not come near to exceeding its approximate 150MPa of compressive strength.<sup>55</sup> The areas that fall under tension are also below the tensile limit of around 15MPa.<sup>56</sup>



**Figure 4.18** Finite element analysis conducted in SimScale



**Figure 4.17** Surface generation

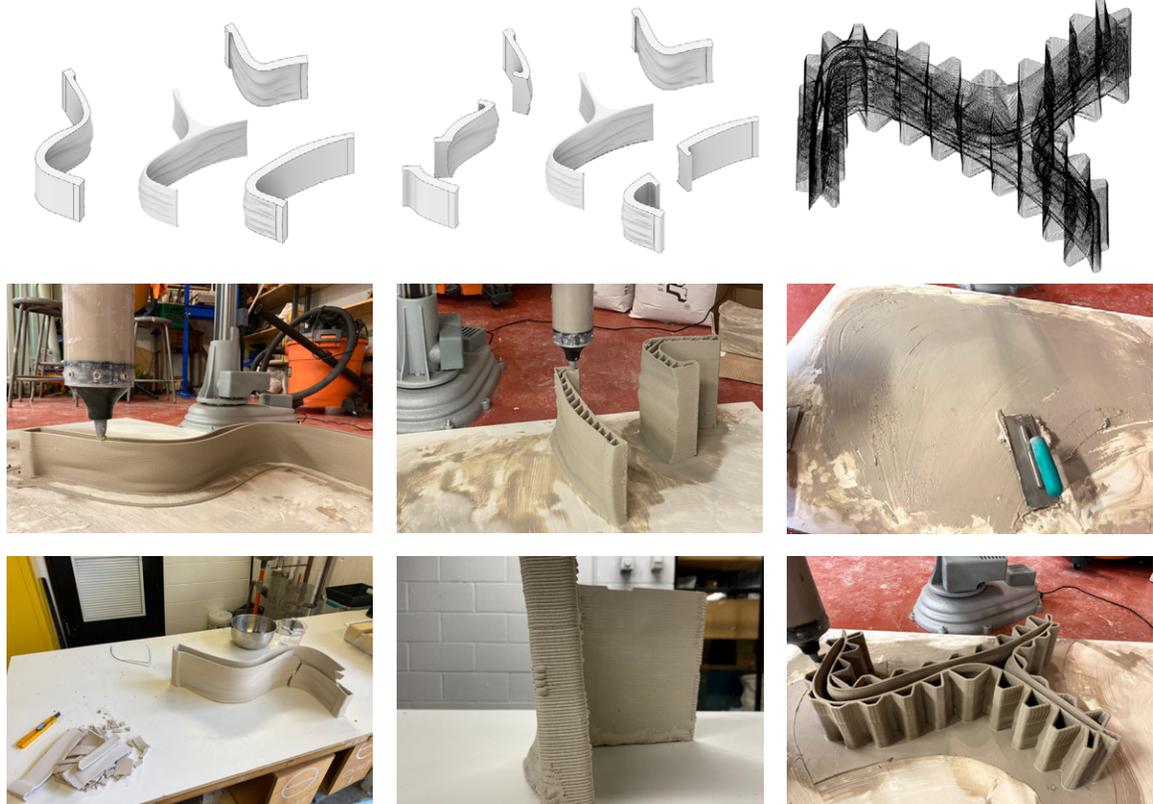
55. Kosmatka, Kerkhoff, and Panarese, *Design and Control of Concrete Mixtures*, 301. 150MPa is an approximate value, at 91 days. Actual compressive strengths can range from 70 – 150MPa based on the design of the mix.

56. Kusumawardaningsih et al., "Tensile Strength Behavior of UHPC and UHPFRC," 1082.

The design and fabrication of the formwork requires multiple iterations because of the introduction of clay as a new material that requires its own level of understanding. The initial print was conceived as a three-part formwork, like the method used in Concept 2. This resulted in a fragile formwork that broke during handling because of the large unsupported surface area. The second iteration then splits the formwork into smaller parts, with additional internal infill for rigidity. This method is ineffective as well, because the forms warp unpredictably as the clay dries and thus cannot be assembled as intended. Additionally, the amount of clay required to print in this manner begins to feel wasteful. The third iteration then addresses the issues of fragility and warping by printing the formwork as a continuous loop with integrated corrugation for rigidity. The clay in this iteration is not allowed to dry, as it is kept moist and covered to prevent warping.



**Figure 4.19** *Manually wedging clay to homogenize consistency and remove air pockets*



**Figure 4.20** *Formwork attempt 1*

**Figure 4.21** *Formwork attempt 2*

**Figure 4.22** *Formwork attempt 3*

Clay as formwork has many advantages, albeit this iteration still needs to address certain technical shortcomings that distract from the advantages. The raw clay can easily be peeled off the cast UHPC once it has dried and can be recycled back into useable clay for further printing. For reasons that are unclear at the moment, the UHPC does not adhere to the clay which allows for this to happen. Evidently there is further research required to determine what the optimal layer height is and what the optimal design of external support structure should be to prevent blow-outs during casting as is pictured in **Figure 4.25**. The chair ultimately is thicker in cross section compared to the design intention because of the static pressure pushing the formwork outwards.



**Figure 4.23** *Peeling clay off formwork*



**Figure 4.25** *UHPC blow-out potentially due to poor layer adhesion in the clay. Potentials for exterior support structure to be redesigned.*



**Figure 4.24** *Peeling clay off formwork*







### 4.1.3.

### Prototype 3 – Printing



Figure 4.26 Genealogy, Object 3 to Concept 3 to Prototype 3

The third prototype continues to explore methods of 3D printing UHPC and builds upon what was learned from Concept 3. The method of 3D printing in a non-planar fashion was put aside as it was becoming clear that it would not allow for the printing of a true chair, inclusive of a back rest, which I consider to be the de-facto definition of a chair. As the design process progressed, it seemed that the non-planar method best lent itself to printing stools or tables, and I felt that was not in line with the work in this thesis up to this point.

For this reason, the chair is instead conceived as a 2D profile that is extruded in the Z-direction – a common typology that was observed with the 3D printed case studies earlier. With a general understanding of the types of curvatures best suited for 3D printing based on the earlier experiments, a short design charette is conducted to find the most pleasing profile. The chair is then sculpted to the human form slightly and an internal loop is added to help distribute load to the ground and to remove tensile stress from the backrest.

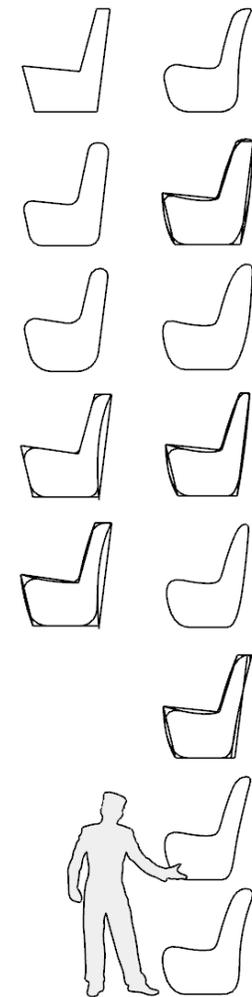
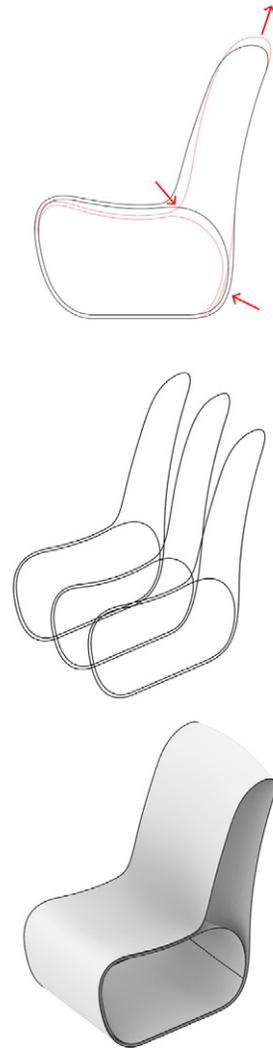


