REAL MATERIAL ETHEREAL

Proceedings of the Annual Design Research Conference 2019

Edited by Laura Harper

Published in Melbourne Australia, by Monash University, 2020
ISBN: 978-1-921994-52-4

The bibliographic citation for this paper is:

Jon Engholt. “Designing Concrete Behaviour: Migrating Material Logics and Contingencies in Digital Fabrication Design.” In *Proceedings of the Annual Design Research Conference 2019: Real/Material/Ethereal,* edited by Laura Harper, 173-191. Melbourne: Monash University, 2020

Designing Concrete Behaviour: Migrating Material Logics and Contingencies in Digital Fabrication Design

Abstract

A hallmark feature embedded in notions of architecture in the digital era is the promise of resolving the reciprocity of digital design and physical manipulation, implicitly allowing the beastly marriage of two ontologically different realms: That of numerical unconditionality and that of natural contingency. This ontological divide highlights a central characteristic of architecture in any historical context: The inherently imprecise manipulation of matter that propagates throughout multi-material assemblies into compound logics of both manufacture and assembly. In digital fabrication research such aggregation of material imprecision is especially revealed within two contemporary attitudes: Digital materiality that addresses the procedural relation between manufacturing and scripting, (Gramazio and Kohler 2008) and digital craft that incorporates the nature of traditional craft into the explorative nature of robotic experimentation (Pye 2007; Kolarevic and Klinger 2008)

Concrete challenges embedded logics traditionally explored in CNC (Computer Numerically Controlled) fabrication due to its dual-material nature: Without redesigning the material itself, concrete relies not only on its material capacities but also on the material capacities of the formwork. Concrete thus offers a uniquely twofold material investigation: Firstly, the behaviour of formwork becoming apparent only in the physical negotiation with liquid concrete during the act of casting. Secondly, the material fabrication of formwork becoming subordinate not only to affordances in the formwork material itself, but its ultimate role as a tensile structure to contain a dense liquid. Concrete thus highlights a present area of interest in digital fabrication research: The transfer of material logic across physical media.

Through several case studies from the author's research-by-design work, the paper discusses how a departure in the behaviour and aesthetics of liquid concrete might engage forms that embrace both digital precision and material imprecision.

Introduction

"Concrete is mud. I work with concrete not against it. I like mud." (Pommer, 1972) While Paul Rudolph's remark indeed inhabits the modernist discourse of his time and work, it also addresses a vital feature of this wonder material of the modern era: Before passively manifesting the imaginative forms of architects it is a resin composed of dirt, sourced from its underground deposits of sand and stone. Despite being the globally most consumed material (U.S. Geological Survey, 2018), concrete is rarely articulated as anything else than a structural means. The delicacy of digital fabrication processes thus might bring forth material qualities and elevate the experience of something usually perceived as primitive and rough. Perhaps this perception can be entirely attributed to industrial sophistication – or the lack thereof – as concrete, despite the general roughness of its execution, holds the ultimate promise of precision when it willingly inhabits every crevice of its mould. Perhaps precision and articulation are secondary concerns to the vast scale and structural performance of most concrete erected around the world. Nonetheless, the material imprecision is a product of both formwork and concrete.

A tectonic ethos

The interdependent relationship between formwork and concrete highlights a principal theoretical framework of tectonics. A solidified memory of the casting process, concrete embodies a classical tectonic classification in which material, technique and form each rely on each other as uniquely interdependent physical factors: Change one, and you change the others. Board-marked concrete presents an obvious example; not only does the unique features of each wooden board imprint on the surface of the concrete, but the assembly of boards present formal possibilities in the formwork design, as the longitudinal fibres allow each board to slightly twist and bend. These structural and mechanical affordances combined with the natural variations of the individual parts in the formwork thus produces a cast form uniquely tied to this technique. This immediate tectonic relation between mould and cast frames the central part of presented work, while the higher-order tectonic question of structural integrity and readability is presently beyond the scale of most of the experimental work.

However, within the research described in this paper, this framework suggests not only an understanding of how processes within different materials affect each other in the orchestrated manoeuvre of concrete casting. It also invokes an ethos: If digital design and fabrication methods open up a precarious territory of material articulations and possibilities, do they not simultaneously invite one to allow the liquid beginnings of concrete to express themselves most clearly in the solidified form? Confronted by mud, this ethos suggests not to domesticate the mud but rather the material systems surrounding it. The research is thus motivated by a notion of ethical tectonics aimed towards allowing the material memory of liquid concrete to manifest in the dynamic negotiation with digitally manufactured material systems.

A spectrum of material precarity

With the exception of concrete 3D printing, the solidified form of concrete is caused by something outside itself, reacting to the immense hydrostatic pressure of liquid rock. The material manipulation of this boundary condition thus forms the design and fabrication space, but the physical form arises only when concrete is introduced as a dynamic negotiation partner. An interface of material collision, this frontier carries a tremendous potential, not only for dynamic physical form negotiation but also as a stage where causes and contingencies collectively carve out precarious opportunities; the chance of something unique to happen in a physical encounter.

This encounter presents a spectrum rather than a limit: Depending on the level of control, the physical form arises primarily from the material behaviour of the formwork or the concrete; from the complete containment of liquid concrete in solid formwork to the absence of formwork in concrete 3D printing. When addressing material affordances and their implicit effect on fabrication design, this spectrum offers navigation: Which part of the casting process do material changes affect and why? This navigation involves the acknowledgement that the design is a material system that reacts to another material system – and that the affordances of one physical manipulation might be subject to a structural logic embedded within the expected output of the fabrication process as a whole.

The spectrum simultaneously follows an etymological categorisation implicit to concrete: The term *concrete* refers to the solidified form of a substance grown together, and thus the hardened shape after the act of casting (etymonline.com), while *cement* coins the act of growing together – the “process of producing cohesion” (etymonline.com). Both these terms stress the interior chemical bonding of the material in stasis. Conversely, the term *beton* employed in several cultures stems from *bitumen*, the ancient meaning of liquid resin (dictionary.com) – of the material in motion. One only has to turn towards Spanish-speaking cultures to appreciate this notion; in Spanish *betún* translates to shoe polish, while in Mexico, the term takes on the delicious meaning of cake frosting (spanishcentral.com). There exists thus a vast spectrum of imagination and physical forces at play between total containment and no containment – between concrete and betún.

Case studies

The following sections describe a series of experiments carried out within the outlined framework of tectonics and material navigation. Each series investigate how material systems react with varying degrees of resistance upon confrontations between material and technique. These material systems – and their tectonic predispositions – include formwork, concrete and in one case reinforcement.

