TAILORED FLEXIBILITY

Reinforcing concrete fabric formwork with 3D printed plastics

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Abstract. The tailored flexibility project seeks to develop a construction system that combines flexible formwork with robotic 3D plastic printing resulting in novel approaches that expand the ranges of both techniques. Combining 3D printing and flexible formwork does not necessarily suggest a unified design space and the development depends on thorough interrogation and critical assessment of the physical intelligence that emerges between digital design, manufacturing processes and structural integrity. This paper describes the initial prototyping of compound material behaviour in formwork and concrete, following the implicit rationales revealed through iterations and variations of physical experimentation. Such iterative feedback from physical prototyping informs and facilitates a discussion of the relationship between the manufacturing process and the design tool: How does the ultimate function as concrete shuttering transform the 3D printing process and how does this transformation conversely affect the shuttering design? How does a hierarchy of involved processes emerge and which composite opportunities do the initial results suggest as a further development into a coherent construction system?

Keywords. Concrete; flexible formwork; 3D printing; robotic fabrication.

1. Introduction

Concrete is the most commonly used building material internationally (U.S. Geological Survey, 2018). Due to its liquid beginnings, concrete offers tremendous formal flexibility. This flexibility is in practice limited, however, due to the cost, complexity and waste associated with the production of formwork. These limitations have led to the dominance of flat forms created from rigid - often timber - formwork, and avoidance of curved geometries. Flexible formwork has been used to create a wide range of concrete structures and has produced exciting new structural and architectural possibilities. Replacing rigid moulds with flexible materials offers many practical advantages as well as opportunities for improved structural efficiency (Hawkins et al., 2016).

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Additional complexities follow the use of flexible formwork, including a reliance on patterning and the creation of joints via sewing. While double-curvature is readily achievable, there remain significant limitations on the specific forms that are practically feasible. The introduction of additive manufacturing via robotic plastic extrusion alleviates many of the complications associated with fabric formwork while increasing the variety of forms and surface qualities that can be produced. The plastic is employed as a reinforcement medium for the membrane and thus transcends the common use of the material as a design medium itself. The strategic reinforcement of the membrane allows for a broader range of formwork materials, including highly flexible fabrics not previously employed in such processes.

2. Background

Despite concrete's dominance in modern building practice owing to its vast plastic potentials, limited efforts have been exerted towards expanding the vocabulary of formwork into variations in flexible materials. The majority of concrete is - and has been - cast in rigid moulds. Common to concrete production is that the shapes realised are constrained much more by the limitations of the formwork than by the limitations of the concrete itself. This formwork is typically timber, and the cost of producing especially double-curved timber forms has severely restricted the opportunities to build curved concrete structures. Curvature is often demanded in structurally efficient structures (e.g. shells), but timber (or milled foam) used for doubly-curved structures can lead to the production of significant waste. Fabric formwork addresses some of these issues as a sustainable alternative to traditional formwork, utilised as both a means to reduce material use in formwork and a means to realise more complex and structurally efficient forms.

The conventional approach to shape control with fabric is sewn tailoring and rigid edge fixation (West, 2006). Additionally, formwork stiffness is adjusted by pre-stressing the fabric or orientating it to articulate the direction of warp and weft (Hawkins et al., 2016). This method is not typically CNC controlled and therefore exhibits larger tolerances. While addressing the overall curvature, the method is thus not capable of addressing additional features, be they for ornament or the accurate incorporation of features such as rebar spacers and holes. However, the combination of, on one side, digital fabrication and analysis and, on the other, fabric formwork presents an appropriate match that in itself is not novel: Managing the contingent nature and strategic control of deformable membranes calls for the level of apprehension and precision that such tools offer. There have been recent advances in CNC 3D Knitting (Ahlquist and Menges, 2013) which solves several challenges of fabric formwork. However, the limitations of this approach include the use of proprietary control software, and (where the first limitation can be overcome) the relative complexity of learning the knitting logics and programming interface. Additionally, the fabric weaving is performed at a comparably microscopic scale, imposing restraints on manufacturing feasibility.

Other approaches employ different means to control the membrane. Several full scale construction elements by Mark West utilise custom timber block-outs, (West, 2006), a point and border constraints approach can be seen in recent work by Matsys Design (Fig. 1c) (Kudless, 2011) and manually placed frame restraints such as rope or wood have been employed extensively in especially projects by Kenzo Unno (Fig. 1a) and Miguel Fizac (Fig. 1b) (West, 2008) (Veenendaal et al., 2011). However, these methods do not allow the full range of possibilities described in this paper, as 3D print reinforced shuttering benefits from several features over the above-mentioned systems: The print does not only control the edge conditions, many more ornamental and textural effects are easily achievable , and target geometries can involve local deviations to the global curvature.