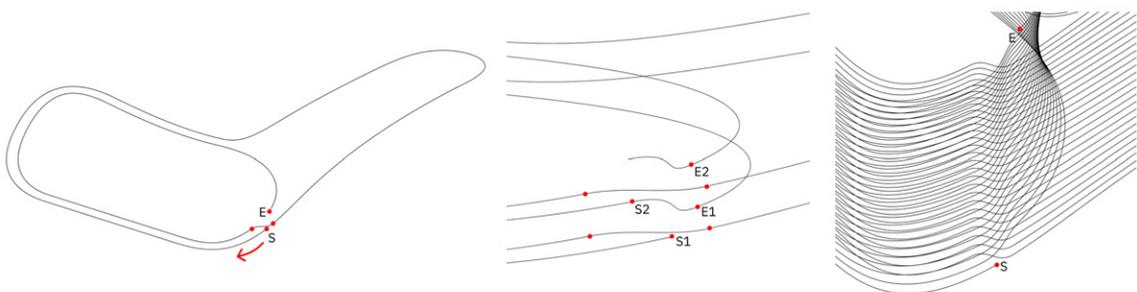
Figure 4.27 Prototype development

The internal loop adds a layer of complexity to the prototype, so it does not become a banal extrusion. The rationalization of the interior loop requires the consideration of start points and end points to each curve and how the print head will transition from one to the other, and then again in the Z-direction in a weaving motion. This is known as the *seam* of the print (**Figure 4.29**), and it is deliberately placed on the back of the chair so that it is simultaneously expressive and non-intrusive to the haptic experience.

It is important to address the issue of curvature when 3D printing with UHPC. Not unlike clay, UHPC has considerable weight, therefore there is a limit to the level of curvature the geometry can have before the print begins to buckle or topple over. This issue is particularly exacerbated when working with UHPC because it exhibits a tendency to ‘roll’ off once deposited from the nozzle – unlike clay, which does a good job at sticking to the layer below. For this reason, the amount of sculpting done to the seat is restrained to ensure a gentle curvature, which can then be assessed after fabrication to determine if the limit can be pushed further.



**Figure 4.28** Continued prototype development



**Figure 4.29** Toolpath seam rationalization and design

The fabrication of this prototype is done with a different batch of UHPC than previous, which was also supplied by Spring Valley Corporation. However, in this batch, the individual components to the UHPC are individually packaged which allows for greater flexibility in tailoring the mix. The new material, as well as the acquisition of additives from Sika Canada, prompted a whole new round of material experiments to find the optimal mix design for 3D printing on the lab's machine. The results of these experiments are summarized at the end of this chapter in **Table 8**.



**Figure 4.30** Print iterations. From top to bottom: Mix 2, Mix 3, and Mix 12. Mix designs found in Table 8.

Once an adequate mix is found, there are still a few issues that need to be addressed prior to moving to the final prototype. There is one of layer adhesion at the plane where the print is stopped to reload the cartridge. As is shown in **Figure 4.32**, this plane is precisely where the UHPC toppled over because it had not adhered correctly. There is then the subsidiary issue of priming the nozzle correctly before the print starts again to ensure material is flowing, shown in **Figure 4.33**. There is also room to improve the quality of the surface by varying some of the ingredients. It is of interest to also experiment with weaving patterns (**Figure 4.31**) across the entire surface of the print, which can have both more tactile and visual interest as well as providing extra rigidity during the print and in the final cured product.



**Figure 4.31** Weaving pattern test in clay

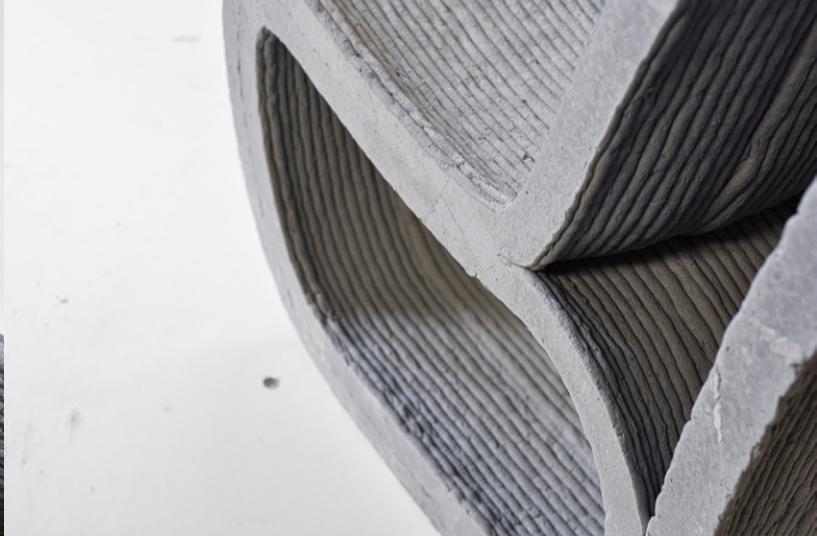


**Figure 4.32** Insufficient layer adhesion at plane where cartridge must be reloaded



**Figure 4.33** Nozzle incorrectly primed, missed an entire layer







—  
4.2.

**Mix Design & Experimentation**



**Table 8. Summary of Mix Experiments**

Ingredients	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12
Portland Cement	3.17kg	3.17kg	3.32kg	2.70kg	2.70kg	2.70kg	2.70kg					
White Portland Cement								2.40kg	3.18kg	2.46kg	2.46kg	2.46kg
Metakaolin	0.33kg	0.33kg		0.30kg	0.30kg							
Silica Fume								0.30kg	0.30kg	0.24kg	0.24kg	0.24kg
Lime, NHL 3.5		0.33kg	0.33kg			0.30kg						
Silica Sand	3.32kg	3.32kg	0.99kg						1.80kg		3.00kg	3.00kg
Expanded Glass, 0.1-0.4 mm				0.037kg	0.069kg	0.074kg	0.074kg	0.074kg				
Expanded Glass, 0.25-0.5 mm				0.051kg	0.101kg	0.068kg	0.068kg	0.068kg				
Expanded Glass, 0.5-1 mm	0.65kg		0.40kg	0.202kg	0.252kg	0.162kg	0.162kg	0.162kg	0.202kg	0.270kg		
High Range Water Reducer	209g	209g	209g					25g	82g	50g	60g	100g
Accelerant	44g	44g	44g						18g			
Viscosity Modifying Admixture								15g	15g	25g	35g	40g
Combined Wet Ingredients				0.802kg	0.850kg	0.750kg	0.800kg					
Water	0.726kg	0.594kg	0.514kg					0.799kg	0.705kg	0.775kg	0.755kg	0.650kg
Fiber	63g	63g	63g	30g	15g	15g	15g	15g	20g			20g
Water/Binder Ratio	0.267	0.238	0.198	0.267	0.283	0.25	0.267	0.274	0.208	0.275	0.282	0.250
Result	Fail	Pass										

Group of experiments conducted with batched UHPC from Spring Valley Corp. used in Chapter 3.

Group of experiments conducted with pre-mixed wet ingredients from Chapter 2, in an attempt to determine what was causing the previous failed mixes

Group of experiments conducted using admixtures supplied by Sika Canada.