Case study: Tailored flexibility I

This experimental series investigated bespoke reinforcement of fabric formwork using additive manufacturing – in particular, a large scale thermoplastic extruder mounted on a 7-axis robotic arm. Conventional methods of fabric concrete casting employ high-strength geotextiles, vastly expanding the traditional vocabulary of concrete forms but limited by fabric stretch and clamping techniques (Hawkins et al. 2016). In this study, highly flexible lycra fabric is reinforced with patterns of thermoplastics printed directly onto the fabric, thus affecting the local behaviour and performance of the flexible formwork. The tests were set up with a rigid reusable frame employed to clamp a fabric membrane reinforced with printed thermoplastics. These casts measured 40x40 cm across while varying in depth depending on the individual membrane designs (Fig. 1). Several considerations of material logic appeared during the development, mainly the affordances of additive manufacturing versus the tensile structural requirements of the formwork and the mechanical behaviour of thermoplastics.

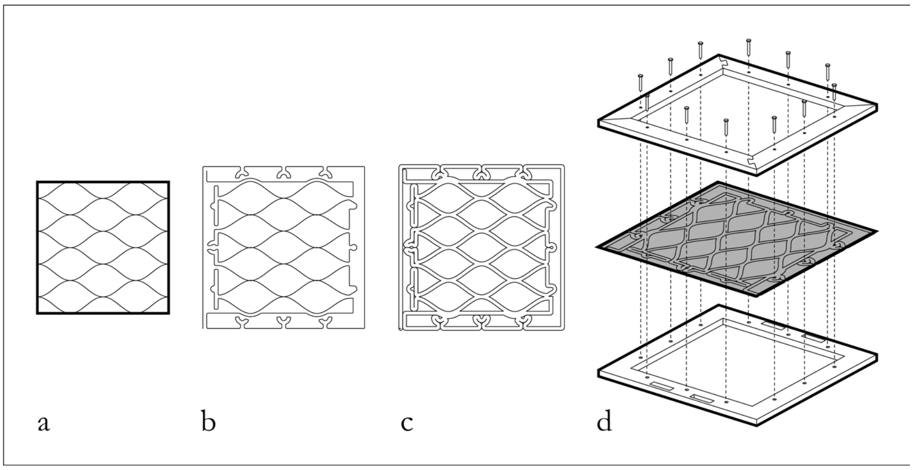

Figure 1. Horizontal rig

The toolpath was initially developed based on a continuous approach to avoid any self-intersections and thus, errors in the print. Using an iterative method of locally subdividing an input curve while expanding its length across the formwork surface, the toolpath density and thus the membrane's ability to stretch could be controlled. However, while this continuous approach guaranteed that the toolpath would not self-intersect – and thus maintained the material strength along the length of the print – the tensile strength of the printed pattern depended entirely on how well the printed thermoplastic laminated with itself (Fig. 2). The membrane's behaviour also became harder to predict due to the low-resolution control – and thus harder to design. This toolpath generation method was thus abandoned.

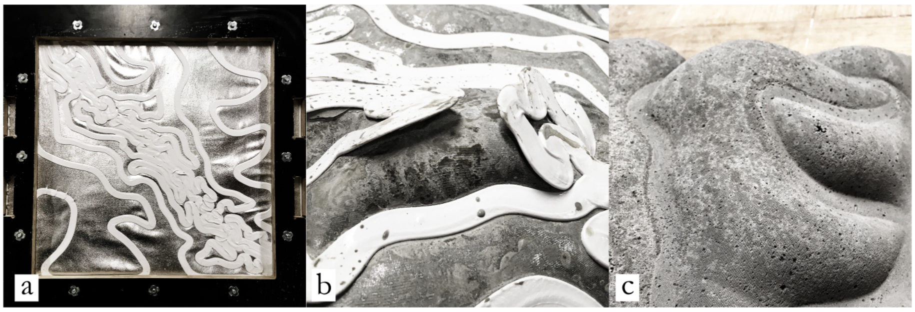

Figure 2. Example of continuous toolpath experiment. Printed toolpath, cast with membrane still attached and concrete.

The second option of toolpath generation approached the challenge discretely by designing variations of Truchet tiles (Carlson, n.d.; Krawczyk 2011). The tile edges are connected by curves equally spaced on every edge, and the curves can thus be joined into one contiguous (tool-)path. Since each tile is a topology of edge connections, this approach is also applicable as a toolpath generator on faces across any quad mesh surface. The local behaviour and strength of the fabric membrane thus change by scaling and distorting tiles while (possibly) applying different tile designs. Fig. 3 shows a small range of tile designs and their applications on distorted meshes and fig. 4 shows one of the corresponding casts in the horizontal 40x40 cm rig. These tests proved valuable to demonstrate the potential of designing tiles to act as tensile structures with self-intersecting and overlapping prints; however, these features challenged the material strength and lamination.

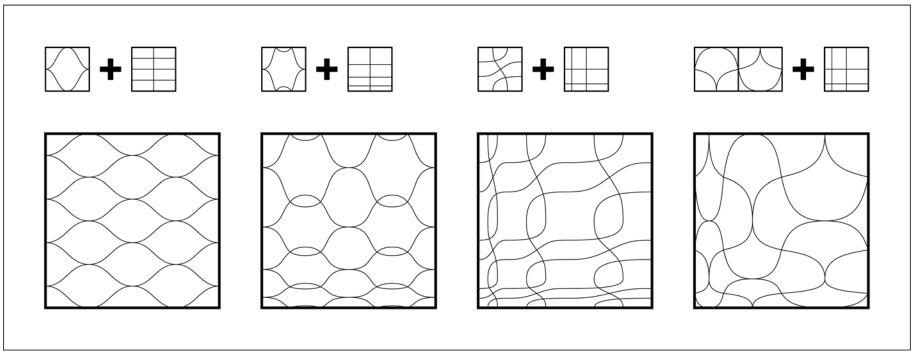

Figure 3. Tiles and distortions on meshes

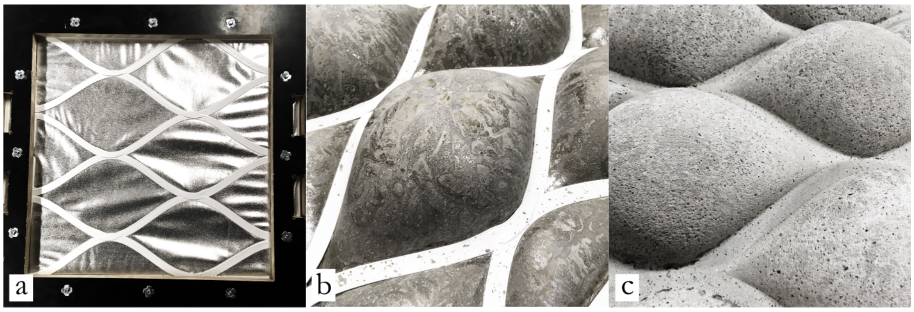

Figure 4. Example of a cast in tiled print.

