COMPLEX ARCHITECTURAL ELEMENTS FROM HPFRC AND 3D PRINTED SANDSTONE

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Abstract

Recent trends have shown that digital fabrication and construction materials and methods are coming together in a significant way. The most visible evidence of this has been the implementation of 3D printing technologies in the construction sector through the increasing availability of large scale systems. Inherent to the process is the ability to produce geometrically unconstrained, high resolution customised architecture. In this work, the authors present a concept in which 3D sand printing is coupled with high performance fibre reinforced concrete (HPFRC) to produce a composite material that can take advantage of the freedom afforded by 3D printing as well as the strength of HPFRC. A prototype slab element has been digitally designed and topologically optimised. The printed element consists of a 6 to 10 mm thin shell structure with internal voids that is then used as a stay in place formwork and infilled with a HPFRC to produce a final element that can be functional and more efficient structurally as well as aesthetically pleasing. Constraints discovered in the production of the prototype and the potential of this method to further produce custom architectural elements are discussed.

Résumé

Les dernières tendances ont montré que la fabrication numérique et les récentes méthodes de construction peuvent être combinés de manière très prometteuse. La plus importante évidence en est l'implémentation de technologies d'impression 3D dans le secteur de la construction par l'apparition massive de systèmes à grande échelle permettant la production d'éléments architecturaux à forme libre de très haute résolution. Dans ce travail sera présenté le concept de combiner l'impression 3D en sable avec des bétons fibrés haute performance (BFHP) afin de produire un élément composite ayant à la fois les degrés de liberté d'expression offert par l'impression 3D ainsi que les propriétés mécaniques des BFHP. Pour ce faire un élément de plafond a été digitalement conçu et optimisé topographiquement. L'élément ainsi imprimé consiste d'une coque vide de 6 à 10 mm d'épaisseur constitué de canaux qui ont servi come coffrage perdu et ont été rempli de BFHP afin de produire l'élément composite final structurellement viable et esthétiquement plaisant. Les contraintes découvertes lors de sa production ainsi que le potentiel d'une telle technique pour produire des éléments architecturaux customisés sur mesure seront présentés et discutés dans ce document.

1. INTRODUCTION

In what has been termed the "third industrial revolution", digital fabrication has ushered in a new era of mass customisation in all forms of manufacturing, and now promises to be a disruptive technology in the construction sector. Freeform architecture, enhanced worker safety, and more sustainable structures are all possibilities with the rise of digital fabrication. New forms of technology in construction are illustrating the type of freedom and new research challenges that digital fabrication brings, technologies such as layered extrusion and slipforming, with the ability to "3D print" the material by placing it only where it is needed. A major issue that has been pointed out with these new technologies to construct reinforced concrete elements is the issue of how to add the reinforcement [1], as reinforcement is typically added post hoc in layered extrusion structures, requiring another infill step. Therefore, there is a very high potential for these new digital fabrication technologies to offer new perspectives on fibre reinforcement. In this work, we present the combination of binder jetting, a 3D printing technology, and high performance fibre reinforced concrete (HPFRC), as a composite system to produce architectural elements.

1.1 Binder jetting

Binder jetting is one of many different additive manufacturing technologies. A liquid binder is selectively applied on successive thin layers of powder material. Its major advantages, compared to other 3D printing procedures, are the high resolution, the virtual absence of geometrical constraints and its availability at large scales of up to 4 x 2 x 1 m^3. These benefits make it particularly interesting for architectural applications and in the following, some important predecessor projects are highlighted and illustrated in Figure 1.

A pioneer working in the field of 3D printing for architecture for already more than 10 years is Enrico Dini and his company D-Shape™. A Cartesian 3 axis frame made from aluminium trusses encloses a 4x4 meter print bed. The produced Sorel cement objects exhibit an increased tensile strength compared to conventional cement [2], but demonstrate rather coarse resolution.

Digital Grotesque, the first fully immersive, enclosed, completely 3D printed structure was realised by Michael Hansmeyer and Benjamin Dillenburger [3]. The 3.2 m high, 16 m^2 large room is materialised with minute details at the threshold of human perception. This is possible thanks to the layer height of a mere 0.13 mm. The total of 11 tons of pure 3D printed sandstone is discretised into blocks, stacked atop each other and carrying only its own weight. No additional material or reinforcement is necessary to erect the structure.