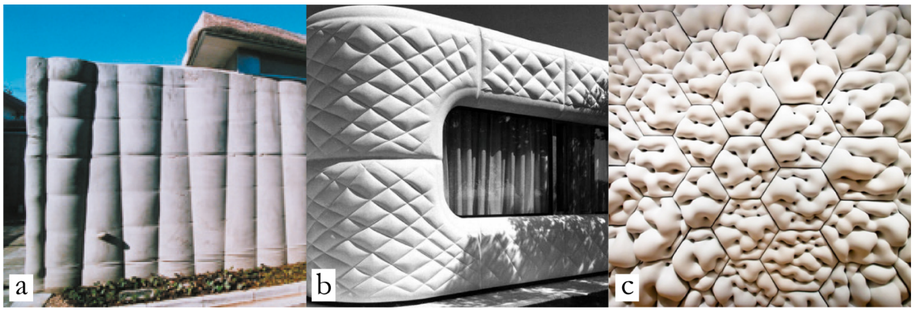

Figure 1. a. Wall by Kenzo Unno (Copyright: Kenzo Unno) b. Facade by Miguel Fisac (Copyright: Miguel Fisac Foundation) c. P_wall by Matsys Design (Copyright: Andrew Kudless).

3. Method

This study proceeded in several phases. The first tests focused on matching extrusion and fabric material to secure efficient adhesion. Secondly, tuning the print technique to account for deformation in the extruded medium, and thirdly, concrete composition. Parallel to the material investigations was a consideration of the potential for upscaling and generalisation involving critical assessment of the logic of additive manufacturing (in this case 3D plastic printing) versus the logic of tensile shuttering (fabric formwork).

3.1. FABRIC ADHESION AND SELECTION

The setup consisted of a large scale plastic extruder mounted on a KUKA 7-axis robotic arm and a 1200x2400 mm vacuum table. Unless stated otherwise, all extrusions were conducted with ABS plastic.

A variety of fabrics were tested to determine the best material for plastic adhesion. The textural quality and resolution of the fabric presented one variable that suggests perfect conditions for mechanical adhesion of extrusion material by partly penetrating the fabric. The coarse resolution of both tulle fabric and geotextile weaves suggested a sufficiently uneven surface for adhesion. However, due to the material composition of these fabrics (tulle made of polyester and geotextile of polypropylene), the chemical bonding properties appeared to be the primary means of adhesion, preventing the extrusion material to bond with the surfaces. Additionally, the porosity of both fabrics inhibited fixation to the vacuum table during printing, and thus the extruder would have pulled the fabric off the table had adhesion been more efficient. The limited mechanical adhesion issues turned the attention towards coated fabrics and lycra. Test with PVC coated fabrics - although being efficiently fixed to the vacuum table - displayed poor adhesion with the extruded ABS. However, liquid foil coated lycra produced the desired result: The coating sufficiently held the vacuum while also adhering excellently to the extruded ABS.

3.2. PRINTING LOGIC

The ambition of a continuous material deposit without any unnecessary stops, starts and vertical movement implied two strategic trajectories: Continuous extrusion in one single surface-filling curve or compositing a toolpath of discrete curve segments. Inspired by recent studies into the similar logic of continuity between material deposition and surface-filling curve algorithms (Efthimiou and Grasser, 2018), (Bhooshan et al., 2017), initial efforts focused on expanding a straight curve to the entire print surface by a physical agent-based simulation of parts. However, this mechanism did not replicate any design features other than the density of curves across the print surface and corresponded poorly to the structural requirements of the shuttering. This method was thus abandoned, turning attention towards methods of toolpath discretisation.