To achieve a structural mesh, the printed thermoplastic needed to laminate well in intersections and overlaps. Fig. 5 shows the small range of possible laminating instances; in particular, the two options of tangential overlaps – horizontal and vertical. While laminating horizontally between two adjacent parts of the toolpath presented the most straightforward approach in terms of minimising extrusion errors, it also minimised the lamination area and thus the strength.

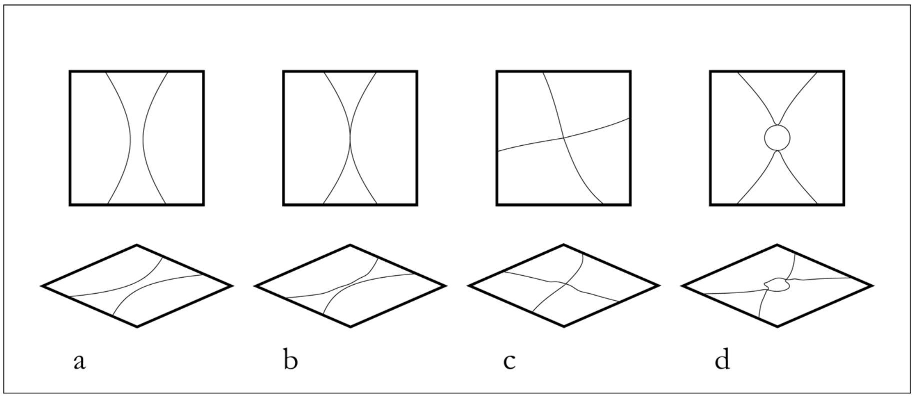

Figure 5. Intersection types

Conversely, by vertically overlapping the toolpath, the shared area was maximised; however, this also demanded a more precise calibration of vertical extruder movement. As seen in fig. 6, the extruded material tended to wear thin if the extruder moved too close against the bottom print, significantly weakening the mesh and thus snap under the weight of the concrete. Widening the toolpath's overlap approach and adding a second layer of thermoplastic solved these issues, but on the expense of toolpath simplicity and aesthetics.

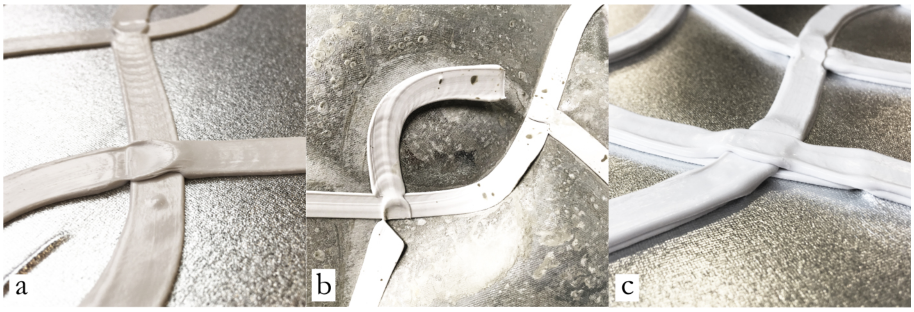

Figure 6. Printed intersections

Case study: Tailored flexibility II

The experiments described in the previous section succeeded in creating a baseline of performance between thermoplastic extruder, fabric formwork and concrete casting. However, as these initial tests were limited in both scale and flexibility, the second iteration of experiments introduced a larger scale, vertical casting and reinforcement.

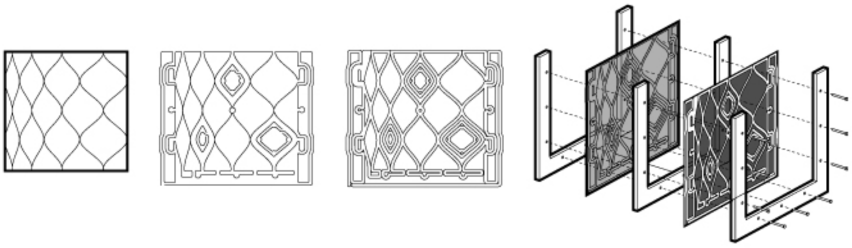

Figure 7. Vertical rig

The small-scale horizontal rig was converted into a vertical setup to fit two membranes in a double-sided cast (fig. 7). In order to locally clamp the shuttering, another intersection detail was added following the calibration of extrusion and toolpath intersections. By bridging itself twice, the print could be fitted around a bolt to control the thickness of the print. Also, closed individual toolpaths were added to be attached from both sides, thus creating block-outs through the concrete (fig. 8). These additions to the design space completed the fabrication method as a system that contains almost all necessary material and geometry to complete a double-sided cast with a vast form potential – a potential that is, however, dependent on the scalability of material performance.

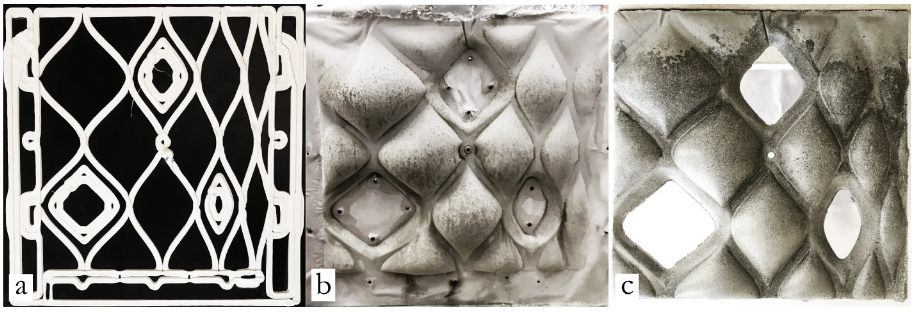

Figure 8. Printed vertical formwork with block-outs and clamp detail, partly de-moulded cast and the finished concrete piece.

While the performance of the thermoplastic printing medium itself had little effect on small-scale testing, its relevance sky-rocketed into the highest level of concern as the fabrication method was scaled up. Initial tests with ABS (Acrylonitrile Butadiene Styrene) thermoplastic exhibited high tensile strength but shrank during cooling, and since the distribution of plastic was uneven and asymmetric in each cast, the shrinking behaved unpredictably. Turning to PLA (Polylactic Acid) thermoplastic solved this issue; however, as the hydrostatic pressure and vibrations during pouring increased with scale, this shuttering proved catastrophically weak in terms of bending: While PLA performed well in tension, it was brittle and broke when challenged across the path of tension (i.e. the direction of hydrostatic pressure) (fig. 9). A third printing medium, TPU (Thermoplastic Polyurethane), performed very well elastically, but unfortunately stretched along the direction of tension. The fourth iteration of thermoplastic adjustment thus combined both PLA and TPU; sharing the same range of working temperatures, these materials were easily mixed in the extruder to produce a printing medium that would bend but not stretch. The feedback from concrete casting thus forced changes in printing medium as well as design and fabrication methods, tuning the shuttering to perform on a larger scale.