The architect and researcher Philippe Morel of EZCT [4] has created a three dimensional triangulated truss structure cast in UHPC to demonstrate this material's load bearing capacities. The 3D printed half shells are infiltrated with epoxy resin and assembled to form the hollow tubular mould prior to being cast. The structure has a very high surface quality, however lacks any reinforcement. Additionally, formwork removal limits to some extent the geometric freedom.

A jump in scale and resolution was made with the realisation of the Swiss pavilion for the Architecture Biennale in Venice, 2016 [5]. "Incidental Space", designed by Christian Kerez is a 9 m long and 6 m high room enclosed by a 2 cm thin shell of polymer fibre reinforced shotcrete. Around a third of the formwork parts were 3D printed in sandstone and infiltrated with a release agent. No other known fabrication method would allow for the production of this level of detail.

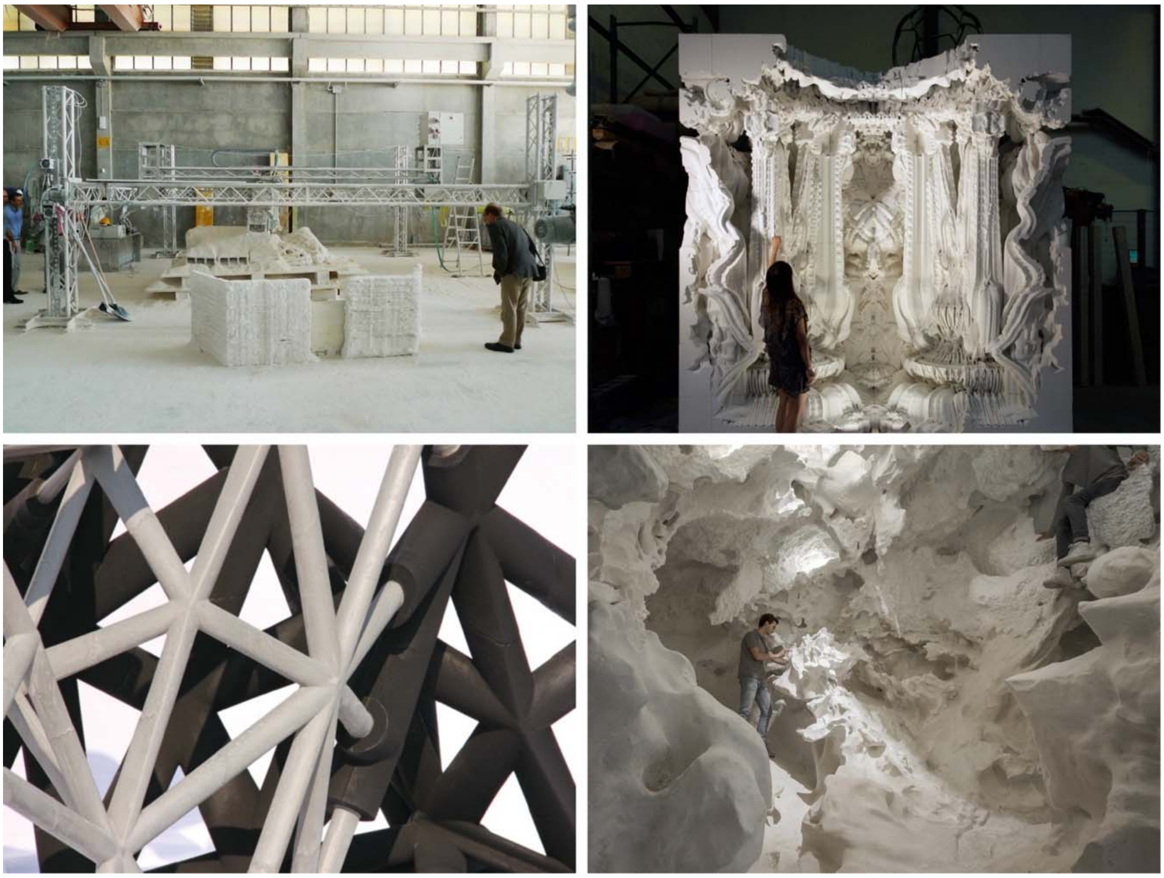

Figure 1: D-Shape printer (top left); Digital Grotesque (top right); UHPC truss structure from Philippe Morell (bottom left); Incidental Space, from Biennale 2016 (bottom right)

Design research firms such as Emerging Objects develop new powder / binder combinations able to be 3D printed using the binder jetting method. Printer system manufacturers and their binder suppliers also have their R&D departments extending the product portfolio to broaden the range of applications.