# CHAPTER 5.

## Phase 4 – Final Prototype

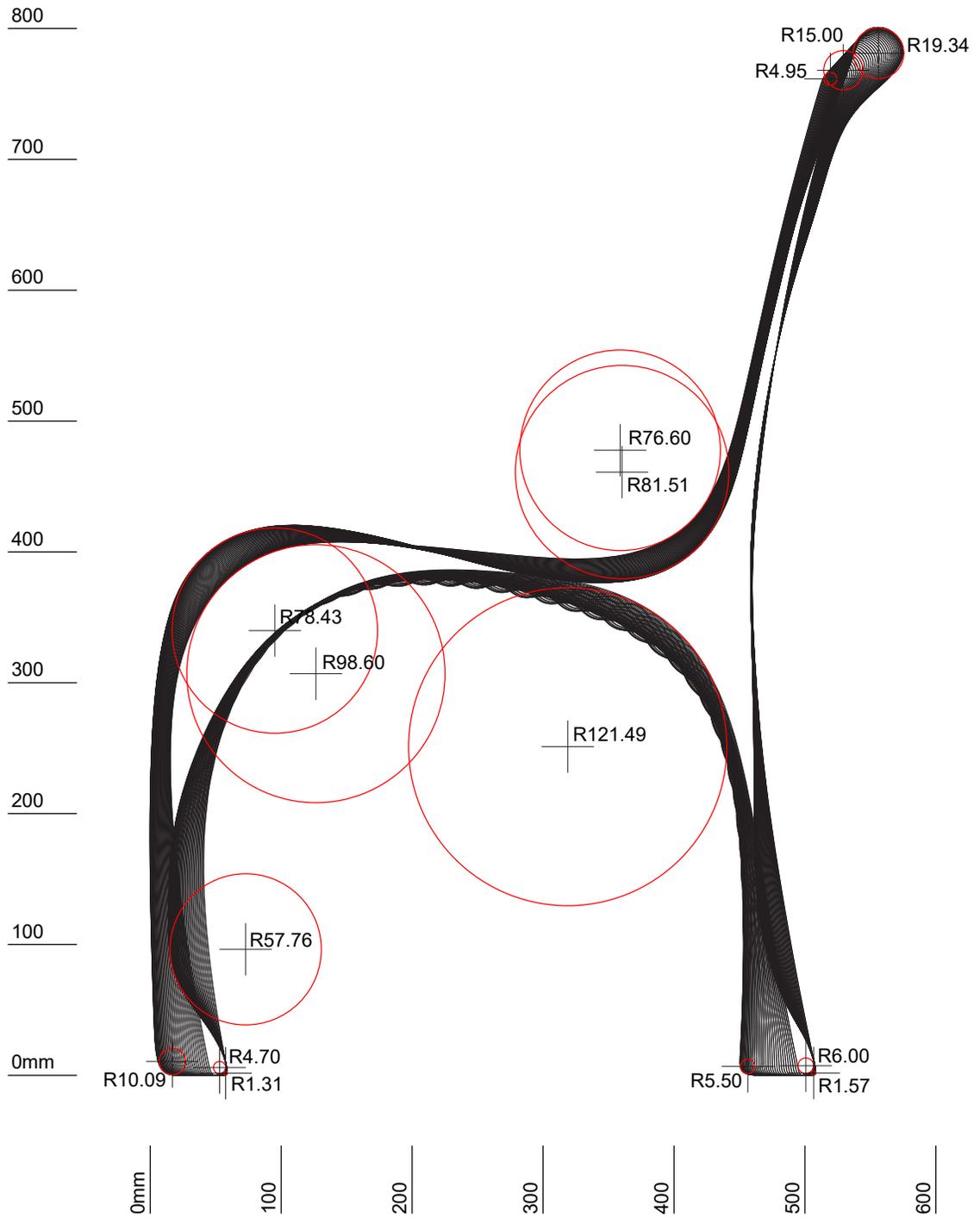


Figure 5.0 Final prototype elevation

## 5.1.

### Design

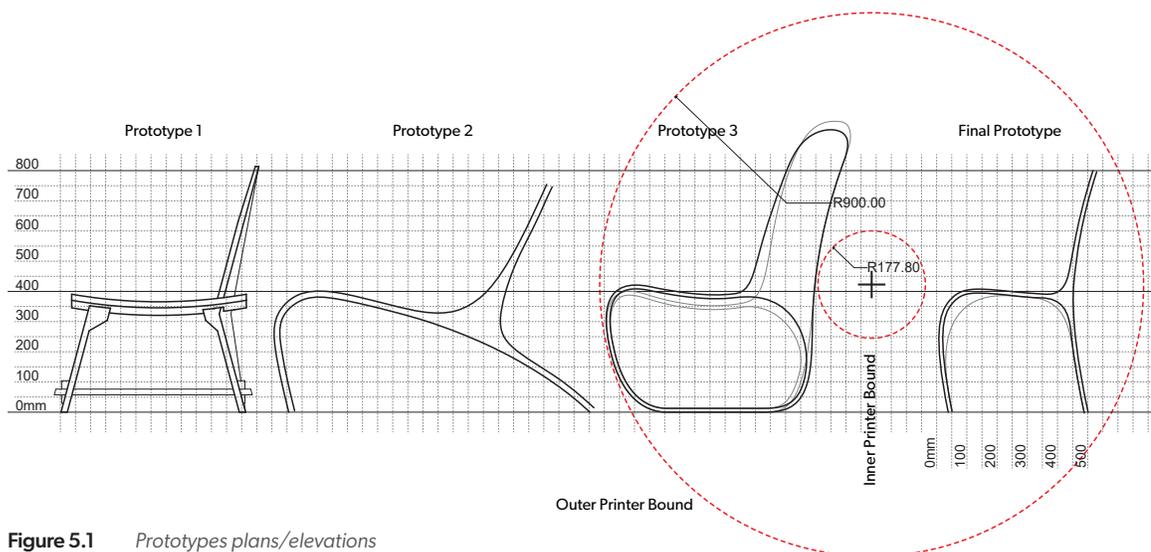
The final prototype is the result of the accumulated knowledge learned of the half-scale prototypes with respect to the material and the techniques associated. The final prototype becomes a hybrid creation using traditional and new digital technologies as it tries to synthesize the three prototypes into one functional chair. It is important to note that although the final chair could be 3D printed in its entirety,<sup>57</sup> approaching it via hybrid methods presents less risk of an unsuccessful print, while still retaining the character and mark of the tool.<sup>58</sup> This will be expanded on shortly. First, it is important to address the primary and most obvious constraint when working with 3D printing technology: the size of the print area. As shown by **Figure 5.1**, the full-scale versions of the previous chairs are slightly too large to comfortably fit within the print area, therefore it is necessary to tailor the overall dimensions while simultaneously balancing the ergonomic requirements.

57.

The current set-up of the lab's printer arm makes high-volume UHPC printing difficult and labour intensive with too much room for error. A single continuously printed chair would be possible if there was a pump to deliver UHPC and if the mix is optimized accordingly.

58.

In this case, the layering of the 3D printer.