Figure 9. PLA clamping detail before casting and collapsed print after the pour.

Parallel to studies in printing media and vertical shuttering, efforts were made to develop a method of bending bespoke steel rebar for reinforcement. This task involved both the development of a robotic steel bending procedure as well as corresponding reinforcement and shuttering topologies. The “sine weave” tile employed in the small-scale vertical test translated well into a rebar topology for a large-scale experiment, designed as a self-supporting wall in three parts. A master surface was drawn by lofting a bottom sine curve with a top straight curve 180 cm in height, creating a self-supporting wall. Subdividing this surface into an asymmetric grid formed a basis to populate by tiles; the grid exhibited the highest density in the bottom to counter hydrostatic pressure, while the number of block-outs would increase as the tiles grew larger along the vertical. The rebar frame was modelled on this master surface and grid, while the shuttering was drawn on surfaces offset to both sides. By overlapping the rebar frame in eyelets corresponding to the clamping detail developed previously in the small scale tests, both sides of shuttering could attach to the reinforcement, locally keeping the shuttering in place (fig. 10). The cast was designed to demonstrate transitions and possibilities in the developed shuttering features while maintaining a tectonic expression as a self-supporting structure with the concrete mass concentrated towards the bottom.

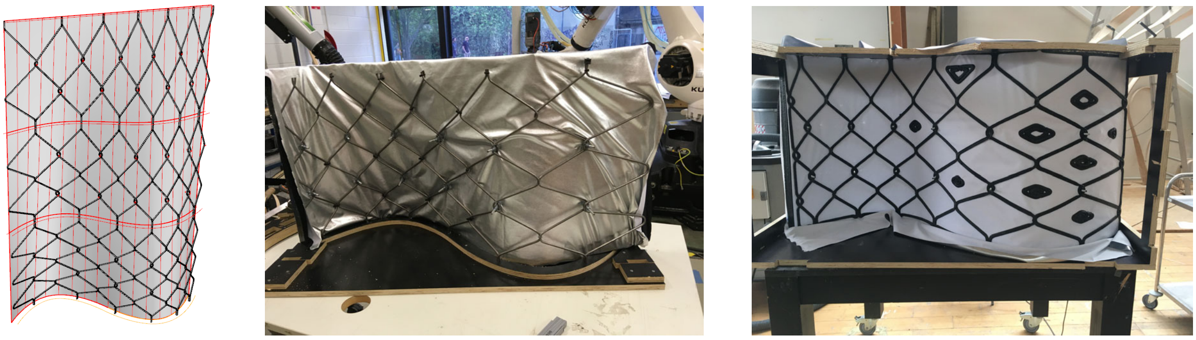

Figure 10. Master surface with rebar grid and details from formwork assembly of the bottom part.

The first generation of shuttering was printed in PLA thermoplastic and thus – as mentioned above – failed violently under the hydrostatic pressure and vibration. The redesigned material, however, performed well and proved exceedingly capable to withstand the substantial forces during casting (fig. 11).

Figure 11. Concrete casts in formwork printed with the redesigned thermoplastic hybrid.

Case study: Leaky geometries

This experimental series explored formwork composed of perforated sheets, initially in rubber and subsequently in plastic and steel. Inspired by the bespoke material potential embedded in kerf cut surfaces, the series departed in two versions (one 60 degrees and one 90 degrees) of a perforation pattern designed to exhibit varying degrees of freedom to expand under pressure. As this freedom depends on the membrane's ability to deform and force open the perforated cuts geometrically, forms would emerge as the liquid concrete forced bulges in the formwork and seeped through these perforations.

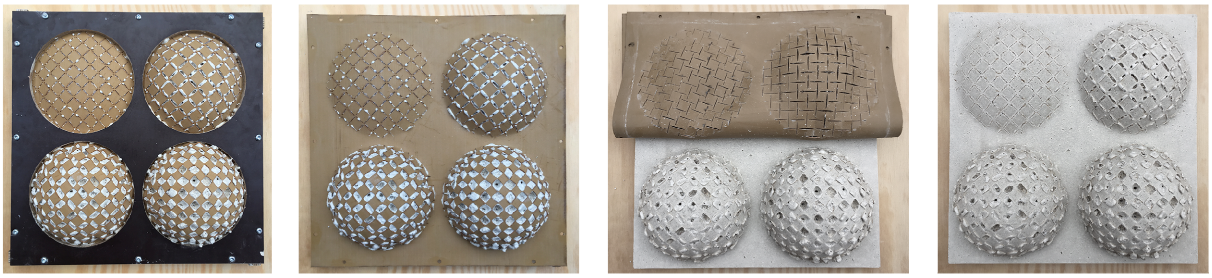

Figure 12. Demoulding of cast in the horizontal rig.

The first iteration of experiments identified and studied how pattern variables affected the physical process of casting in a 1 mm rubber membrane with perforations cut by laser. The setup consisted of a small rigid horizontal rig measuring 30x30 cm across with four circular cut-outs in the bottom to study membrane deformation (fig. 12). Both variations of the pattern demonstrated three distinct variables affecting their ability to deform: Pattern resolution, curve length and curve rotation (fig. 13).

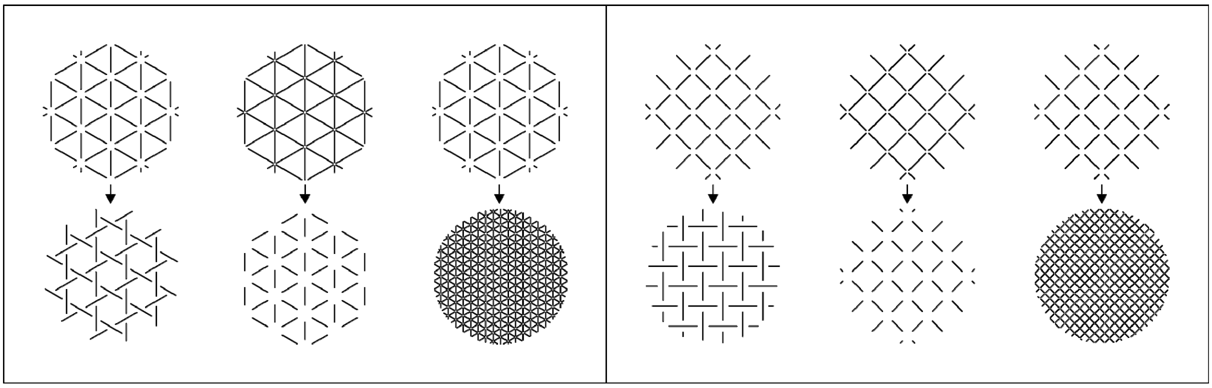

Figure 13. Three variables of both 60- and 90-degree pattern variations: Curve rotation, curve length and pattern resolution.

