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Research Aim and Objective

The wider aim of this research is to explore the architectural potential of additive manufacturing (AM) for prefabricating large-scale building components. It investigates the use of AM for producing building components with highly detailed and complex geometry, reducing material use and facilitating the integration of technical infrastructure.

In order to achieve this aim, the concept of stay-in-place 3D-printed formwork is introduced (Fig. 01). AM is employed to produce sandstone formworks for casting concrete in any shape, regardless of geometric complexity (Fig. 02). This approach explores the synergy between the geometric flexibility of 3D printing sand formworks and the structural capacity of concrete. It allows the production of composite components with properties superior to either individual material.

Figure 1. Stay-in-place 3D-printed sandstone formwork for high-performance fibre-reinforced concrete.

This new fabrication method is demonstrated and evaluated with two large-scale 1:1 ceiling slab prototypes (Figs. 03 and 04), which are described in this paper.

Figure 2. Casting of ultra-high-performance fibre-reinforced concrete in 3D printed sandstone formwork.

Large-Scale Binder Jetting Technology in Architecture

3D printing, or additive manufacturing, refers to the process of producing artefacts by successively adding material using a Computer Numeric Control (CNC) system. A digital 3D model of an artefact is created and is sliced along a vertical axis. The data about each slice is then translated and fed to a 3D printing machine, and the machine creates the artefact by building up material, layer by layer.

There are a few different types of AM technological processes. In the context of architecture, the interest lies in those AM processes that enable the production of large artefacts on-site and prefabricated components off-site. This research focuses on binder jetting for prefabrication (Fig. 05). Binder jetting is an AM process in which a liquid bonding agent is selectively dropped on thin layers of powder material to bind it.

Several characteristics of binder jetting make it interesting for prefabrication in architecture. Due to the nature of the process, binder jetting can theoretically be used with any powder material that can be bonded (cement, plastics, ceramic, metals, sand, sugar, plaster, etc.; Rael and San Fratello, 2011). Moreover, this process has the advantage that within a set bounding box, increasing geometric complexity results neither in longer production time nor in higher cost. Complex cantilevering forms and even interior structures can be 3D printed without auxiliary support, because the powder bed itself performs this function. Lastly, there are a number of larger-scale facilities that use binder-jetting technology to produce large-scale artefacts. An example is the D-shape system by Enrico Dini (Dini, 2009). This is one of the largest 3D printers in the world, but unfortunately this system only reaches a limited resolution. This resolution depends on the grain size of the powder, the layer-height, and the resolution of the printhead. In contrast, there are industrial 3D sand printers that can produce parts that are both large and highly detailed. Currently, they are used by the foundry industry for producing moulds for metal casting. These moulds can be printed at a very high resolution, in the range of a tenth of a millimetre, and at a maximum volume of 8 m^3.

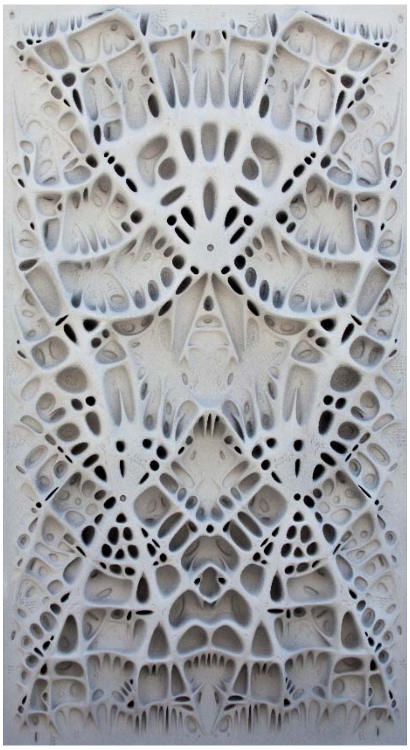

Figure 3. Prototype A: material is efficiently distributed in a ribbed substructure to reduce weight.

Figure 4. Prototype B: material is efficiently distributed in a porous, tubular structure to reduce weight.