**Figure 5.1** Prototypes plans/elevations

The form is a cross between Prototype 2 and Prototype 3, with consideration given to the material’s abilities – both in the fresh and in the cured state. As the final prototype is smaller in size, it would benefit from a lighter expression by removing the inner loop that Prototype 3 had and relying only on the width of a single extrusion to support the seat. I find that by removing the double internal loop, it provides the chair with more breathing room and gives the appearance that it occupies less volume, while also reducing the total weight of the UHPC because of the removal of excess filament length. The expression of the form in the X-Y plane<sup>59</sup> does not need to be overly complex simply because the printer can achieve the complexity. This is because the level of curvature possible in the Z-direction is limited,<sup>60</sup> and therefore I think it is more appropriate that the curvature in the X-Y plane compliments the gentle curvature in the Z-direction – so there is coherence in the whole. There is also the added benefit of there being less filament length with gentle curvatures, and thus less total weight. (Table 9)

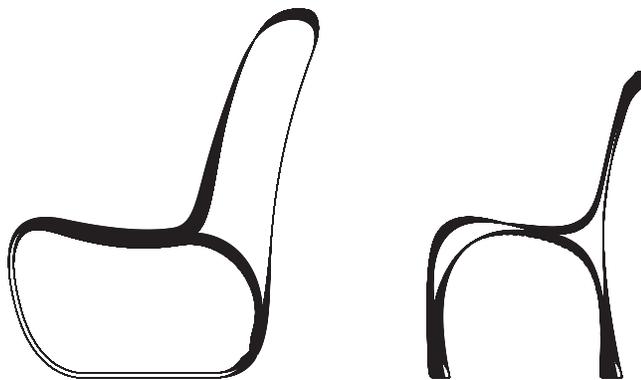
59.

The X-Y plane being the ground plane, the orientation in which the chair is printed.

60.

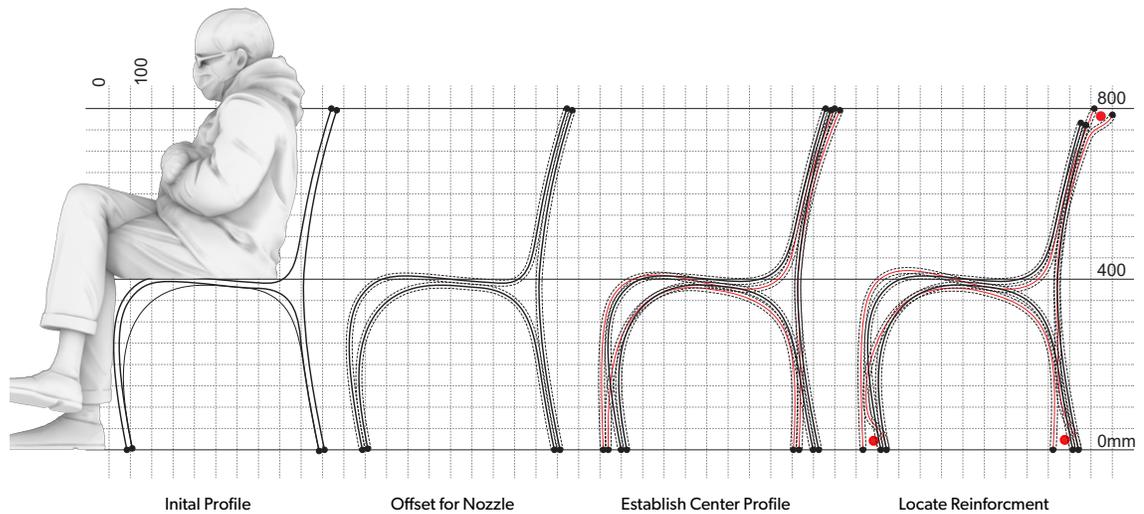
As was shown in Prototype 3, the more curvature in the Z-direction the higher the risk of the print toppling over because of the weight of UHPC.

**Table 9.** Prototype Weight Comparisons



Prototype 3	Final Prototype
Filament Length	
334 115mm	229 449mm
Nozzle Size (Filament Diameter)	
12.7mm	12.7mm
Estimated Weight, 2350 kg/m <sup>3</sup> material density	
99.4kg	68.4kg

There is an opportunity to peel back the bottom line of filament from the seat surface, which creates moments of porosity between the two layers and reinforces the idea of lightness despite the chair being printed in UHPC. It is important to note that the initial profiles being designed are *the* path that the printer will follow – the actual deposition of material will offset this center line by 7mm on both sides. The center profile of the chair is the ergonomic constraint, as noted for example by the slight depression in the seat and backrest to allow for better engagement with the human form. The exaggerated center curves at the legs and top of the backrest have two purposes: to add more surface complexity that compliments the sculpted seat, as well as to create internal pockets that will be used to cast reinforcement within them to connect the two separately printed halves.

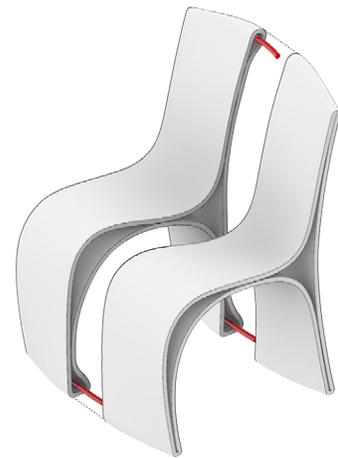


**Figure 5.2** Profile evolution

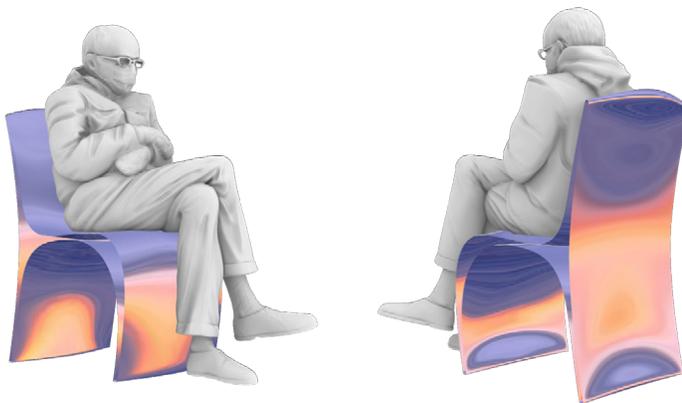
This variation in the center profile is the curvature in the Z-direction, and therefore must be kept gradual to reduce risks of the print toppling over. For this reason, the chair will be printed in two halves to eliminate this risk. By printing the two halves separately,<sup>61</sup> the thicker portions of the chair act as foundations to the layers above, allowing the load of the fresh UHPC to be distributed safely downwards. The overhangs that do occur in this scenario are gradual enough and anchored by the “foundation” that there is minimal concern of the print toppling. The general constraints that govern the size of these internal pockets is an assumed reinforcement diameter of about 13mm, with enough remaining volume that the cast UHPC will have an adequate thickness. The size is optimized in relation to the general appeal of the curvatures, and with consideration of the extra weight in the cast UHPC.

After the general profiles are drawn, the three surfaces of the chair are generated and then connected using the SubD tools in Rhinoceros® to ensure complete curvature continuity without any kinks that may cause the print head to abruptly move and cause vibration. (Figure 5.4) This resulting surface will serve as the base for the drawing of tool paths which are generated from the Grasshopper® plugin.