Across combinations of the three variables, a total of 18 casts were produced: A matrix of 3x3 casts for both versions of the pattern. The four circular bulges in each cast demonstrated four values of curve rotation, while the three rows and columns in each matrix represented three values of pattern resolution and curve length (fig. 14)

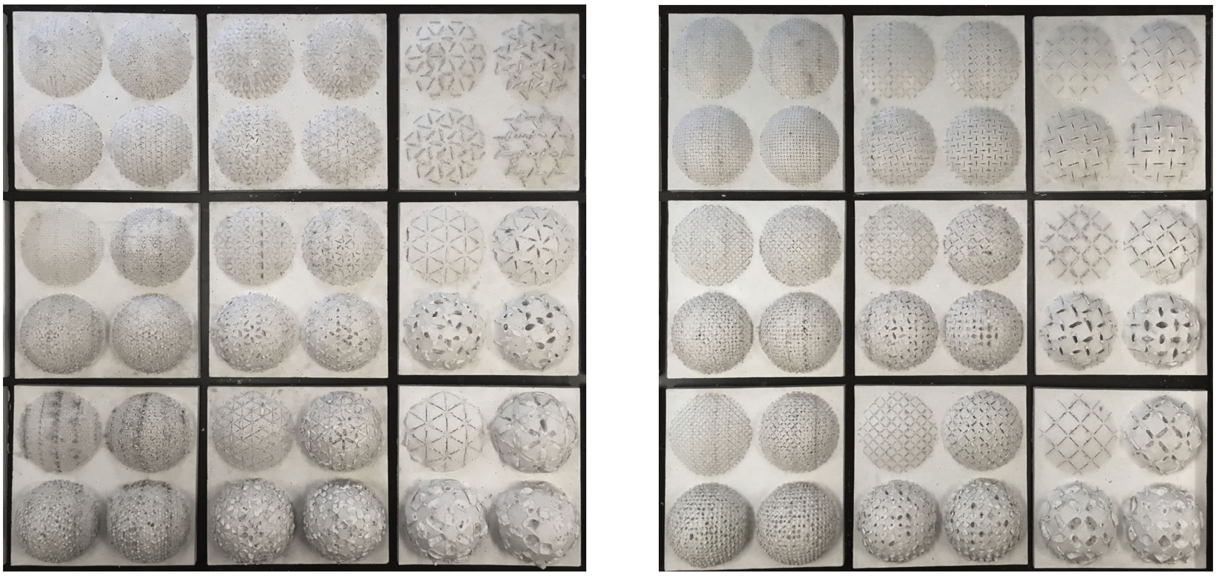

Figure 14. 18 casts in two 3x3 matrices surveying the range of variable combinations.

While the library of small scale tests covered the range of variable combinations, the studies were singular: Each bulge demonstrated a single combination of variables rather than a surface of transitions between local geometric behaviour. Three horizontal casts in a larger scale complemented the variable mappings: Each cast investigated a gradient transition in each of the three variables across the length of a 30x100 cm slab (Fig 15). These casts confirmed the deformation behaviour experienced in the small scale studies. However, since each membrane pattern was designed with a linear transitional gradient across the bottom surface, the concrete casts revealed any deformation deviating from this linear transition. The cast with a gradient in pattern resolution displayed the most extreme variation in deformation: With the tensile surface distributed across multiple more small connections in the high-resolution end (5 mm grid vs 20 mm grid), the rubber membrane deformed considerably beyond expected (fig. 15)

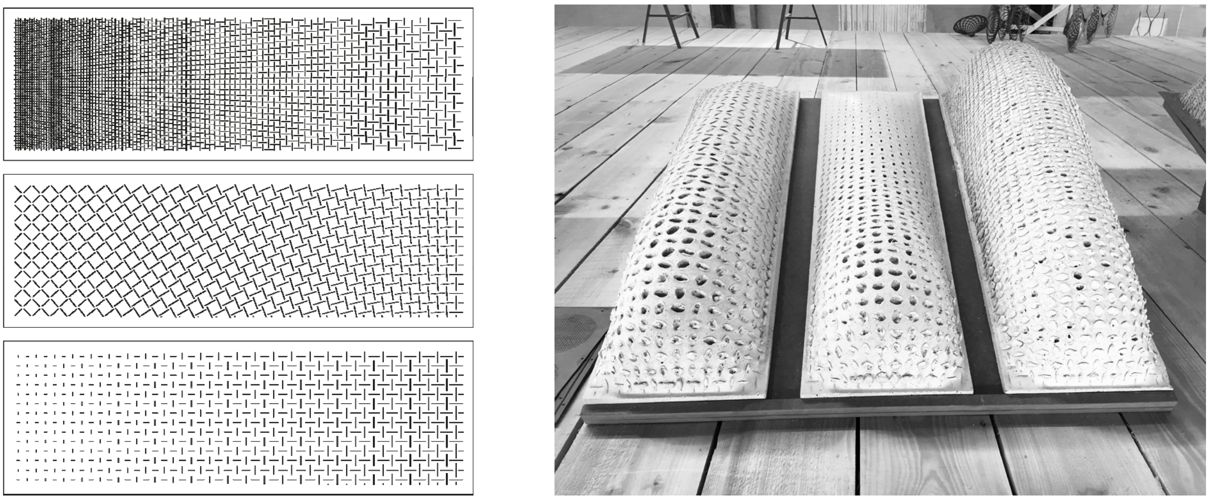

Figure 15. Three tests of transitions in the pattern – one for each variable.

Confronted by both the potential of the casting technique and the limitations of scalability in rubber, the third iteration of experimentation studied the method by replacing rubber with plastic and steel. These materials required the heavy-duty CNC machinery of a 3-axis router and a 5-axis water jet cutter. A column rig composed of three rigid sides and a fourth side of perforated sheet was designed to explore the effect of hydrostatic pressure on presumably stronger sheets of 0.5 mm steel and 1mm PTHD (Polyethylene High Density) and PETG (Polyethylene Terephthalate Glycol) plastics. This work was carried out as an undergraduate workshop, requiring the students to undergo three iterations of casting following their own articulated goals and agendas.