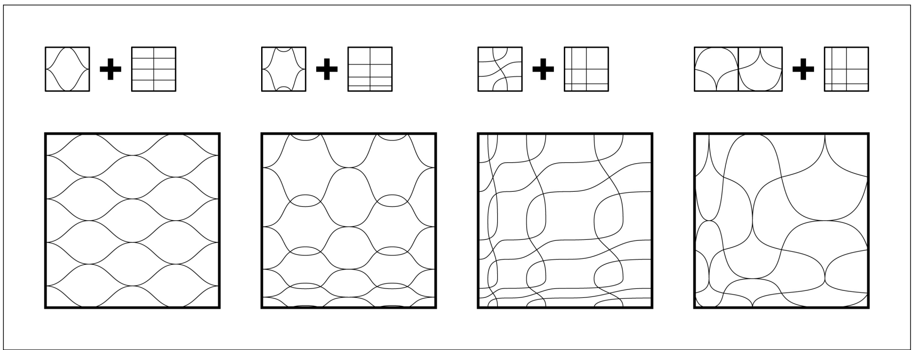

Figure 2. Small selection of combinations of tile designs and pixel distributions.

A voxel-based approach (Retsin and Garcia, 2016) - or in this case pixels - allows both intricacies in designing individual pixels and a large degree of control in varying the scale of pixels across the printing surface. The second trajectory focused on designing pixels based on variations of Truchet tiling, in which any tile edge connects to neighbouring tiles with curves of equal amount and distances. Any edge between two pixels thus aligns regardless of deformations of the pixels themselves, guaranteeing a continuous curve across pixels. By combining pixel rotation with curve amount and placement on pixel edges, a library of discrete parts was developed to evaluate and test their implications on shuttering performance (Fig. 2).

3.3. DETAILING

The tiling of discrete pixels introduced more control and thus local tuning of shuttering through both scaling and tile selection. Tiles with overlaps and crossings worked well with the tectonics of concrete formwork as a tensile mesh but introduced bridging and self-adhesion to the manufacturing process. Tangential toolpath intersections presented two options: A horizontal intersection with the benefit of no vertical motion and complete adhesion to the fabric - but a small area of attachment between the intersecting print material (Fig. 3a) - and a vertical intersection with larger overlap area, but locally weaker adhesion to the fabric (Fig. 3b). Toolpath crossings involved the print bridging itself (Fig. 3c) with a risk of dragging the printing layer thin and thus locally weaken the shuttering at structurally essential nodes in the mesh. Lastly, a third detail incorporated formwork clamping into the toolpath design, bridging itself twice, creating a loop through which a bolt and nut would fit (Fig. 3d).

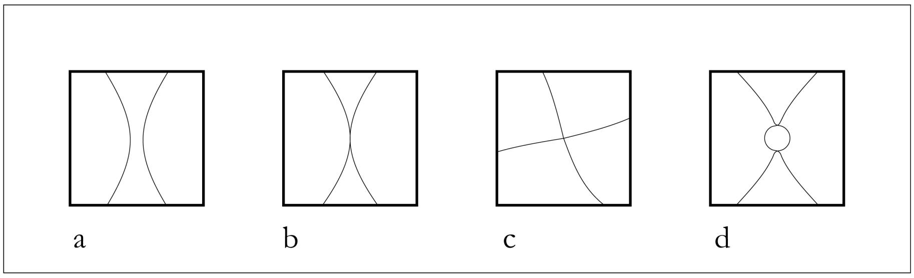

Figure 3. Intersections: a. Horizontal overlap b. Vertical overlap c. Crossing d. Clamp opening.

3.4. HORIZONTAL CASTING

Initial casting tests consisted of a horizontal rig with rigid sides and the tailored shuttering acting as the formwork bottom. The tailored shuttering was clamped in between two frames and mounted on vertical supports to allow the shuttering to expand and deform under the weight of the concrete (Fig. 4d). The frame - and thus the concrete casts - had a square measure of 400x400 mm. The printed shuttering was strengthened through several iterations of design transformation from the pattern (Fig. 4a) to the toolpath design (Fig. 4b), securing sufficient clamping in the rig. Designing the toolpaths to wrap around clamps and fitting these paths within the rig frames supported the printed shuttering and cast with a solid fixture in the rigid casting rig, preventing the weight of concrete to pull out the printed shuttering (Fig. 4b and 4c).