61. The full geometry cut in half, then printed seam-side down.



**Figure 5.3** Proposed connection between two parts. Cast-in place reinforcement



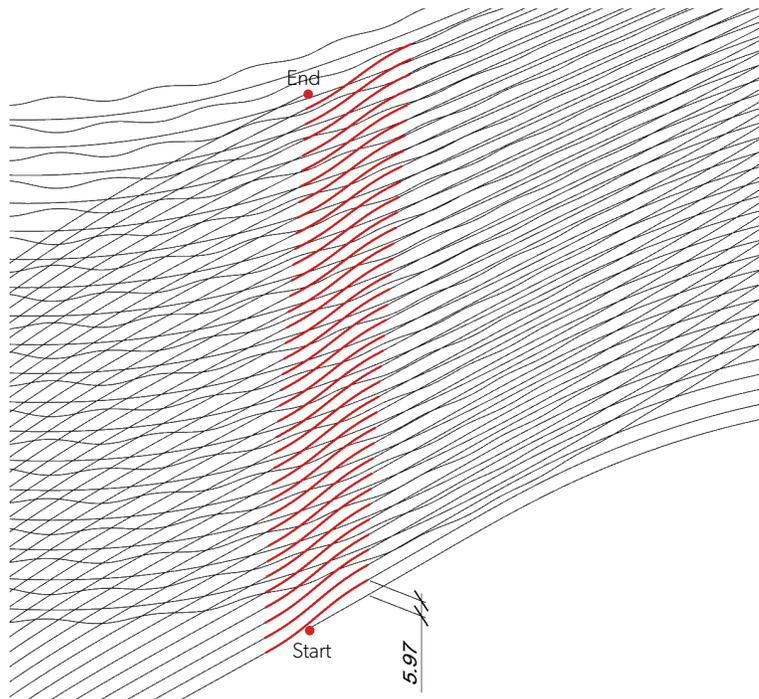
**Figure 5.4** Environment map on surface to check for curvature continuity

The tool path is drawn based on the same nozzle used in Prototype 3, which is 12.7mm in diameter. Prototype 3 displayed considerable strength using this extrusion size, so when printing at full scale, the thinness of the extrusion will be visually amplified while retaining the strength characteristics of the material. The layer height used is approximately 5.97mm, which is slightly less than the 6.35mm used in Prototype 3. The reason for this difference is to better facilitate the “pressing” together of layers,<sup>62</sup> which promotes layer adhesion as well as mitigates the risk of the UHPC rolling off the base layer as it is deposited from the nozzle.

62.

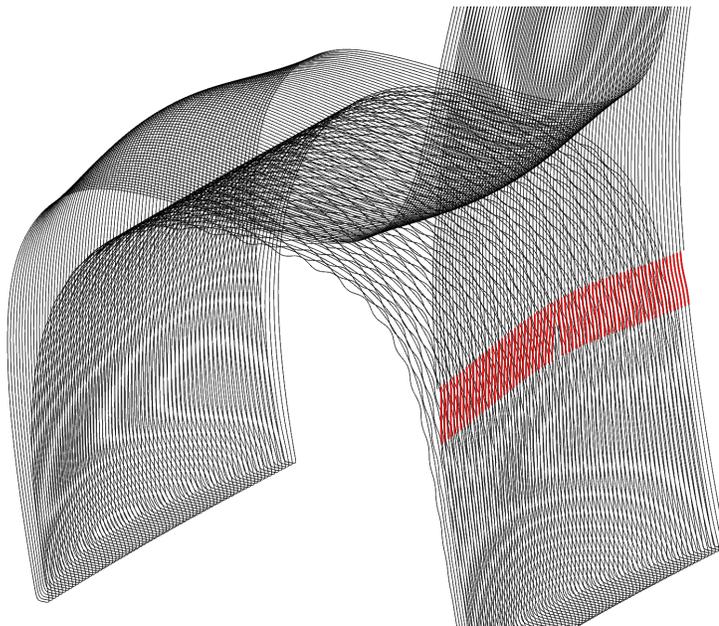
Carneau et al., “Characterisation of the Layer Pressing Strategy for Concrete 3D Printing.” The authors identify an optimal correlation between print speed, nozzle size, and layer height to ensure the successful pressing together of printed layers.

The location of the seam between changes in layer height is placed on the back of the chair to express it (**Figure 5.5**). Unlike Concept 3 which had no seam, and unlike Prototype 3 which required weaving inside and out at the seam, this chair has a simple seam condition. The primary constraint is a gradual change in Z-height, so vibration marks are not visible in the printed surface. Therefore, the layers are blended with an approximate 50mm long tangential curve.



**Figure 5.5** Toolpath seam detail

The area of highest complexity is the underside of the seat where I have chosen to introduce an alternating weave pattern, as shown in **Figure 5.6**.<sup>63</sup> The primary reason for this is to increase the haptic experience when sitting in the chair. It may be uncomfortable to sit directly on the weaved surface, so instead it is located to the underside, where the user would still be able to interact with it. For example, when getting up out of the seat and pulling the chair back with your hands, there is a moment of interaction between the hands and the weaved surface. It also provides visual complexity and intrigue to the print while adding extra rigidity to the arch, which is the primary load transferring surface. The waves then gradually disappear towards the legs so there is no interference and vibration as the printer turns the corners. I believe that the gradual reduction of wave amplitudes also compliments the general curvatures of the chair.



**Figure 5.6** Weaved underside detail and location of print seam

63.

The technique of developing a sine-wave toolpath that is perpendicular to the base surface is borrowed from Cuevas and Pugliese, *Advanced 3D Printing with Grasshopper, Clay and FDM*, 131–47.



**Figure 5.7** Weaving pattern print example in clay

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## 5.2.

### Fabrication



Figure 5.8 Printing process reel

The fabrication process is incredibly involved and labour intensive, counter to what some might think digital fabrication is. Each half taking roughly eight consecutive hours to complete. The clips shown in **Figure 5.8** give a small glimpse into what that process looks like. Unfortunately, these clips do not show the process in its entirety. There is much behind-the-scenes work that simply is unfeasible (uneconomical) to capture (**Figure 5.9**) when there is a limited amount of open time available when working with UHPC, and therefore much of front-end process is extremely time sensitive.

This fabrication process is undoubtedly hybrid in its nature, and in many ways has more risk associated with it than if I had chosen to build a formwork to cast in. What I mean by this is that the outcome of the 3D printed part is unpredictable, as is shown in **Figure 5.10**, and can fail for seemingly no reason at any point in the process. The difference is that when I am working to make a formwork with a combination of digital tools and analogue tools, there is a certain level of confidence in my own workmanship, as well as in the stability in forming material, that I know it cannot fail in the same way. For example, a CNC milled (or manually cut) foam block is inherently stable as a material – as is a sheet of plywood – but when 3D printing a material like UHPC, there are many rheological factors that can cause failure in multiple ways: buckling, toppling, layer crushing, and so on.



**Figure 5.9** Extruder tube loaded with UHPC



**Figure 5.10** Layer collapse as layers below began to slide out from the top layers

This is not to say that all the risk involved is with the machine or the material, but because of the hybrid nature, some of the risk associated with the 3D printing process comes from my own bodily movements with the machine. How accurately I choose to measure and mix the ingredients, how thoroughly I choose to clean the nozzle and tubes from the last batch, how fast I re-assemble the nozzle when the material is packed, where I choose to step when reloading the printer, and how firmly I hold the tube when reloading to make sure it does not slip and crash down on the printed part (**Figure 5.11**), are all factors that could cause the print to fail due to human error on my part.

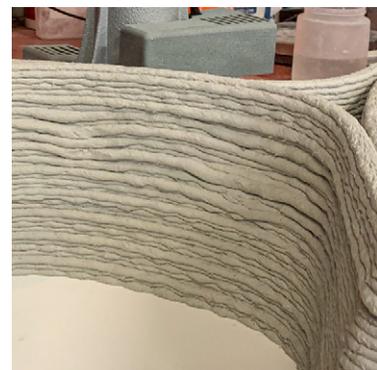
There is an interesting cross between the imperfect human touch and the precision of the machine at times in the process as well. For example, to ensure proper layer adhesion between tube batches, I had to intervene and paint on a bonding admixture after each of the tubes were expended (**Figure 5.12**). This would lower any risks of the top layers wanting to topple over as was experienced in Prototype 3 earlier. Luckily, the chemical matches the colour of the UHPC, so the drips and runs from my hasty painting between batches is not visible in the final product. There is also the possibility to “catch” the print from falling which is typically impossible to do with other digital tools like a laser cutter, CNC mill, or even a typical plastic 3D printer (**Figure 5.13**). When something goes wrong with these processes, the craftsperson can only either restart or improvise the rest of the process once the machines are finished. In this case, I was simply able to push the material with my fingers into the correct position to ensure the print would not start to buckle. Assuming all aspects of the printing process could be optimized, “catching” the filament would not be necessary, as I personally think that it negatively affects the craftsmanship of the final product because it is obvious that the fingerprints were not intentional to the design.