1.2 Binder Jetting as Lost Formwork

Binder jetting presents the designer with excellent design freedom for geometric complexity which makes it a versatile production method for prefabricated architectural components. However, the relatively low flexural strength of the sand based 3D printed material render it unsuitable for structural applications.

This drawback can be overcome by combining the 3D printed sandstone with another material which has high structural capacity, such as concrete. To achieve this, a minimal digitally fabricated shell is used as formwork for casting HPFRC. 3D printing contributes with its excellent geometric flexibility and material efficiency, while concrete can take (almost) any shape given by the form and provides the load bearing properties.

The porous nature of the 3D printed formwork makes the bond with the concrete very strong. This was apparent when removing a 9 mm layer of 3D printed formwork, a water jet with

400 bar pressure was necessary. To avoid such a labour and energy intensive process, release agents can be used to coat the interface between the two materials.

Alternatively, the strong bond can be an opportunity and the 3D printed shell can act as a stay in place formwork. This simplifies the fabrication process by eliminating the demoulding step, while the added dead load can be justified by additional functional roles that can be performed by the formwork. In this scenario, there is a differentiation in the way the two sides of the form are treated. The internal interface is smooth to optimise the flow of concrete, while the external surface integrates additional geometric articulation, textures and microstructures for ornamental or functional purposes (e.g. acoustics, thermal dissipation, lighting integration).

2. MATERIALS & METHODS

2.1 3D Printer Technology

Prototypes were manufactured with a large scale binder jetting 3D printer (ExOne S-Max), designed for the sand moulded casting industry. The machine can produce parts within a print box of 1.8 x 1 x 0.7 m^3 with speeds of up to 85 l/h at 250 DPI resolution.

The first step in the 3D printing process is the preparation of the CAD model, which is sliced by a proprietary software into 500 horizontal sections at 0.3 mm intervals and sent to the 3D printer as bit maps. For each horizontal slice, a 0.3 mm coating of silica sand is evenly spread in the print box. The silica sand used has grain sizes smaller than 0.28 mm, guaranteeing a perfectly smooth coating surface. The inkjet print heads then selectively inject a furan based organic binder reproducing the computed CAD slices. The binder cements the sand into a composite material similar to sandstone. This material needs no curing time or oven baking and the 3D printed parts are available for processing immediately. In areas where no binder is deposited, sand retains its granular flow, while still providing at the same time support for subsequent layers above. This loose sand can be removed, mixed with fresh sand and reused. After all the layers are 3D printed, the part is left to cure in order for the binder to reach its maximum strength.

Following the curing stage, the solid 3D printed part is extracted from the surrounding unconsolidated sand inside the print box. Loose sand particles that adhere to the part are vacuumed out or brushed off.

While the 3D printed part only acts as formwork and does not have any structural role in the final part, sufficient strength is necessary to prevent damages during transportation, site manipulation and concrete casting, in particular resistance to formwork pressure. Therefore, the last post processing step is the application of an epoxy surface infiltration to the entire part. On the one hand this treatment hardens the exterior of the part making small details more resistant to dents, and on the other hand it doubles the overall flexural strength of the part to approximately 6.5 MPa.

Special tools may be required during the post processing steps for reaching narrow, coiled or generally inaccessible geometric features.

2.2 HPFRC Mix

2.2.1 Formula

The materials used for all mixes in this work and their proportions can be seen in Table 1.

Material	Name	Producer	Proportion [kg/m^3]
Cement	Durabat X-trem - CEM I 52.5 N SR 5 PM-CP2	LafargeHolcim	670
Sand	0.1-0.45 mm	Baubedarf	506
Silica Flour	K6	Carlo Bernasconi AG	670
Silica Fume	Elkem Grade 971-U	Elkem	84
Superplasticiser	MasterGlenium ACE 30	BASF	62
Steel Fibers Type I	6 x 0.15 mm	Dramix	218
Steel Fibers Type II	10 x 0.16 mm	Dramix	
Steel Fibers Type III	13 x 0.16 mm	Dramix	
Water	-	-	189

Table 1: Materials used for the mixes.