The project *Digital Grotesque* by Dillenburger and Hansmeyer (2013) demonstrated the potential of 3D printing sand for the fabrication of highly detailed freeform components in architecture, yet the use of 3D sand printing in architecture has barely begun to reach its potential. A reason for this is that large-scale 3D-printed sand parts are too weak to operate as a building material—the bending strength of 3D-printed sandstone is very low. As a result, the current applications are limited to building components which are mostly under compression.

Figure 5. Industrial binder-jet 3D printer fabricating the formwork for Prototype A.

Research Questions

The central question of this research is how to use the unique advantages of 3D-printed sandstone and overcome its limitations in order to enable the fabrication of large-scale building components. The research introduces and examines the concept of stay-in-place 3D-printed sandstone formworks as a solution that combines the geometric flexibility of 3D printing sandstone and the structural capacity of concrete (Figs. 06). Specifically, the following questions are investigated:

- How do concrete and 3D-printed sandstone interface? To answer this question, the fabrication constraints of 3D-printed formwork and the performance and efficiency (functional, structural, material) of the resulting load-bearing building components are investigated.
- What is the impact of this new fabrication process and geometric freedom on the design of architectural components? Can this approach facilitate the fabrication of fully integrative building components with reduced material?

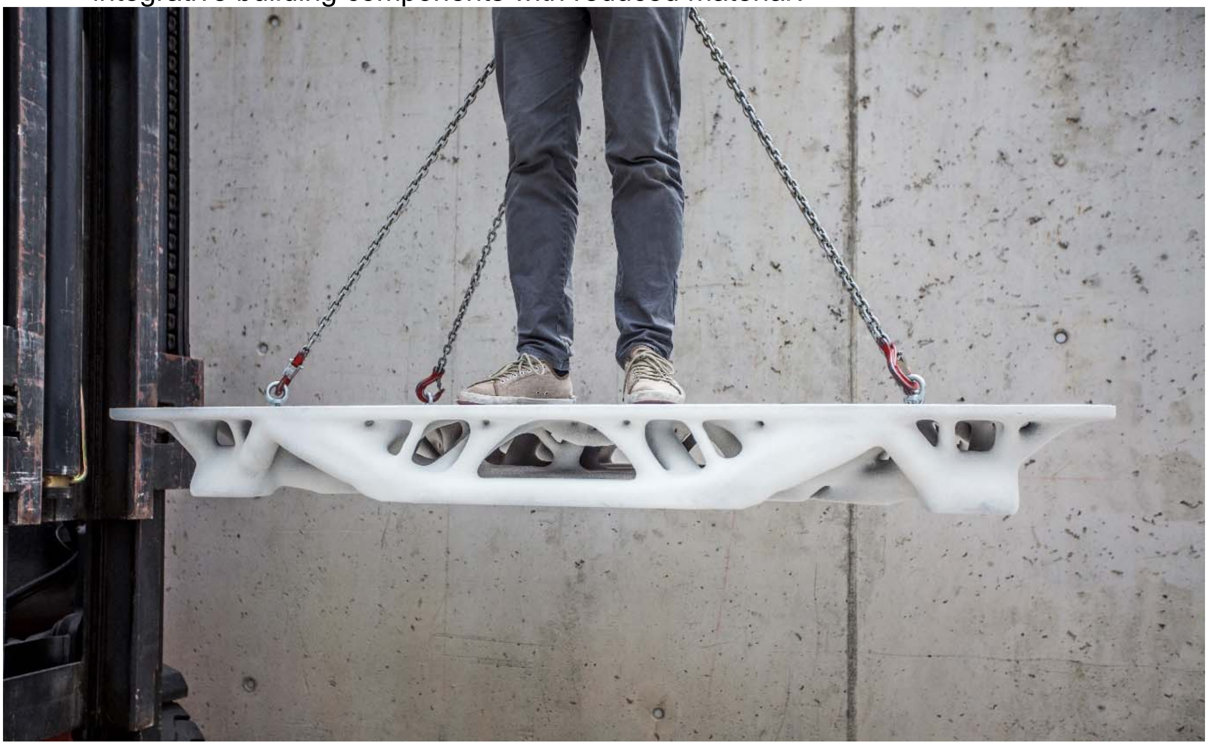

Figure 6. Prototype B: structural slab element with load-bearing capacity.