**Figure 5.11** Loading printing arm with filled tube without disturbing printed part below



**Figure 5.12** Applying bonding admixture to last printed batch to ensure adhesion



**Figure 5.13** Traces of fingerprints on the filament when “catching” layers from falling

In this process there were three parts printed in total. The second print ultimately collapsed (**Figure 5.10**) despite being identical to the first print which was successful – albeit it did require a bit of human intervention to make sure it did not. I was unable to catch the second print at the right moment, and thus it began to buckle. Ultimately this means there is an issue that could be a combination of any of the following: material consistency, designed curvature, design of the weaving pattern, layer heights, or speed of printing. Of course, I was unable to change the design at this point – since I already had one successful half and did not want the second half to be visually different. The only variables remaining are changing the speed of the print or the consistency of the material, which when paired with a little more “catching” of the material, resulted in a successful third print.

I used the failed second print to demonstrate the importance of proper curing processes of a 3D printed UHPC part (**Figure 5.14 and 5.15**). Since the UHPC is not contained within a formwork as it traditionally is, the moisture in the mix that is necessary for proper cement hydration evaporates far too quickly due to the large area of exposed surface in the print. Therefore, it is imperative that each 3D printed part is continually misted with a spray bottle during the printing process, sufficiently misted after printing is complete, and then covered with a vapour impermeable sheet to prevent evaporation. This ensures a properly cured part that can withstand the forces it was designed for.



**Figure 5.14** *Informal load test on the failed second print after one day of curing uncovered*



**Figure 5.15** *Detail of fiber separation & distribution in the 3D printed part*

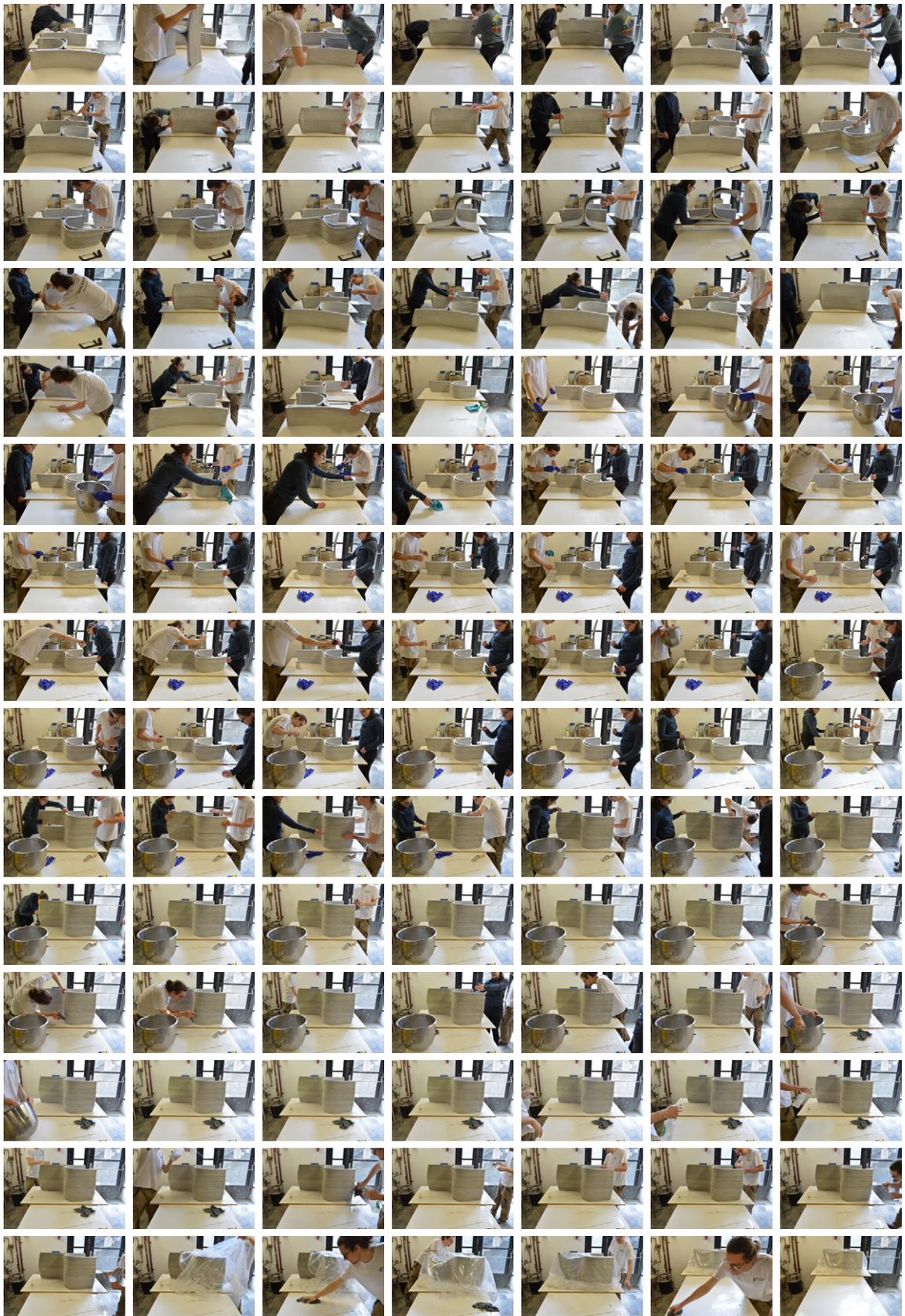
The final step in the process is the assembly of the two printed halves, shown in **Figure 5.18**. The only issues encountered at this point was that the designed openings ended up being smaller because the UHPC filament spread slightly more than planned. This was easily resolved by filing the openings down slightly and moving to a smaller rebar section, which is not problematic since the rebar serves little structural purpose. The two halves are then cast together using a slightly altered mix of the same UHPC used for printing (**Figure 5.17**) but optimized to maximize the flowability of the mix into the pockets, and to ensure proper bonding to the rebar.



**Figure 5.16** *Cutting threaded rod rebar with additional notches to allow for better UHPC adhesion*



**Figure 5.17** *Casting rebar into first half of chair*



**Figure 5.18** *Assembly process reel*

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5.3.

Product Photos





**Figure 5.19** *Top: front of chair. Bottom: rear of chair.*



**Figure 5.20** *Top: front elevation of chair, first printed half on right, third printed half on left. Transitions between tubes clearly visible, as well as distinction between the two halves. Bottom: sitting on chair.*



**Figure 5.21** *Detail of backrest. Note the attempted clean up of excess material extrusion when the print is paused. The subsequent pauses for reloading were then timed to occur at the bottom of the legs, so these imperfections would not be directly visible.*



**Figure 5.22** *Top: profile of chair and porous moments in the tool path. Bottom: detail of seam between the two halves and the layer seams as the print grows.*



**Figure 5.23** *Top: tactile experience with chair seat. Bottom: weaving pattern detail, with traces of finger prints in the UHPC filament.*

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## 5.4.

