3D Concrete Printing – A Structural Engineering Perspective

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Abstract. 3D Concrete Printing (3DCP) is being developed in an increasing number of places around the globe. The focus is mainly on a trial-and-error based exploration of the possibilities. However, to obtain a viable manufacturing technology and realize the 3DCP potential, a higher level of process control is required. Four levels of control are therefore identified. Research efforts and key results to achieve a higher level of control than the current one are presented. As a final goal, optimization algorithms should be able to define optimum print sessions, based on allowable print strategies and structural analysis models describing both the fresh and hardened concrete state. This will result in new geometries appropriate to this specific manufacturing technique. These geometries, however, can only be applied when structural safety is achieved, either by loading conditions (compression structures), hybrid solutions (combination with conventional reinforced concrete), embedded reinforcement, FRC and prestress. Such solutions are therefore being explored.

Keywords: 3D printing · Concrete · Ductility · Reinforcement · Fibers

Introduction

Around the globe, ground breaking projects and case studies are being presented to showcase the potential of Digital Fabrication with Concrete. On a trial-and-error basis, the frontiers of the new technology are rapidly being explored, primary focusing on geometries only. However, the progress of gaining fundamental understanding of the structural properties of such geometries is not keeping the same pace. To bridge this gap, TU/e is directing research efforts for 3D concrete printing (3DCP) to become a viable solution for the building industry.

In 2015, a 3D concrete printing facility was designed and established at the TU/e Structures Lab (Bos et al. 2016, Fig. 1). It consists of a M-Tec Duomix 2000 mixer-pump with a linear displacement pump that feeds concrete by a Ø25 mm hose to a 9.0 × 4.5 × 2.8 m 4-DOF gantry robot. Since taking the facility in operation, the research has developed around 3 core areas:

- Exploration of possibilities;
- Process modelling & printing strategies;
- Structural printed concrete.

Fig. 1. 3D Concrete Printing facility at the TU/e.

Exploration of Possibilities

Before any fundamental research is possible, a basic understanding of 3DCP needs to be developed. This is done by trial-and-error based exploration of the possibilities of the 3DCP system, which consists of 3 main components:

– a printable concrete,
– a 3D printer,
– the printable geometries.

Many of those active in additive manufacturing of concrete (AMoC) materials, focus on this exploration. This has resulted in a range of impressive showcase projects.

At the TU/e, the exploration phase yielded a number of more and less obvious insights on large number issues ranging from the practical to the fundamental. Examples in the former category include appropriate mixer/pump settings in relation to robot movements, appropriate minimum curvature radii (insufficient radii cause tearing on the outside or clogging on the inside of the corners), and the interdependency of buildability, viscosity, setting time, filament shape and robot movement (stable print geometries with a slow setting, no-slump concrete require a

Fig. 2. Twisting of the filament occurs when a non-circular nozzle does not stay aligned to the print path direction.

rectangular filament section, in turn calling for a rotating z-axis of the printer that aligns to the print head to the print direction; Fig. 2).

On a more profound level, it was experienced that, for instance, scaling up in printing geometry size leads to increasing printing times, which induces temperature gradients in the printing process as the system heats up while running. As a result, material properties vary throughout the geometry. Furthermore, the nozzle height above the print surface has significant influence on the shape and properties of the printed product.

The most fundamental awareness raised by the exploration part of the research, is the multi-parameter interdependency of the main components of the 3DCP system (material, printer, and geometry). Each of these components constitutes a range of parameters and variables (Fig. 3; all parameters together are referenced as the system parameters), some of which can be managed completely, whereas others are subject to influences that are difficult to control beyond a certain extent. In order to be able to fully control the 3DCP process, and be able to predict both the printability and the properties of the printing geometry, these parameter relations need to be understood and quantified.