2.2.2 Mixing Procedure

All mixes were produced using a Hobart A200N mixer except the up scaled mixes used for the slab element that were produced on a Collomatic 65/2 K-3 mixer. The mixing procedure consisted first of a dry mix for 5 minutes, followed by water addition and a low mixing speed for 1 minute before adding superplasticiser. Mixing was then performed at low speed for 6 minutes and then medium speed for 5 more minutes. Fibres were then added in two parts with 30 seconds slow mixing in between, and with 3 minutes mixing on low speed with all fibres.

2.2.3 Measured properties

Mix workability was assessed with a mini slump flow test [6]. Compression and bending strengths were measured on a Walter+Bai FTS Typ 502/4000/100 at 7 and 28 days on 4x4x16 cm prisms.

3. RESULTS & DISCUSSION

3.1 Digital design of the slab

To investigate the potential of 3D printed sandstone for acting as formwork for concrete, a slab component was designed with the aid of topology optimisation algorithms and fabricated in the proposed way.

Topology optimisation is an iterative computational process that works within a given discretised modelling space. For a specified set of loads and supports, the algorithm refines material distribution in order to meet one or more set performance targets (Fig. 2). Topology optimisation can be used to reduce weight and improve functionality and structural performance of concrete building components [7]. While significant improvements can be achieved with this method, the resulting geometry is often too intricate to be fabricated in concrete with conventional methods [8]. Given the promise of complete geometric freedom with binder jetting, the fabrication of such designs becomes possible.

The prototype was developed through the TOSCA topology optimisation algorithm of Simulia ABAQUS, a commercial structural analysis software package (Fig. 3). The 1.8 x 1 x 0.15 m^3 design domain was discretised into 83,072 nodes with a volume of approximately 3.4 cm^3 each. The target set for the optimisation process was to reduce material to a 0.18 set fraction of the initial volume while keeping to a minimum the von Mises stresses of the slab under uniform surface load. Boundary conditions were set to four simple supports located close to the corners.

Topology optimisation is initially used as a form-finding design tool and the result is interpreted as described by Kim and Baker [9]. The parameters used in the algorithm to describe the behaviour of concrete were a density of 2,400 Kg/m^3, a Young's modulus of 50 GPa and a Poisson ratio of 0.2. The compressive and tensile strengths of HPFRC can be used in the algorithm to constrain the optimisation to safe results.

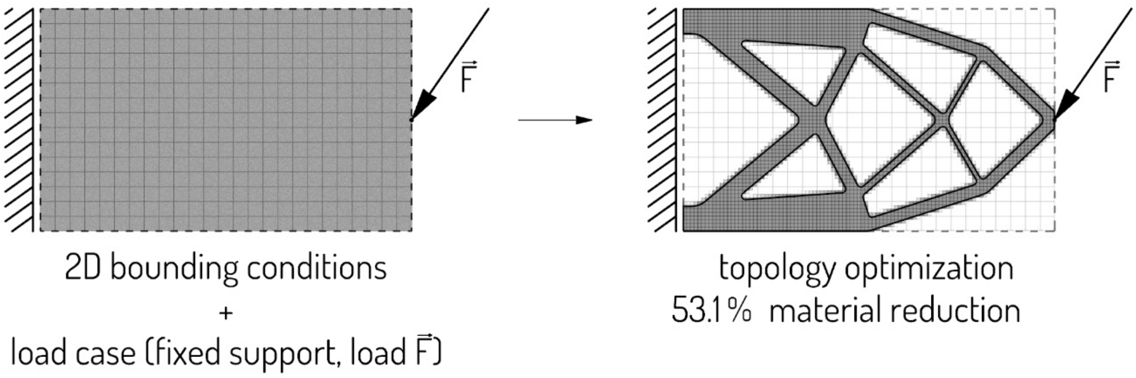

Figure 2: Topology optimisation for an example load case on a generic sample material.

The result has geometric features typical to topology optimisation algorithms: interconnected networks of narrow tubular structures with different diameters. Further refinement of the design had to be included after the topology optimisation in order to address the fabrication constraints:

- undersampling artefacts resulting from the discretised nature of the topology optimisation process were corrected.
- geometric features under 5 mm were considered too fragile for further manipulation and were discarded.
- hollow geometric features under 20 mm were made solid as they are too narrow to permit 3D printing post processing (unconsolidated sand removal and surface infiltration) and prevent the flow of concrete because of local fibre clogs.