### Reflection

It may be curious as to why I choose to call the final product of this thesis a “final” prototype. In the spirit of what this thesis set out to do, I believe that there are many more avenues of exploration and areas of improvement for both the design and fabrication of this chair. Evidence of the constant looping-forward process that I have spoken of is present even during the seemingly linear process of making the final chair. For example, during the fabrication process, the outcome of first printed half was okay, but required some refinement. The second print failed entirely, which prompted reconsideration and further refinement of the material mix and of the techniques used. The third print succeeded, and even though it visually may appear identical, there are a myriad of nuances in the techniques used – both digital and analogue – that differentiates it from the first printed half. Learning from the making process does not necessarily end simply because the chair was printed successfully. Speaking in terms of fabrication, there are ways to improve the surface quality, to optimize the mix of UHPC, and to reduce the weight of the final product. Speaking in terms of design, there is the potential to continue pushing the amount of possible surface curvature before the print fails. There is the possibility to adjust and explore the types of weaving patterns possible when working with UHPC.

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## CHAPTER 6.

### Conclusion and Critical Reflection



Chapter 1 set out to establish the theoretical framework of the argument, and to situate the work in context with other authors concerning themselves with issues of materiality and craftsmanship. Chapter 2 then uses this framework to work towards creating an embodied relationship with UHPC as a material through direct manipulation of the material with technology, and in this specific chapter, with traditional techniques in order to establish a strong relationship between maker and material.

Through the manufacture of the small-scale “objects” in Chapter 2, I discovered that there is freedom in working *alongside* a material during the design process, which I consider different from trying to fabricate a predetermined abstract design which may not fully resonate with what the material is capable of nor its limitations. In this manner of thinking by making, I can effectively establish a strong relationship between maker and material, which is the goal of this chapter. This chapter allowed me to learn how the material felt when freshly mixed, how it felt while curing, and what felt like fully cured. Understanding all three of these material states is the key to holistically *knowing* the material. In this first phase of making, I discovered that many of the decisions I was making was a result of what I knew concrete to be from my past experiences, and not indicative of what is possible with UHPC, and thus inappropriately drawing parallels between traditional concrete and UHPC where they did not exist. This is the value of this chapter. I simply needed the freedom to explore, to learn from the material, and to test a few different techniques in tandem with the design process.

In chapter 3 I began to fold in the things learned from the previous phase into the manufacture of conceptual models for a potential chair. In this chapter, I began to have a feel for the material's mechanical properties by trying to push how thin elements could be. This phase of the work allowed me to reflect on the failures of these tests, to understand why they happened, what could have been done differently with the tools at hand moving forward, and how these lessons can affect the design of the subsequent phases. Each tool used to work the material, whether it is analogue or digital, poses a unique set of issues and opportunities that forced me, as the maker, to critically reflect on when it is appropriate to use one tool over another. This phase taught me the value of appropriate tolerances in connections when working with UHPC as well as the incompatibility between the scale of the thing being made and the internal one-to-one scale of the material. In other words, there is an understanding that the material's true potential cannot be realized when only working at small scale models.

Chapter 4 then produces half-scaled prototypes which are designed according to what was learned of the material and of the techniques from the previous chapters and continuing the conceptual departures. The significant increase in scale during this chapter results in having to grasp an entirely new set of problems that can only be addressed by engaging in the making process. In chapter 4 I began to encounter issues involved when working at a half-scale as well having to take into consideration the sheer weight of the material as the scale increases. The prototypes all performed well structurally, some slightly more fragile than others, but the primary concern was the anticipated weight of the final product and how best to control the outcome of the final product. Chapter 4 introduced many different and interesting avenues for future explorations: the casting of thin parts and how to assemble them, casting within 3D printed clay as a formwork, as well as discovering

a custom mix design for 3D printing applications. Ultimately, only one avenue could be sufficiently explored in making of the final product due to the limited scope, but I believe that as the designer/maker there is value in understanding the broad range of making techniques in order to know how to execute any future design visions, whether it be at the scale of a chair, or more architectural scales.

Finally, chapter 5 culminates in the 3D printing of the final chair. It should not be mistaken that this chapter is independent of all the work completed up to this point simply because only one avenue of making was pursued. Any of the successes in this chapter are entirely dependent on the explorations and the mistakes made in the prior, regardless of what making technique is used. Despite all the knowledge gained from the previous explorations, there are still moments where the outcomes cannot be anticipated because there is again another increase in scale of working. Therefore, as the designer/maker, I am faced with having to experience moments of failure once again. This is not to be considered a negative aspect, because it simply reinforces the notion that the looping-forward process of making does not end here. What is important is that the prior work provided me with the knowledge to avoid making initial fundamental errors that could have resulted in a failed final product. Naturally, there are always technical tweaks that can be made to make the surface quality better, to make it lighter, or to make it more comfortable. Engaging in the process of making these adjustments is predicated on the designer/maker's will to do good work and improving their technique, which Richard Sennett points out as the "dialectic between the correct way to do something and a willingness to experiment through error."

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64.  
Sennett, *The Craftsman*, 160.

This dialectic between making things correctly and willingness to experiment through error I believe is fundamental to the education of the designer and their agency within the realm of architecture. I believe that by engaging in the process of thinking by making, the designer exposes themselves to ways of knowing that they would not otherwise if design problems were only worked out through drawing, regardless of the tool at hand. In order to be critical of what was learned through my process of thinking by making, it must first be clear that this process is personal and unique to me. What I learned and how I did what I did is simply one version of this process and is my interpretation. My hope is that for the sake of design within architecture, designers will see the value in how processes of making are not independent from cerebral processes of designing, but rather that the two are deeply interwoven. I believe that knowing how to *make* with a hybrid use of technology directly correlates to knowing how to design *better*.

Working in a hybrid manner is not to say that using a single tool produces poor products or results. Through my process I have learned that some processes require no more than perhaps a single tool, whether it is analogue, hardware, or software. On the other hand, the process of thinking by making as an infinitely on-going endeavor requires the designer/maker to understand the appropriate application of technology at certain points in the process. This is the hybrid nature of making; it is also a dialectic between knowing comfortably how to use one tool and being curious of the outcomes using other tools. For the designer/maker to produce good work (to be a *craftsman* of their trade), I believe it is predicated on knowing at least *about* the tools associated with architectural design and fabrication.

Due to the nature of tacit knowledge, it would be an impossible and perhaps a fruitless task to enumerate all of the things learned over the course of these material exercises. Beyond the broad definition of “technical knowledge” of coding and operating the 3D printer and the quantifiable things learned about the mechanical and chemical properties of UHPC, this thesis has brought to the forefront the importance of the intersections that occur between thinking and making and design. I believe that as a designer one of the most important things learned in this process is experiencing the phenomena of the material as it is being worked and looping that knowledge back into the design in-situ. Feeling how material behaves in my own hands allows me as the designer/maker to work with not only the quantitative properties of the material, but also the qualitative properties, in the process enriching the act of design as a process that is material in nature. Like master builders of the past whose hands-on knowledge created a body of experience which informed future design decisions, the process of this thesis is a call to the act of design to remain “in touch” with material – through thinking and making – in the increasingly digital processes which guide and inform the work of the architect.

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## 6.1.

### Postscript

Material research at the CSALT lab is ongoing and this thesis has opened many new avenues for 3D printing UHPC to be explored in the future. These avenues include new pump and robotic processes for scaling up work to create architectural components, further exploration for reducing the content of portland cement in the mixtures to reduce the carbon footprint, innovative processes using clay as removable formwork for UHPC, and finally structural testing of UHPC mixtures in the civil engineering testing facilities to determine precise comparisons of these early recipes.