The necessity to generate this level of in-depth knowledge of the 3DCP system could be debated, as several developments in the field of AMoC seem to directed at low-cost / crude-quality applications, but when high-quality applications are considered (usually coinciding with prefabricated, off-site production) an appropriate level of quality control can only be obtained if these dependencies are understood. Actually, for other 3D printing processes, like laser powder bed fusion (used among others for metal printing in the automotive and aeronautical industries) full numerical modelling of the printing process, including all key influences on the printing geometry (both during and after printing) is already being applied. Software packages, such as Autodesk Netfabb, are commercially available for such analyses. In these industries too, experimental validation of numerical models of the print process are current research topics (Denlinger and Michaleris 2016; Dunbar et al. 2016). This has instigated the second core area of research on 3DCP at the TU/e: process modelling and printing strategies.

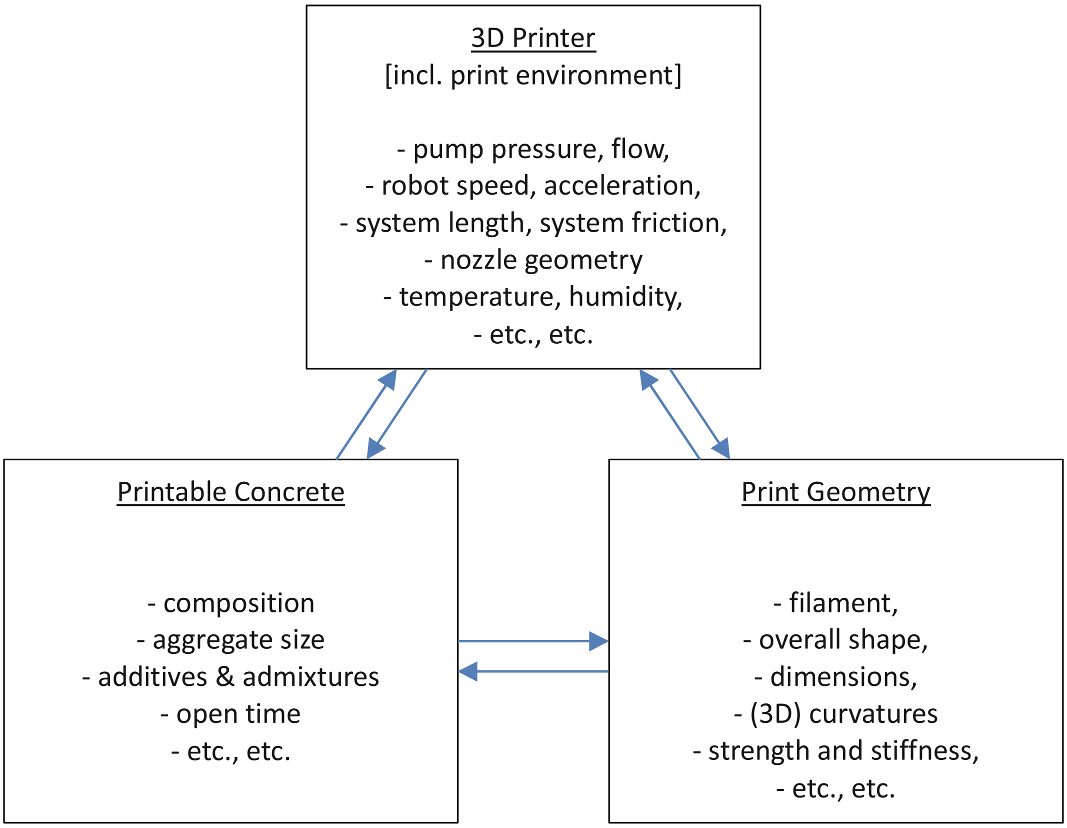

Fig. 3. Interdependency of system parameters (selection) of the 3DCP system.