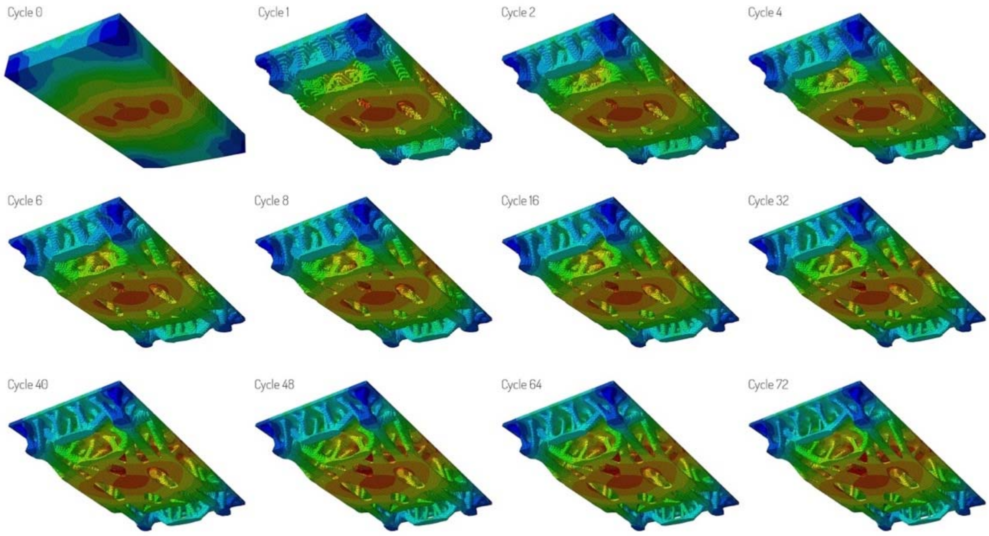

Figure 3: Topology optimisation iterations for the slab prototype

Given the bigger geometric freedom possible with this construction technique (compared to more conventional CNC milled formwork), the architect's design intention regarding specific shape features, surface quality, ornamentation, edge details, etc. is easier to integrate for concrete building components.

3.2 Mix requirements and optimisation

Several requirements were stated for the fibre reinforced mix used in this project. As the main challenge was the infilling of the slab element, a good workability of the mix was necessary in order to be able to flow properly through the channels.

The first step of optimisation was realised by measuring the mini slump spreads of mixes containing various amounts of superplasticiser. These mixes were kept at constant W/C ratio by taking into account the water contained in the superplasticiser and adjusting the amount of added water. The mix used for this optimisation was containing Type II fibres. A plateau of the mini slump test was observed for a superplasticiser dry extract between 2.75 and 3.00%. Further in the study the amount of 2.75% was used.

Three different types of fibres (presented in Table 1) were tested for both mechanical properties and workability. In all tests the amounts of water, fibres and superplasticiser were kept constant.

3.2.2 Filling tests

The suitability of the three mixes to flow through the printed channels was tested by infilling L-shaped 3D sand printed tubes as presented in Figure 4. This test was realised as a complement to the mini slump flow test in order to be closer to the infilling conditions of the slab element. All three mixes had at the time of the experiment the same age and a constant mini slump at 26.0 ± 0.5 cm.