The current cartridge-extruder based system is adequate for small-scale objects but found its limit at the scale of a chair due to the size of the cartridge that holds the cement. This small-batch process is labour intensive and creates breaks between mixing and printing that are not ideal. Using a progressive-cavity pump to move fresh UHPC to the nozzle has become the industry standard for larger projects.<sup>65</sup> This shift in scale will inevitably create an entirely new level of complexity which will in turn require a new mix design, control of the pumping system, and the design of a specialty nozzle that can mix accelerant into the fresh mix right before deposition.

The carbon footprint of buildings is a primary concern for any future buildings. By refining the “recipe” for concrete, the worlds primary building material, to require less portland cement and material to perform the same structural task, architects can discover a new lightness in form and design in a similar process that I have undertaken in this thesis. I believe that other UHPC additives such as expanded recycled glass aggregates that were unsuccessful in this project due to

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Gosselin et al., “Large-Scale 3D Printing of Ultra-High Performance Concrete – a New Processing Route for Architects and Builders,” 104.

the limits of the current 3D printing system offer expanded potential for lightweight UHPC and further design implications. Traditional concrete used in North America typically has a far higher coarse aggregate content in proportion to cement when compared to UHPC, so addressing questions of how we can use other materials to reduce the cement content of UHPC while keeping its mechanical properties desirable is important and very relevant – it is time to rethink concrete!

## Glossary of Terms and Ingredients

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**Bleeding & Segregation:** Bleeding is the flow of water in a concrete mix caused by the settlement of solid materials in the mix. Segregation is when the aggregates and mortars separate, resulting in a nonuniform mixture. In the context of this thesis, bleeding has been observed to occur in the print cartridge, as the water drains due to gravity, resulting in a gradient of rheological properties during the printing process.

**Expanded Glass Aggregate:** This thesis conducts experiments with lightweight expanded glass aggregate, which has many benefits such as low densities, high strengths, thermal insulation, and acoustic dampening properties. This greatly reduces the weight of the UHPC mixture, which is also beneficial to the printing process as the layers have less pressure building on top. The aggregate is supplied by Poraver North America Inc. and comes in sizes from 0.04 – 0.125mm, 0.1-0.4mm, 0.25-0.5mm, 0.5-1mm, and 1-2mm. The aggregate is produced entirely from recycled glass.

**Fibers:** Available in polypropylene, fiberglass, steel, wood cellulose, and basalt fiber. Fibers do not necessarily replace reinforcement but do allow for greater tensile resistance in the cured product. In terms of this thesis, the fibers are used to: 1) increase the initial yield strength (buildability) of the UHPC as it is deposited from the nozzle, as the fibers help to hold the mixture together, and 2) increase the ultimate compressive and tensile strengths of the printed products so they can be categorized as UHPC. The fibers used in this work are polypropylene, with an average length of about 19mm, supplied by Spring Valley Corporation.

**High-Range Water Reducing Admixture:** Also interchangeable with the term *superplasticizer*. As the term implies, this chemical admixture reduces the amount of water required in a mix while increasing the workability. The HRWR used in this thesis is supplied by Sika Canada and helps to reduce water demand between 12% to 30% depending on dosage. This admixture is especially important to the 3D printing process because it helps make the fresh UHPC more fluid, increasing the extrudability of UHPC, and ultimately increasing the strength of the final product by lowering the w/b ratio.

**Hydration (Heat of):** The chemical reaction between hydraulic cement and water which produces new compounds that contribute to the strength properties of concrete. Heat of hydration is the energy that is let off during the reaction. Accurately testing and measuring this reaction during 3D printing processes falls out of scope for this thesis. Instead, the heat is haptically felt during mixing stage to determine when the concrete is ready to be transferred into the cartridge for printing.

**Metakaolin:** Is a pozzolanic calcinated clay supplementary cementitious material used to help reduce permeability of the cured product, as well as to help improve the rheological properties necessary for 3D printing. The powder has a cement like particle size of approximately 10  $\mu\text{m}$ . The metakaolin used in this thesis is supplied by Poraver North America Inc. and is also entirely a byproduct of their expanded glass aggregate production, requiring no additional energy to produce.

**Natural Hydraulic Lime (NHL 3.5):** In terms of this thesis, NHL is added to the mix as an extrusion aid because it also helps in making the mix more 'sticky', as well as improving surface quality due to the fine particles that are distributed in the mix. Limestone filler is a typical ingredient used in cement manufacturing to help offset the amount of portland cement required. In this work, NHL is used as a partial cement replacement and has shown promising results.

**Portland Cement, Type GU & White:** The world's most versatile and widely used construction material. Portland cement is finely ground clinker, which is formed by burning calcium and siliceous raw materials in a kiln. Type GU specifies general-use concrete which is used in this thesis. There are a variety of types, each suited to a specific application. White portland cement is simply clinker that is produced by using raw materials containing no iron minerals.

**Pozzolan:** The term used generally in this thesis to refer to a material containing the same hydraulic properties as portland cement. A more precise definition is provided by Kosmatka et al.: "siliceous or siliceous and aluminous materials, like fly ash or silica fume, which in itself possess little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties."

**Set Accelerating Admixture:** Accelerates the setting time of the mix. In context of this thesis, this admixture is a double-edged sword. Set acceleration is required to ensure proper buildability of the layers, but with the cartridge extruder used in this thesis, the mixture cannot set within the tube during the printing process. The accelerant used in this thesis is supplied by Sika Canada.

**Silica Fume:** A supplementary cementitious material. It is the byproduct of the manufacture of silicon or ferrosilicon alloys by burning high-purity quartz with coal in an electric arc furnace. Silica fume has a particle size averaging  $0.1\mu\text{m}$ , about 100 times smaller than cement particles and twice as fine as the particles found in tobacco smoke. Silica fume greatly increases the impermeability of concrete due to its fineness. In the fresh state, silica fume causes the mixture to become 'sticky', which has proved to be valuable when printing UHPC, but increases water demand in the mix. The silica fume used in this thesis is supplied by Sika Canada.

**Silica Sand Aggregate:** UHPC contains no coarse aggregates, but rather relies on fine aggregates to create a homogenized internal structure. The silica sand used in this work has an average particle size between  $0.210 - 0.125\text{ mm}$ . To ensure a proper bond between binders and aggregates, they must remain clean. Sharp, angular aggregates create better internal bonds, but increase water demand in a mix (increasing w/b), while round aggregates have less effect on water demand. There is far more complexity involved when specifying aggregate for UHPC, which falls out of scope for this thesis. The sand used in this thesis is supplied by Spring Valley Corporation.

**Slag:** Blast furnace slag is a byproduct of iron manufacturing used as a supplementary cementitious material that can replace upwards of 70% of portland cement in a mix (depending on application). Molten slag is rapidly quenched in water to form a glassy sand like material. The material is then granulated to less than  $45\mu\text{m}$  and behaves in a hydraulic manner like portland cement. The slag used in this thesis is grade 80 and supplied by Lafarge Canada.

**Viscosity Modifying Admixture:** Used to alter the viscosity of the UHPC to make it more suitable for 3D printing. UHPC treated with a HRWR produces a high slump, high flowing mixture that is not optimal for 3D printing. Adding the VMA helps to consolidate the mix into a more plastic state, while simultaneously helping to distribute air voids, as well as help reduce bleeding and segregation in the mix. The VMA used in this thesis is supplied by Sika Canada.

**Water to Binder Ratio (w/b):** The ratio of mass of water to mass of all cementing materials (binders) in the mix. Can include any of portland cement, blended cements, fly ash, slag, silica fume, calcinated clay, metakaolin, calcined shale, and rice rusk ash. This ratio is important when designing UHPC mixes because the w/b ratio directly correlates to the compressive strength of the product. Typically, the lower the w/b, the more compressive strength the material has. UHPC mixes are in the range of 0.15-0.30, while traditional concrete can be well over 0.50.

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