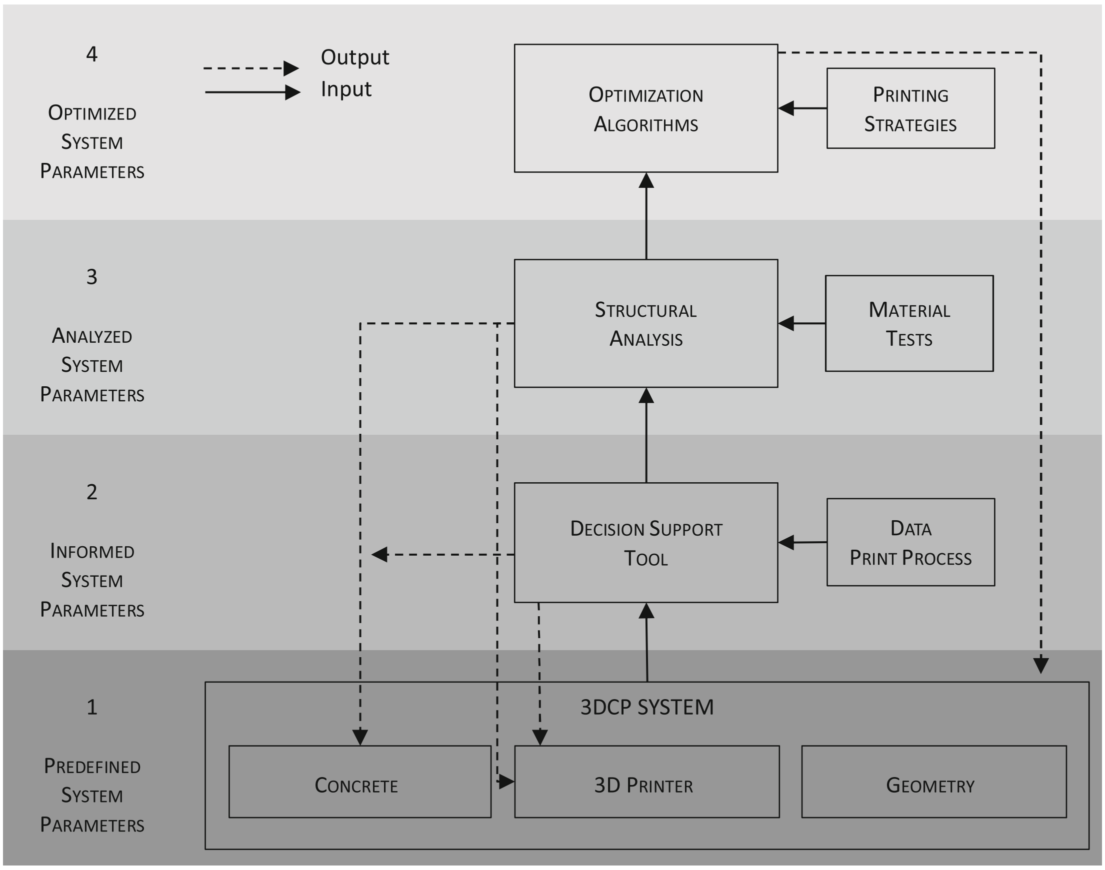

Fig. 4. Levels of system parameter control.

Process Modelling and Printing Strategies

In order to understand the problem of process control of 3DCP, we discern 4 levels of control of the system parameters. Consider Fig. 4. The levels of control are further discussed in the following subsections.

Level 1: Predefined System Parameters

The most basic level of control, Level 1, with 'Predefined System Parameters', refers to a situation in which a certain set of system parameters (1 concrete, 1 3d printer setting, 1 geometry) is applied, that is however, not fully known, but will result in some printed product. As the system parameters are only partially known, the result is difficult to repeat.

This level of control is (and can only be) obtained by trial-and-error, and is a prerequisite for higher levels of control. However, within this level each new combination of system parameters would require a new trial-and-error process. The lack of repeatability renders this level of control insufficient, both for any practical application and for scientific research.

Level 2: Informed System Parameters

The second level of control requires the most relevant system parameters to have been identified and quantified. For the 3DCP system, they include: material composition (after mixing), pump pressure, system and ambient temperature and humidity, printer speed, nozzle geometry, nozzle height (above the printing surface), and print path. As a result, the printing process is repeatable, i.e. the user can reproduce the process and its result within acceptable limits of variation – a prerequisite for any serious consideration of the technology.