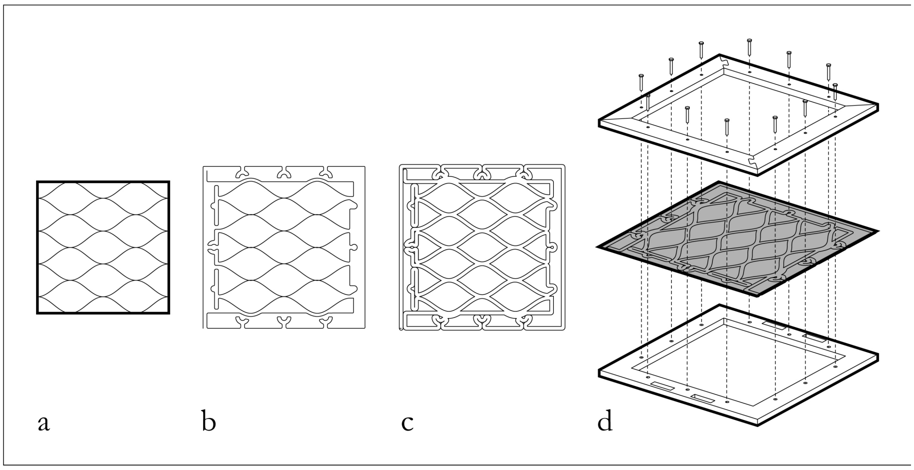

Figure 4. a. Tiled pattern b. Toolpath c. Print preview d. Casting rig.

3.5. VERTICAL CASTING

The horizontal casting tests fine-tuned the printing process and allowed a shift towards vertical double-sided casts. A 400x400 mm rig clamped together the printed membranes with an 18 mm form ply edge in between as formwork edge and thus minimum membrane distance (Fig. 5d). The vertical casting technique maintained the clamping rationale of the rigid frame developed in horizontal casts (Figs. 5a, 5b and 5c) and the printed clamping detail on both membranes provided precise reference points for matching the two sides and control their distance. Furthermore, block-outs created openings through the concrete related to Mark West's *pinch mould* (West, 2006), however with expanded flexibility: The block-outs do not introduce any additional manufacturing techniques while maintaining a vast potential for possible forms. With the addition of block-outs in the vertical formwork, the vocabulary of the tailored shuttering consists of three distinct parts: Fabric, a semi-rigid printed mesh and rigid printed block-outs.

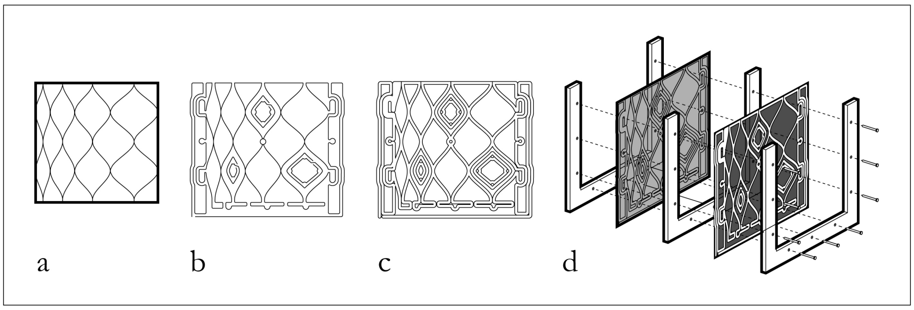

Figure 5. a. Tiled pattern b. Toolpath c. Print preview d. Casting rig.

4. Findings

4.1. PRINT PROCESS

The ABS print shrank during cooling, thus warping the fabric and change the fit with the casting rig. This effect only increased when more printing layers were added, irregularly warping the plastic due to the asymmetry of the prints. PLA solved the issue of shrinkage but introduced weaker tensile strength and brittleness. The printing overlap details locally weakened the tensile strength of the plastics, as the extruder would pull the print layer thin in the transition between fabric and print (Fig. 6a and 6b). More layers were introduced (Fig. 6c); however, the added material thickness decreased the global flexibility of the shuttering. These issues with material strength and shuttering flexibility suggest further studies into printing media with different mechanical properties.

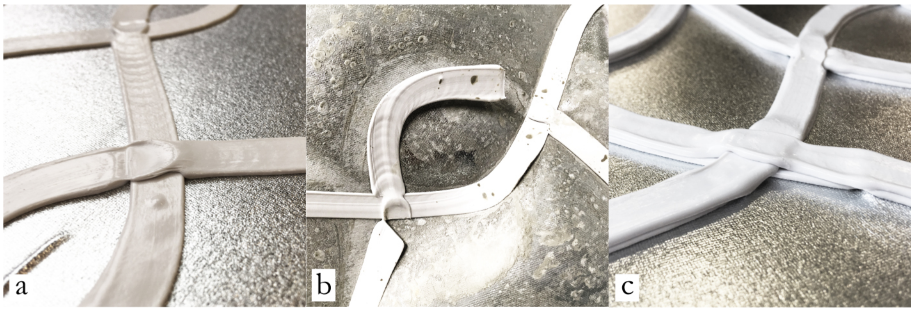

Figure 6. Print details. a. Single-layer bridge b. Bridge fracture c. Multiple layer print.