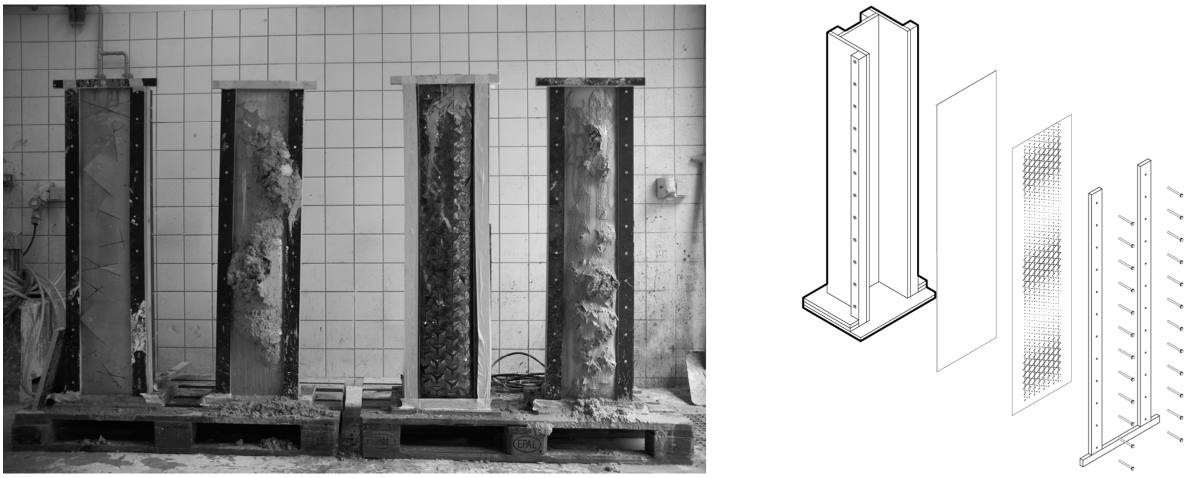

Figure 16. Casting rig diagram and physical casts in plastic and steel.

The steel series group focused on countering the effects of hydrostatic pressure in three distinct areas along the vertical, aiming to reach identical degrees of deformation. The first iteration employed identical perforation patterns in all three areas and demonstrated how the increased pressure towards the bottom caused more deformation than in the top — recognising that the variable limiting deformation was the number of rigid connections, the students designed each area with a different resolution of the pattern in the next iteration. However, since the low-resolution pattern had few connections, it was also the weakest and thus placed to withstand the least amount of pressure – and vice versa for the high-resolution pattern. In the second iteration, the students thus achieved their stated goal of similar deformation despite different hydrostatic pressure. The third iteration thus studied a continuous transition between pattern resolution from top to bottom (fig. 17)

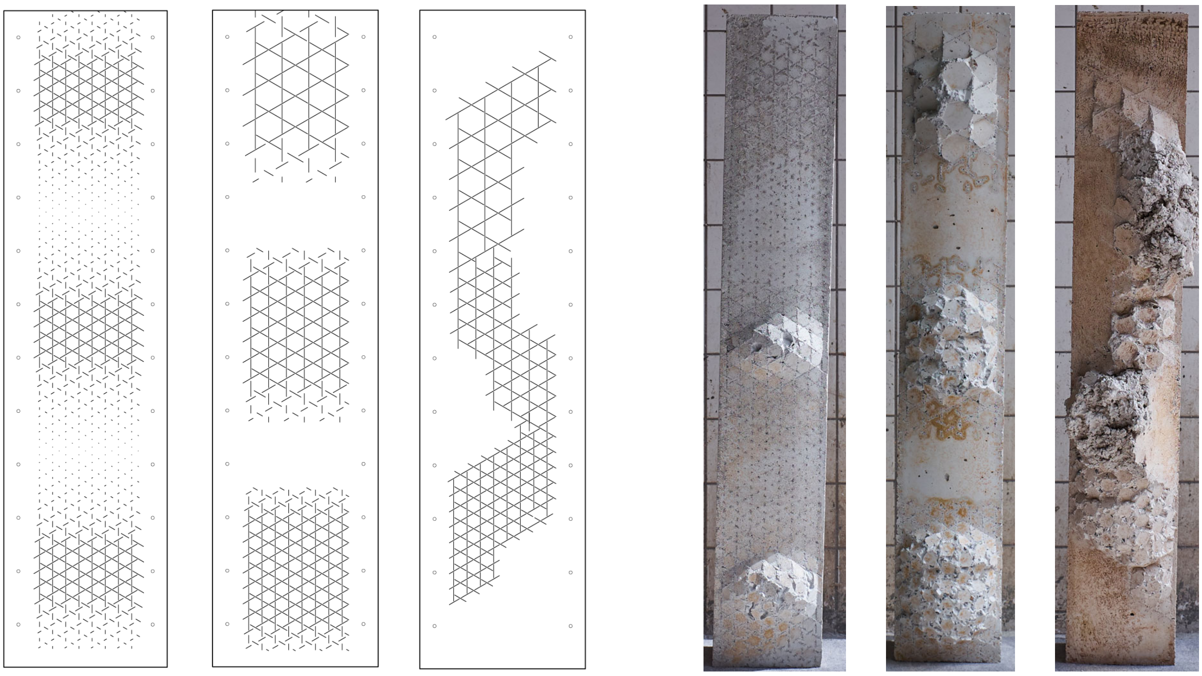

Figure 17. Three iterations of steel sheet design and corresponding concrete casts.

The plastic series group were intrigued by the limits of control and thus studied how changes in the hydrostatic pressure would affect the risk of sheet rupture and collapse. Utilising a weighted semi-random distribution of line lengths from top to bottom of the sheet, this group pursued a cast with ruptured areas sufficiently small to contain the concrete but sufficiently large and abundant to communicate the immense pressure change from top to bottom. The first two iterations demonstrated how strings of neighbouring weak links would rupture in long streaks and compromise the formwork entirely. In the third iteration, however, these areas were deliberately and precisely managed, and the sheet ruptured in small areas as desired (fig. 18)