In a basic variant, fixed parameters are selected based on simple parameter studies. For instance, early in the 3DCP research, the influence of pump pressure and print head speed on the filament section dimensions was established this way (Figs. 5 and 6a, b). A more sophisticated form of Informed System Parameter control is achieved when the system parameters are monitored during the printing process and the process parameters are adjusted real-time to the measurements. A method to do this for an important parameter, namely the nozzle height, is presented in (Wolfs et al. 2017a, Fig. 6).

Crucial to achieving an informed level of control, is having a Decision Support Tool that allows to decide how a certain system parameter has to be adjusted to obtain a desired effect in printing. Either variant (basic or more sophisticated) requires such a tool, although this may be rather trivial for the basic variant.

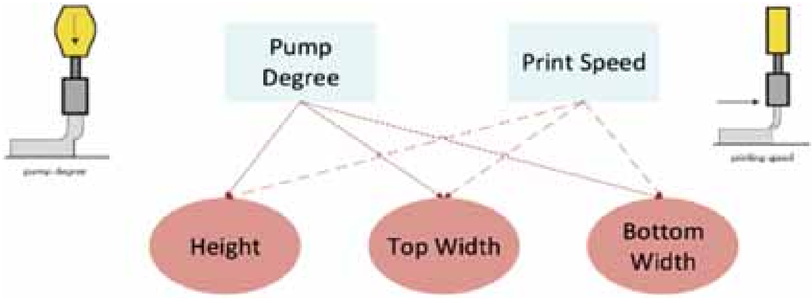

Fig. 5. Simple scheme of printer parameter and geometry parameter relations.

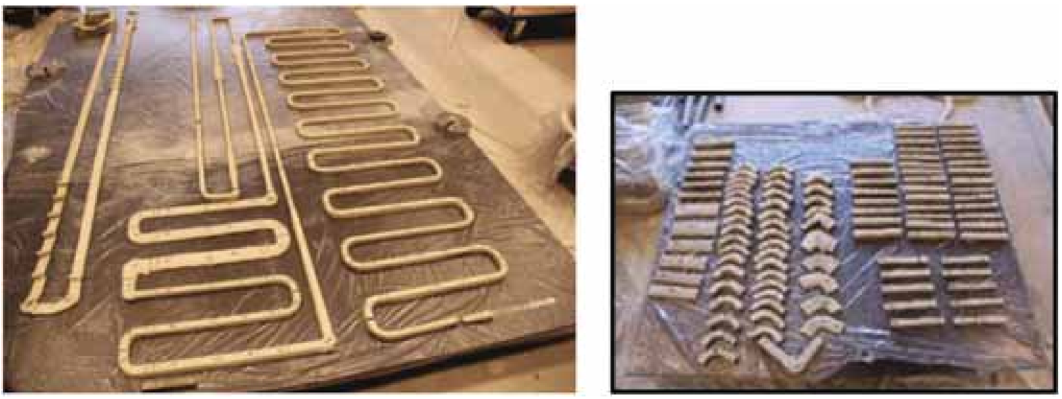

Fig. 6. (a, b) Collecting data on the cross-sectional geometry of filaments.

Level 3: Analysed System Parameters

Control levels 1 and 2 still assume an independency between the printing process on the one hand and the behaviour and properties of object that is being printed on the other. However, in reality the opposite is true: even when considering a known geometry, the printing process heavily influences the printed object. Vice versa do the object properties during printing determine what can and what cannot be printed.

A level 3 control of system parameters requires the ability to analyse a print geometry in terms of printability (e.g. stability during printing) and expected product properties (such as interface strength). Within the core research area of process modelling & printing strategies at the TU/e, a preliminary FEA-based method has been developed to perform such analyses (Wolfs et al. 2017b). The current version includes time-dependent stress-strain behaviour of the print material, as well as the time-dependent modelling of the material deposition. It allows identification of both strength and stability related failure modes (Fig. 7). Thus, it allows to accurately predict what geometries can be printed, at what speeds. The material behaviour has been modelled based on extensive experimental testing on the fresh concrete, with an age of between 0 and 90 min after leaving the print nozzle. As no suitable codes or guidelines existed to obtain these material properties, a uni-axial compression test and a shear-box test have been custom developed (Fig. 8a, b). Subsequently, an optical measuring system had to be developed also (Fig. 9a, b), to be able to track the object displacements during printing and thereby verify the FEA predictions, which initial results show to be promisingly accurate. To increase the accuracy further, the method will be extended to include other parameters, such as object temperature development.