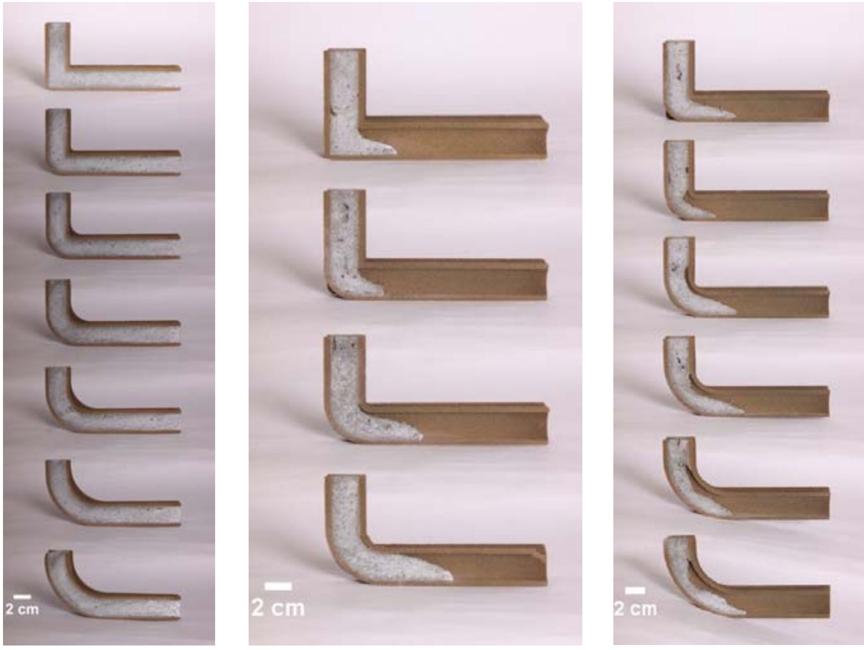

Figure 4: L-shaped tubes with varying bending radii, left 6x0.15mm fibres; middle 10x0.16mm fibres; right 13x0.16mm fibres. Bending radii (left picture), from top to bottom [mm]: 0,10,20,30,40,50,60. Arms on both sides of each L-shaped tube were originally 15cm long.

As one can observe, the flow distance decreases with the increase of the fibre length which is to be expected. Also for fibres of type II and III it is clear that the flow distance decreases with the decrease of the bending radius of the L-shaped tube. This is giving important information on any further development and optimisation of bigger elements containing channels.

Additional tests showed that 3D sand prints have a certain limit regarding the formwork pressure. Indeed, several of the infilled forms burst during infill because of pressure applied by the fibre reinforced mix. The epoxy coating provides an additional mechanical resistance of the 3D printed sand formwork and have the added benefit of reducing water sorption from the infilled concrete mix.

3.2.3 Resulting mechanical properties

Mechanical properties of the tested mixes are presented in Figures 5 and 6. As expected, a noticeable increase in flexural strength is observable when increasing the fibre length. This increase is less visible but still present for the compressive strength. Considering these results together with the filling tests described previously it was decided to use the mix containing type II fibre for the final slab element. A limitation of the mix, however, comes from a lack of strain hardening behaviour in flexure. This clearly limits the potential structural application of this particular mix and prototype, and remains a required avenue for research for the implementation of this type of technology in a meaningful way.

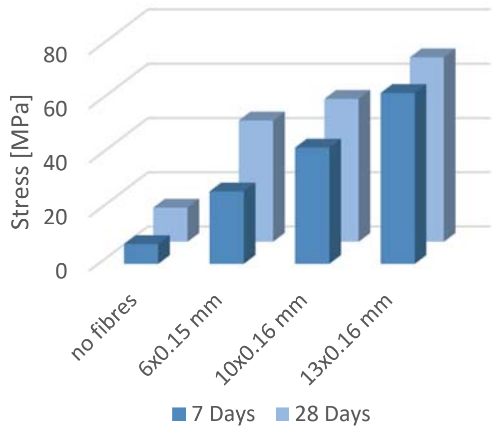

Figure 5: Flexural strength for different fibre types.

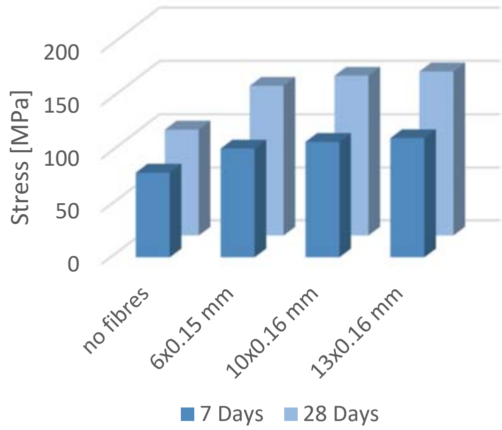

Figure 6: Compressive strength for different fibre types.

3.3 Slab element preparation and infill

The finished slab element and casting process is shown in Figure 7. In order to ensure a maximum quality of the infill, the fibre reinforced mix was cast through one side of the main channels until it was overflowing from other smaller channels. This minimised the chance of air pockets trapped inside.

The amount of fibre reinforced concrete necessary for the infill of the slab element was produced in three batches, with fibre addition occurring just before infill of any batch. Four lifting anchors were positioned on the top of the slab element. It was then hermetically covered with plastic film and let to cure for 7 days prior to moving.