4.2. CONCRETE CASTING

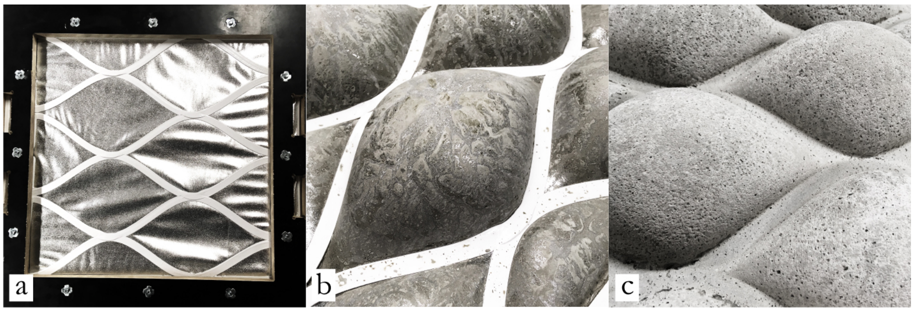

Figure 7. a. Printed shuttering in rigid frame b. Shuttering before demoulding c. Concrete cast.

The initial casting tests addressed the strength of the combined shuttering of fabric and plastic extrusion in negotiation with the weight of liquid concrete. While the agent-based toolpath generation approach produced a weak and low-resolution printed tuning - and was thus abandoned - the discrete part toolpath generation allowed structural considerations to enter into the shuttering design as individual tiles incorporated intersections and overall predictability (Fig. 7a and 7b). The liquid foil side of the fabric adhered very well to both ABS and PLA but left the untreated side of the fabric as the casting surface. The rough structure of this side of the fabric prevented air pockets in the surface from escaping efficiently and unfortunately adhered very well to the hardened concrete, impeding demoulding of the fabric formwork (Fig. 7c). This issue was solved by lining the formwork with a layer of fabric turned smooth side in, totalling four layers of fabric for a double-sided cast.

The printed parts of the shuttering stabilised the fabric in the vertical formwork rig while retaining the necessary flexibility to accommodate assembly and disassembly. While the plastic regained some rigidity during casting, the concrete pressure challenged its tensile strength and forced it to stretch, requiring clamps at regular intervals to locally fix the distance between the two formwork sides (Fig. 8a). The limited strength of the plastic thus introduced two resolutions of support: An overall distribution of clamps and a finer-resolution mesh of printed material - both of which had a finite limit in scale to prevent collapse. Printing bespoke ‘pinch-mould’ details to block out the shuttering and locally create openings through the casts mainly relied on the rigidity of the two clamped sides rather than adhesion and tensile strength - and thus proved efficient (Fig. 8b and 8c).

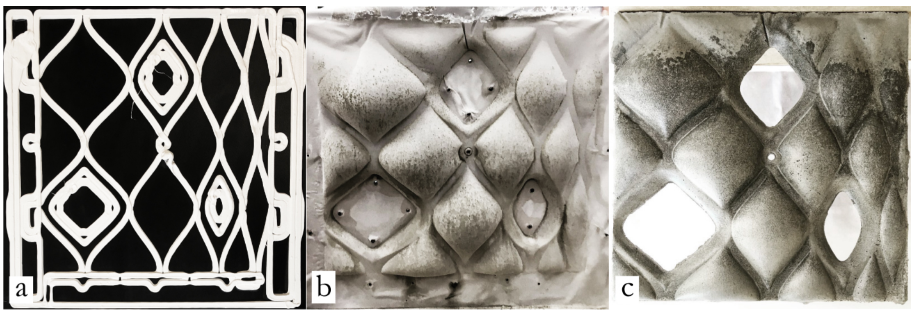

Figure 8. a. Printed shuttering b. Fabric shuttering with cast c. Concrete cast.