Research

One reason to search for new ways to fabricate complex forms with fewer constraints is that doing so allows us to reduce material use through the optimized design of components: wall thickness can be adapted, and undercuts, microstructures, and complex branching topologies can be fabricated.

With its excellent geometric flexibility—recesses, undercuts, internal voids, and tubular structures are possible—3D-printed sandstone formwork lends itself well to the production of such complex architectural elements. The main means of demonstrating the feasibility of this construction method in this research is the production of two large-scale 1:1 slab prototypes. The two prototypes investigated forms which were found by computational strategies (e.g. topology optimization). The target objective of the optimization was to reduce material use and efficiently distribute the remaining material in order to maximize the slab’s strength.

Figure 7. Detail of prototype A, showing the precise details of the finely ribbed substructure.

Prototype A (Figs. 04 and 07) is a slab designed for a load-case with three supports in the centre. This slab folds into a hierarchy of ribs that give stability to the large cantilevering areas. Prototype B addresses a load case of four perimetral support points (Figs. 03 and 06). It features a sophisticated topology of tubular elements branching in three dimensions (Figs. 08 and 09). The amount of concrete contained within (50 litres) corresponds to a solid slab a mere 3 centimetres thick.

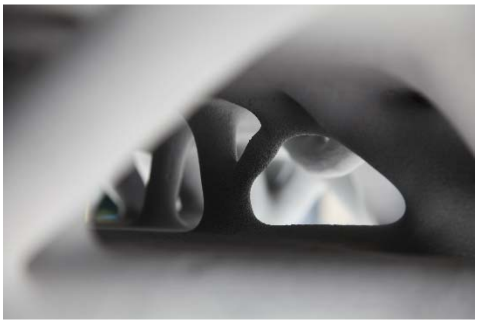

Figure 8. Tubular structures of prototype B.

Figure 9. Intricate network of channels with undercuts in prototype B.

To produce the large prototypes, the following steps were taken:

- compression and bending tests of combinations of different types of powders and binders;
- structural tests of different concrete mixtures considered for the potential combination with sand-print;
- rheology studies of casting concrete in sand-printed formworks of different geometries to derive a formal vocabulary as a design guideline (Fig. 10);
- exploration of various computational design strategies to optimize the use of the chosen fabrication method with respect to the structural limitations of the material.