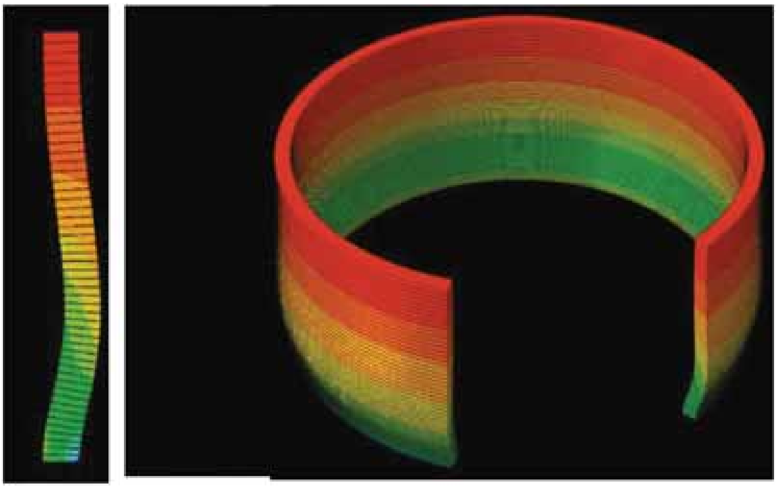

Fig. 7. Time-dependent FEA of printing geometry.

Fig. 8. (a, b) Custom developed uni-axial compression test and shear box test.

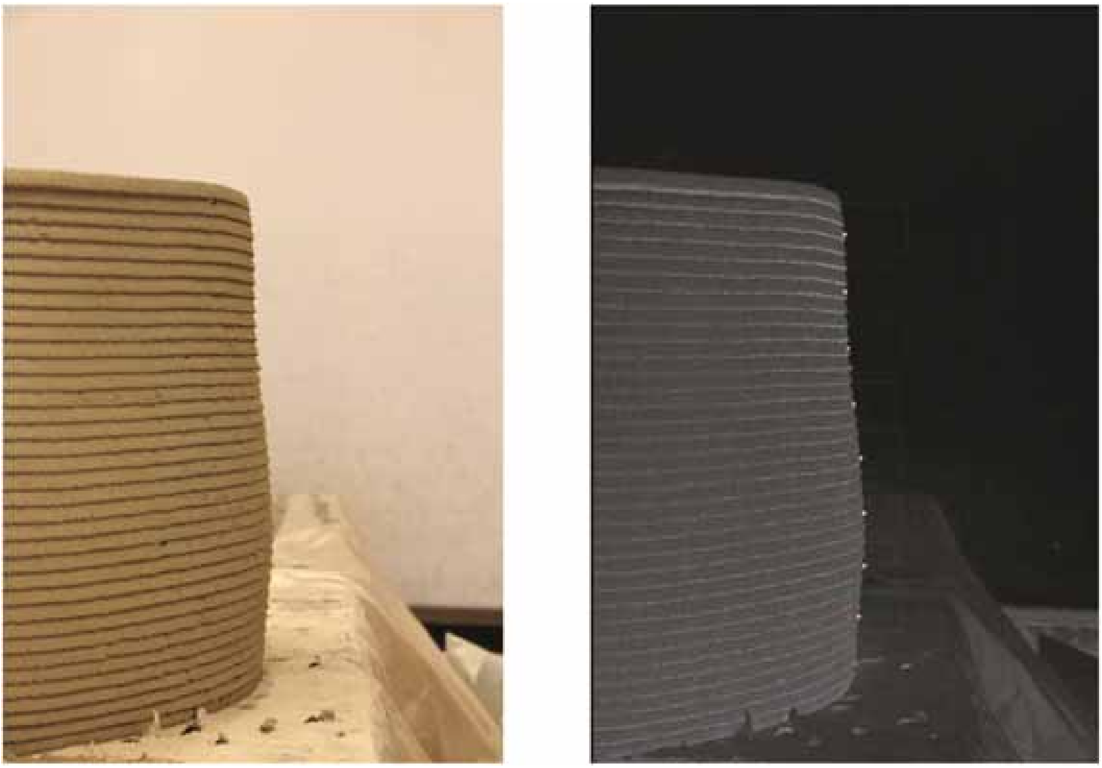

Fig. 9. (a, b) Tracking deformations of a printed object with optical measurements.