4.3. FEEDBACK

Initial persistent modelling feedback between virtual and physical design spaces was initiated through scanning and simulation. The horizontal casts were photogrammetrically scanned to study the deformation of both fabric and printed shuttering parts. The section drawings of the scanned casts (Fig. 9) show that both parts exhibit degrees of deformation. The two-directional stretch of the fabric seems proportional to the unreinforced area, while the printed plastic mesh only stretches slightly under the weight of the concrete. Tuning the shuttering by locally changing mesh density appears to have the desired effect; however, the large and heavier concrete bulges in low-density print areas affect the printed shuttering asymmetrically, emphasising the need for modelling feedback. The scans of the physical casts are supplemented by simulated geometry generated by dynamic relaxation employing unary downward vertical pressure and differentiated elastic properties of fabric and plastic shuttering (Fig. 9). A comparison of the section drawings of virtual and physical geometries indicates overall similarities in shuttering behaviour; however, further iterations of the simulation method will incorporate the uneven distribution of concrete pressure in the formwork. This evolution of virtual feedback should be able to sufficiently anticipate the cumulative effect of material build-up in the formwork and progress into a design tool that incorporates the compound effect of concrete, fabric and plastic extrusion into the shuttering design.

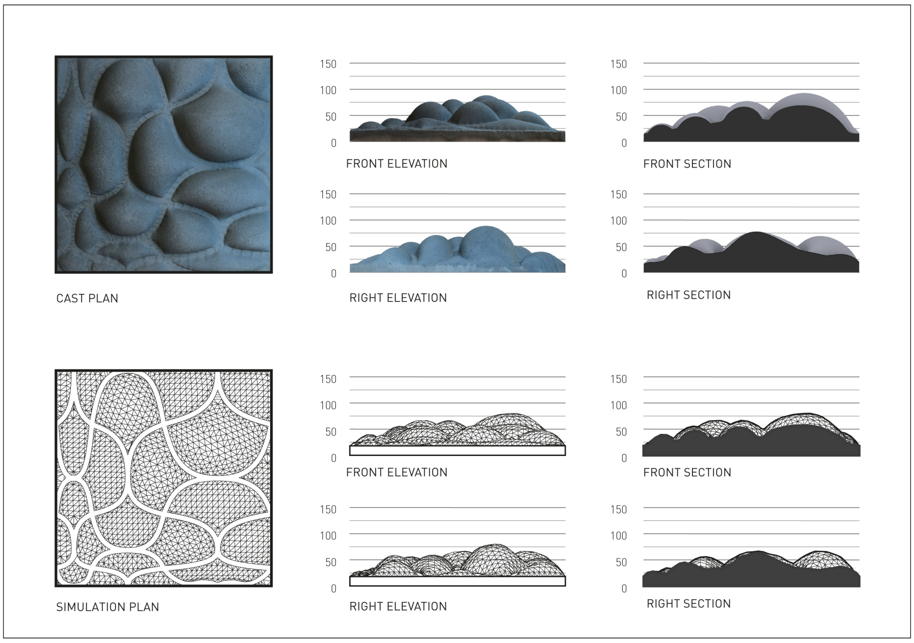

Figure 9. Plan, elevations and sections of the scanned cast and simulated geometry.

5. Conclusion

The process of tailored shuttering presents a vast space of possibilities from a limited amount of variables: Tile design and pixel scale as well as clamp geometry and distribution. All operations are performed on a two-dimensional surface, yet the output maintains enough flexibility to bend into a three-dimensional form and rigidly stabilise it when in place. The process thus affords a high complexity in material manifestation through a low complexity in formal operations and design. Since the flexibility of the tailored shuttering allows it to adapt and attach to non-flat geometries, the process suggests a combination with bespoke bent rebar reinforcement that might offer enough rigidity to avoid any additional formwork components.

The balance between rigid formwork strength and the brittleness of extruded plastic underlines a transfer of hierarchy in logic from additive manufacturing to the tectonics of concrete formwork as a tensile structure. While not ignoring the specifics of material deposits that are central to successful printing, these specifics did become subordinate to the ultimate performative rationale of shuttering. The method thus introduces three principal levels of material rationale: The logic of additive manufacturing, the logic of mechanical adhesion and the logic of tensile shuttering. By implementing the large-scale plastic extruder as a manufacturing tool to facilitate other physical processes rather than as a design tool itself, the process benefits from communicating with the nuances of the architectural manifestation as a multi-material synthesis of order and form rather than a naïve mechanical manipulation. Introducing bespoke reinforcement in future studies will only underline the disciplinary multitude of combining multiple manufacturing processes in realising concrete casts.

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