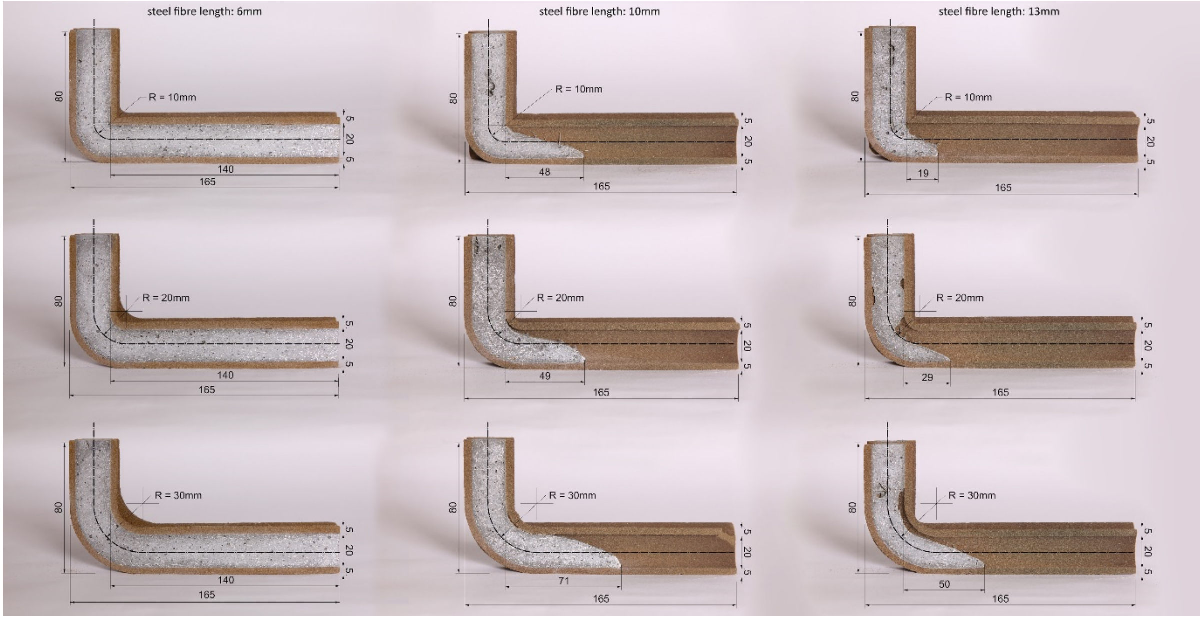

Figure 10. Development of a lexicon of formal constraints from rheology studies.

Because its main use is casting moulds for metal, relatively little was known about the structural properties of 3D-printed sandstone. A series of tests was therefore initiated to measure its resistance to compression and bending forces. The tests showed that 3D-printed sandstone has reasonably good resistance to compression, but is brittle when exposed to bending forces. Below is the list of parameters involve in the compression and bending tests:

- Parameters of the compression tests:
  - size of the specimens: 50 x 50 x 50 mm;
  - binders used: phenolic and furanic resin, with and without epoxy surface infiltration;
  - spatial orientation in the printer bed: X, Y, and Z;
  - number of specimens per combination: 3;
  - total number of specimens: 36;
- Parameters of bending tests:
  - size of the specimens: 250 x 50 x 50 mm;
  - 3-point bending, supports at 200 mm distance, central point load;
  - same binders, orientation, and number of specimens as the compression tests (36 specimens in total);

The compression and bending test was also applied for parts with different types and binders; as Table 1 shows, the difference between binder types is only marginal, apart from the bending strength of infiltrated parts. This is because the sand is less densified during printing, and heat curing vaporizes more of the liquid. As a result, more resin infiltrates the part. As expected, additional infiltration hardens the parts significantly and increases their strength.

	Phenolic binder (PDB)		Furanic binder	
	without infiltration	with infiltration	without infiltration	with infiltration
Compression strength [MPa]	8.56	12.32	8.46	12.80
Bending strength [MPa]	2.95	8.85	2.96	6.49

Table 1. Experimentally determined load-bearing capacities of 3D printed sandstone.

The behaviour of 3D-printed sandstone in combination with ultra-high performance fibre-reinforced concrete (UHPFRC) was investigated together with the group for Physical

Chemistry of Building Materials (PCBM, D-BAUG, ETH Zurich), with the following four main intentions (Fig. 11):

- develop a concrete recipe with adequate admixtures that has the desired rheological properties;
- adjust the length and content of the steel fibre reinforcement to achieve ductile behaviour while maintaining ability to cast in narrow channels;
- understand the impact of the porosity and sorptivity of the 3D-printed sandstone formwork (how do the capillary absorption and transmission of water of the 3D-printed sandstone influence the hardening of the concrete?);
- mechanically test the bond between the two materials as a composite.

The details and results of the study are documented in “3D Sand-Printed High Performance Fibre-Reinforced Concrete Hybrid Structures” (Stutz, Montague de Taisne, 2016).