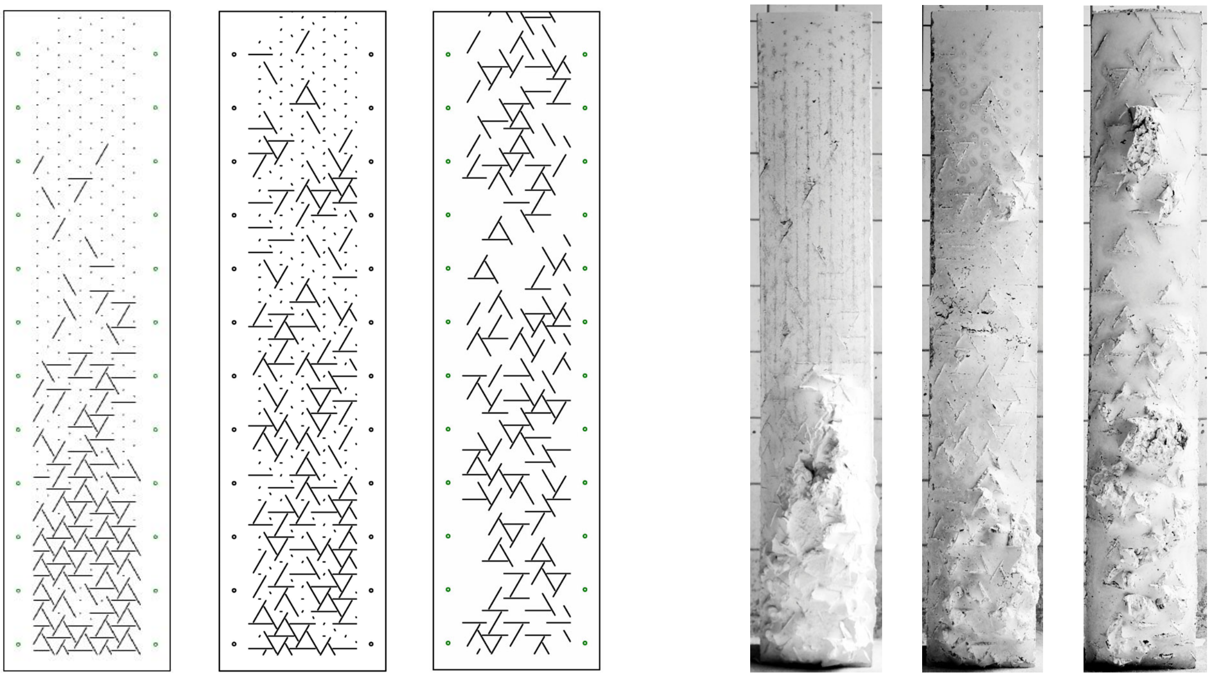

Figure 18. Three iterations of plastic sheet design and corresponding concrete casts.

Case study: Drawing concrete

The third experimental series explored variations of concrete 3D printing. While substantial resources have been and are currently being allocated towards research in and implementation of concrete 3D printing as one of the crucial new building technologies, most of these efforts focus on technical challenges like scalability and rheology. A part of this technique's appeal lies in reducing parts of the complex building into one single process; however, as with any critical application of building techniques and materials, asking what might emerge when one ignores any utilitarian demands may turn out impressive results. The experiments described in this section thus focus on the relationship between liquid concrete, extruder and external geometries rather than structural performance.

Concrete 3D printing depends heavily on control with and understanding of the microscopic interior performance of concrete. Tuning the rheology and aggregate composition to a substance that is fluid enough to pump yet robust enough to stay stable after depositing it is a delicate act of designing the concrete mix itself with suitable additives. Among others, recent work by the French enterprise XtreeE demonstrates both advanced control of printed layers (adding accelerator immediately before extrusion) and intriguing investigations of emergent aesthetics (XtreeE). As the cement-based mortars pumped in between concrete elements in the building industry to a certain degree meet these requirements, the experiments departed in such a standardised concrete product. Later studies and collaboration with the mortar manufacturer have brought products more specifically designed for 3D printing; however, these studies are not part of the work described in this section.

Initial studies focused on designing and manufacturing a concrete 3D printing end-effector with interchangeable nozzles, both motivated by calibrating concrete rheology and settling on suitable nozzle designs. By varying nozzle mouth sections, a range of prints was produced to study stability, material flow as well as aesthetics - initially sketching with the extruder by hand followed by controlled studies in printing with a 6-axis robot (fig. 19)

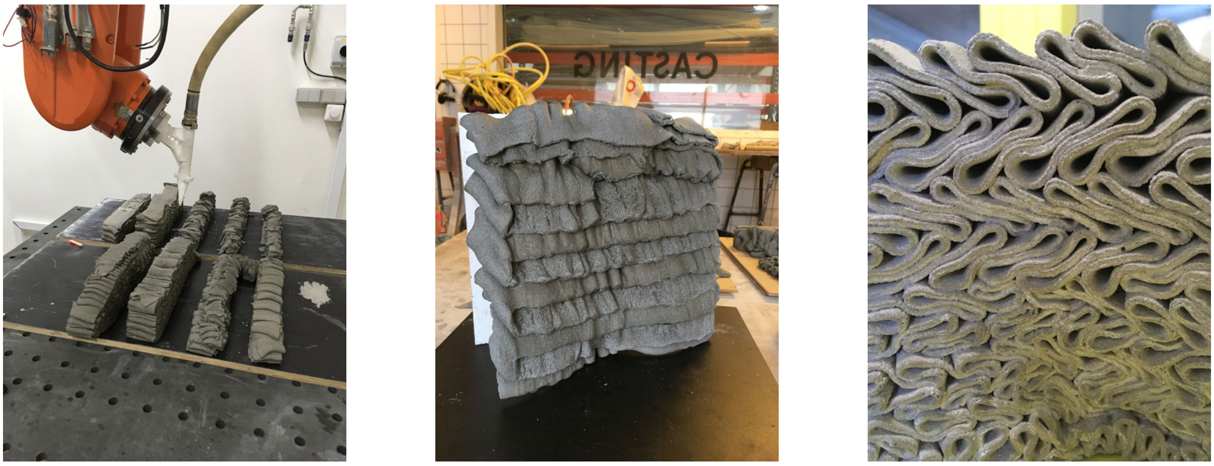

Figure 19. Initial concrete 3D printing test, both by robot and by hand

During a two-week undergraduate workshop, students designed and manufactured a range of bespoke nozzles employed to horizontally print an array of 60x80 cm concrete panels with vastly different material qualities. These panels were assembled into a wall section, exhibiting the range of textural qualities within each toolpath and nozzle combination.

Figure 20. End-effector nozzles, detail from a printed panel and wall assembly.

The workshop studies served as a catalogue to develop a series of facade elements for a local municipal pump station. Mounted into a steel frame, a total of 72 panels made up the semi-transparent façade, designed to allow a glimpse into the technical setup inside (fig. 21).

Figure 21. Detail of façade element and composition

Case study comments

The case studies each address and develop their agenda of materially informed digital fabrication and feedback. Initially departing from a well-calibrated process, the *tailored flexibility* project demonstrates the agility of large-scale thermoplastic 3D printing: The project departed from studies specific to liquid extrusion, but the technique proved able to not only adjust to the structural requirements of the small-scale formwork and rig but also scaling up to withstand a substantial amount of hydrostatic pressure. In this process the material logic and hierarchy governing the design changes moved iteratively further away from the fabrication itself, until the topological negotiation between steel reinforcement, hydrostatic pressure and thermoplastic ingredients.