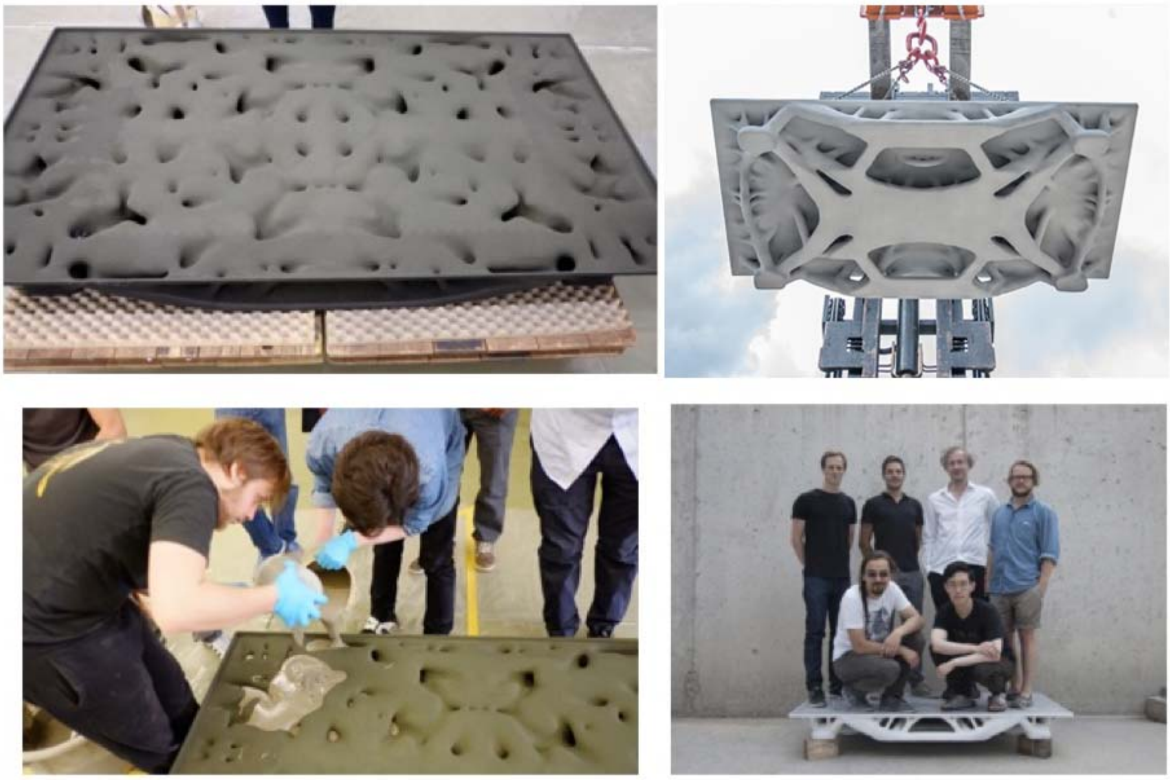

Figure 7: Top view of element, pre infill (top left); Bottom view of element, post infill (top right); Infill process (bottom left); Final element after casting (bottom right)

4. CONCLUSION

The successful casting of the slab element presented in this work shows very interesting perspectives for this kind of technology in the future for both aesthetics and mechanical optimisation of structural elements.

The possibility to develop a strain hardening behaviour of the infill mixes would provide an unconditional improvement to the structural properties of such composite elements. However, strain hardening behaviour usually implies higher fibre amounts and lengths which would reduce the mix workability. Considering the possible channel geometry of elements such as those presented in this work, important improvements should be realised both on the fibre reinforced concrete mix formula as well as on the elements design.

Additionally, a flow induced fibre orientation would be also very interesting and promising to investigate. This would involve a proper design of the channels network coupled with adequate fibre orientation metrology, such as X-ray micro CT.

Upscaling the production of such elements presents several challenges, but opens very interesting possibilities such as the direct integration of precise post tensioning ducts inside the elements. While the production of fibre reinforced concrete on large scale is manageable nowadays, 3D printing is still an emerging technology. Current research considers making 3D printing a more accessible technology, with lower costs, improved speed and lower environmental impact. Nevertheless, the proposed method only relies on 3D printing to produce a minor proportion of the final product, which has however a major impact on overall performance, behaviour and aesthetics. The results of this study will provide direct feedback into the implementation of an instance of this technology on the NEST building at the Swiss Federal Institute for Materials (Empa) in Dübendorf, Switzerland, expected to be completed in 2018 [10].

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