However, for the process modelling, not only the properties of the object during printing should be considered. As the goal of process modelling is to predict both the printability and the end product quality, the latter's dependency on print process parameters also needs to be established. An obvious one is the relation between interface interval time (i.e. the time between subsequent layers are being deposited onto each other), material setting time, and interface strength. Experimental testing has shown the tensile strength to decrease significantly with long interval times (several hours to days). When an interval time in the range of minutes is applied, however, this dependency has disappeared. It is important to note that this result is valid only with the concrete mix currently applied in the TU/e research. Other, faster-hardening material formulations may be more sensitive to interface interval time. Within the control level of Analysed System Parameters, conscious choices can be made to balance in-print and after-print structural requirements.

It should be noted that for these tests on set, printed concrete, new test methods had to be developed to as the existing prescribed test methods for concrete are not directly suitable for 3DCP print geometries, and/or do not aim at obtaining the parameters that are most relevant to 3DCP geometries (Fig. 10a–d).

Remarkably enough, a juxtaposition occurs in 3DCP when compared to conventional concrete construction: whereas in the former, a structural analysis of the object has to be made twice (for the situation during printing, and the final product), the object is only manufactured once (as a positive), while in the latter, a structural analysis is generally only made one (for the end situation), and the object is made twice (as a negative – the formwork, and as a positive).