Leaky geometries initially took inspiration from steel and wood to employ rubber as concrete formwork, only to turn back towards rigid materials following an increase in scale. The most remarkable experience is how the geometric logic turns on itself depending on the elastic properties of the membrane; while the high-resolution pattern can distribute the tensile forces along all the little bridges left in the perforated rubber, the rigidity and brittleness of steel removes the possibility for any such material behaviour without collapse. Instead, the logic reverses, and minimising the number of connections in the pattern becomes a tool to weaken the membrane, thus distributing the hydrostatic load on as few links as possible. Geometric and elastic properties in sheet materials are thus clearly illustrated through the liquid concrete.

Drawing concrete moves into the most abstract territory of designing conditions for liquid flow; not only is the printer designed to affect the cross-section of the extruded material, but this dynamic liquid also responds to the design of the movement. With the absence of any structural agenda, the design space exploration allowed approaches to emerge that were agile in response to specific design tasks outside the traditional range of concrete 3D printing –agility that allowed a comparably small distance to practical applications.

Findings

The three case studies each navigate uniquely in a field of two systems surrounding the concrete cast: One material and one technical (fig. 22). The horizontal axis outlines the difference between arm-based (6- or 7-axis robot) and gantry-based (laser cutter, water jet cutter, flatbed router, 3D printer) systems. The arm-based system is primarily characterised by flexibility: The end-plate interface of the robotic arm offers an open platform for bespoke tool design and complex three-dimensional processes; however, at the expense of precision and resolution. Conversely, gantry-based systems are characterised by high precision; however, they are highly specialised with comparably modest possibilities of customisation. The vertical axis outlines the material systems: From soft to hard, the materials explored in the case studies include liquid concrete, molten thermoplastics, fabric, rubber, solid thermoplastics, timber and steel.

The three case studies collectively cover a large part of this field: *Tailored Flexibility* benefits from the flexibility of the robotic arm in both formwork and reinforcement fabrication, while exploiting the precision of the gantry-based systems in manufacturing the rigid formwork as well as the robotic reinforcement bending rig. *Leaky Geometries* utilises the intricate tolerances of laser cutter, flatbed router and water jet cutter in a range of materials from soft to hard; the fine-tuning of both plastic and steel membranes both approached tolerances below 1mm and thus present clear examples. *Drawing Concrete* employs only soft material process; however, in widely different contexts: The extruder depositing the liquid concrete is a product of rapid prototyping by a small-scale thermoplastic filament printer. The emergent material behaviour produced through the movement of the bespoke robot arm end-effector is thus a product of a complementary and highly controlled process in another medium and scale.

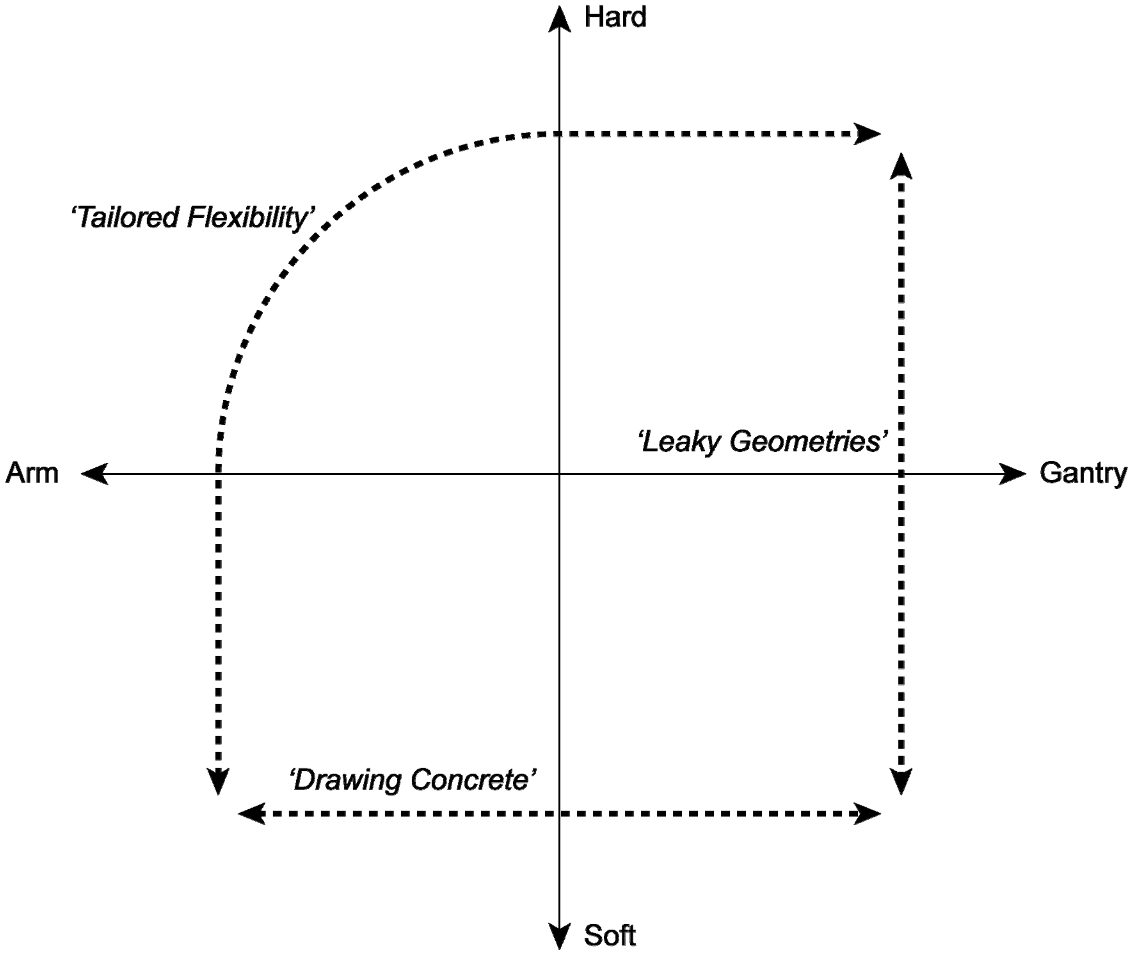

Figure 22 Fabrication means and material characteristics in the three case studies.

This navigation in material and technical affordances might suggest a discussion of appropriate levels of control and precision – and their effect on the cast concrete. While the digital fabrication processes of the *Leaky Geometries* series are undoubtedly the most precise, this precision ultimately serves the goal of articulating the gritty imperfections of the concrete compound. This counterbalance repeats itself in the execution of concrete extrusion vs concrete extruder. Conversely, the large-scale thermoplastic extrusion and steel rebar bending combined with the robotic arm produces a low-resolution result that nonetheless does not transfer to the cast concrete

The discussed case studies collectively inhabit a broad range of the material negotiation spectrum between total and no control. By each insisting on a departure in the ethical tectonics of allowing fluid memories to emerge, they might suggest not only individual modes of material negotiation but the outlines of intuitive navigation in the hierarchy of material affordances.

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