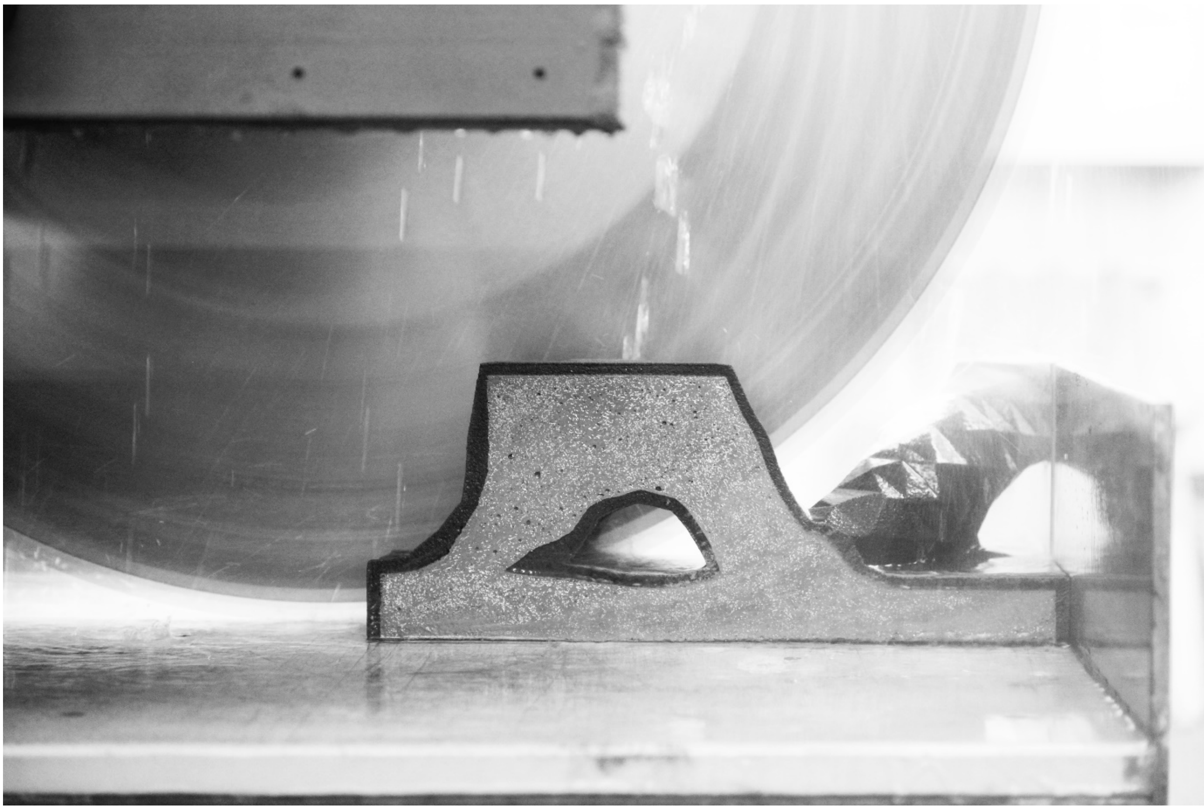

Figure 11. Slicing a sample to investigate the quality of the casting process.

From a design perspective, an important finding of this thesis project is a series of formal guidelines. According to these, cavities and tubular structures in the formwork can be dimensioned in relation both to the length and volumetric content of the fibres in the concrete mixture. These guidelines informed the design of the two prototypes in terms of dimensioning and controlling rheological aspects with regard to the concrete casting process. Moreover, both prototypes exploit the entire size (180 x 100 cm) of the Ex-One S-MAX 3D printer bed.

Research Evaluation

Production of formworks with a high degree of detailing and precise geometric features for large concrete components is very challenging—and sometimes impossible—if using other formwork fabrication methods such as robotic wire cutting, three- and five-axis CNC milling, and fabric formworks. The described 1:1 slab prototypes show how 3D printing can facilitate the fabrication of such formworks.

3D printing is particularly suitable for producing stay-in-place formwork. This is because the bond between the sandstone formwork and UHPFRC is very durable. Mechanically removing a nine-millimetre-thick layer of 3D-printed sand completely requires pressures greater than 3,000 atm with a water jet. Removable temporary formwork is possible (and was successfully tested in another project), but requires a coating treatment of the formwork which closes the pores to prevent the concrete from percolating through the sandstone formwork.

The geometry of the formwork and the minimum dimensions of its hollow features were dictated by the constraints of the fabrication processes, post processing of the 3D-printed formwork, and rheological properties of the concrete mix.

Parameters Related to 3D Printing Sand

The post-processing involved removing loose sand from and infiltrating the outer surface of 3D-printed formworks. Thus the geometry and diameter of the hollow features had to be designed in such a way as to facilitate removal of the loose sand (Fig. 12).

Figure 12. Post-processing of a 3D-printed sandstone formwork for prototype A.

The thinness of the 3D-printed formwork as it relates to the fabrication process was also studied. This dimension was tested from 6 to 10 mm, and thinner walls were found to be unstable during the removal of loose sand (due to erosion from compressed air jets or vacuuming) as well as during casting (as hydrostatic pressure built up in deeper channels and penetrated the thin formwork walls).

At 1.8 m^2, the overall size of the components also approached a limit in terms of both the manipulation of the formwork and the stability of the 3D-printed piece. While smaller parts can increase the complexity of the assembly, they are easier to handle. Therefore, the dimensioning of the parts is always a trade-off between weight, number of connections, and logistical factors.

The tests revealed the fact that the friable nature of the 3D-printed sandstone needs to be carefully considered, especially when scaling up the manufacturing process and fabricating components in larger volumes. A strategy to avoid damaging the formwork before casting by integrating a protective bed of unbonded sand contained within a closed 3D-printed box that also provided auxiliary support during casting was successfully tested (Fig. 13).

Figure 13. Integration of an auxiliary bed of unconsolidated sand contained within a closed 3D-printed box under the prototype.

Parameters Related to Concrete

The specific post-processing operations of the 3D-printed parts (i.e. vacuuming loose sand, infiltrating the outer surface of the formworks) and the rheological properties of concrete dictate minimum dimensions for the hollow features (Fig. 09). UHPFRC mixes work well with 3D-printed channels with diameters as low as 20 mm and bending radii of 10 mm. For features below these minimum dimensions, the stay-in-place sandstone formwork can take the role of an ornamental exposed surface that does not necessarily transfer all the details to the cast concrete inside.

A full complement of structural tests is scheduled for the next stage of the research, but the empirical tests performed so far by applying a 2500 KN/m^2 distributed load on a concrete component with an average concrete thickness of 30mm were encouraging. The indication is that material savings of up to 70% are achievable.

Conclusion

The proposed method advances the idea of using 3D printing as an indirect fabrication method for producing composite building components with elaborate geometry. Potential applications are in the realm of one-of-a-kind, non-standard building components rather than that of mass-production. While further tests are necessary to quantify conclusively the advantages of this fabrication process in comparison to others, the prototypes have shown that the method is feasible and has a significant potential for application in architecture at a larger scale.

For applications of this method to larger-scale building components, such as entire ceilings, structures would need to be assembled from multiple parts prefabricated in the proposed way. To prove that large spans and cantilevers are achievable, further research has to address following challenges:

- Reinforcement considerations: Steel-fibre reinforcement was enough for the smaller prototypes, but in order to increase the structural spanning capabilities, traditional reinforcement bars or pre-stressing strategies are considered. Again demonstrating its suitability, 3D printing can be used to fabricate guiding features for the precise integration of reinforcement.
- Additional functionality: A consequence of the durability of the concrete-sandstone bond, the 3D-printed formwork is ideally suited to stay in place and host additional functions. Acoustic surface treatment, heat-transfer-regulating geometry, and detailed ornamentation are possible, as is the integration of enclosures for mechanical and electrical services. This opens up the possibility of fabricating smart, integrative building components.
- Fabrication process development: Up to this point, the research has relied on commercially available generic 3D printers. Nevertheless, this research hints at certain improvements to the technology that would benefit this specific application, such as new powder and binder combinations and the integration of post-processing.
- Digital design tool: The findings from all the experiments are to be compiled in a computational design tool specifically dedicated to the design for indirect binder-jetted fabrication. This application will incorporate relevant design constraints and optimization procedures.

The results suggest that indirect fabrication approaches can be generalised to other types of 3D printing technologies. The solution relies on a hybrid fabrication process in which a precious *smart* material is used minimally, only where necessary, and relies on another *strong* material to perform structurally. Digital fabrication is used to produce a minor proportion of the final product, but has a major impact on its performance and behaviour.

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