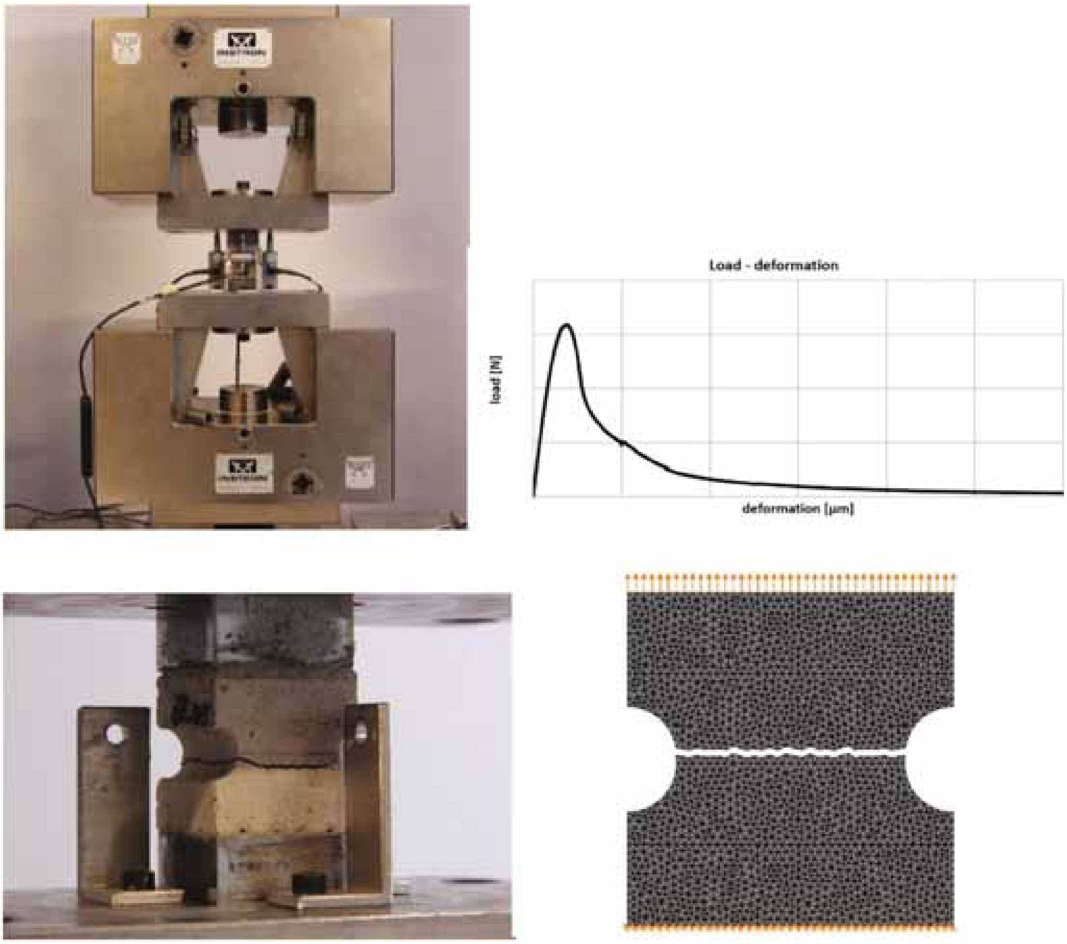

Fig. 10. (a–d) The development of structural tests on the bond properties in the interface.

Level 4: Optimized System Parameters

The most advanced stage of system parameter control is achieved when, rather than analyzing a predefined printing protocol (as in Level 3), it would become possible to generate an optimized printing protocol directly from performance requirements of the end product (most notably geometry and structural behaviour). System parameters are then determined by optimization algorithms that could for instance be generic, based on form-finding or on topology optimization. These optimization algorithms would draw their input from structural models (e.g. to predict printability) and printing strategies that describe the print process boundary conditions. The printing strategies may for instance determine maximum element sizes, print path orientation, filament resolution, curvature limitations, cantilevering limitations, fill pattern strategies (of an object core), and so on. Such print strategies are currently already incorporated to some extent in various 3D printer systems, such as small size consumer market polymer printers, that include e.g. filling strategies for 3D objects.

An example in 3DCP could be a cantilevering object (Fig. 11). In the current TU/e 3DCP system, the extent of cantilevering is limited by the setting time of the concrete. In a situation of optimized system parameter control, a print strategy would be generated that e.g. adjusts the material formulation for the print, the print speed or the extent of cantilevering (depending on which parameter the designer allows to be variable), to an extent that a printable design which fulfills all set requirements results.

Fig. 11 Example of a simple type of vault printed with an unbounded Material (coarse sand).

Structural Printed Concrete

An optimized control over the printing process, however, is of little importance without an understanding of the properties of the end product. There the structural properties and applications of 3DCP are also a main area of research. Studies are performed at different levels of scale, ranging from structural material properties to structural design studies of several meters in scale.

Structural material tests have shown no significant directional dependency of stiffness, compressive and flexural strength of both the bulk and layered material. Only the tensile strength of the interfaces diverges, increasingly so when the interval time grows (Bos et al. 2017a).

A major obstacle for structural applications of the current 3D printed concrete, however, is the lack of tensile strength and ductility, caused by the absence of fibers or reinforcement. There are several ways to approach this deficiency.

First, one could consider to limit applicability to compression loaded structures, thus obviating the need for tensile capacity. Though the possibilities of the print process allows vaults and shells to be manufactured without additional costs, e.g. on an adjustable curved print surface as shown in (Fig. 12), this sets serious limits to the applicability of 3DCP, and, moreover, does not address the fact that even compressive structures require a certain robustness and impact resistance.

Using 3D printed concrete as lost formwork rather than the actual load-bearing structural component is another strategy to obviate the need for ductility in the printed product itself. This strategy is currently the most common to realize structures with 3D printed concrete (Fig. 13). Although the most easily applicable,

Fig. 12. Printed compression shell (3TU Lighthouse 2016 project, TU/e with TU Delft).

Fig. 13. Hybrid solution: printed concrete as lost form work for conventional cast concrete with reinforcement.

Fig. 14. Printed beam with embedded cable reinforcement in 4-point bending.

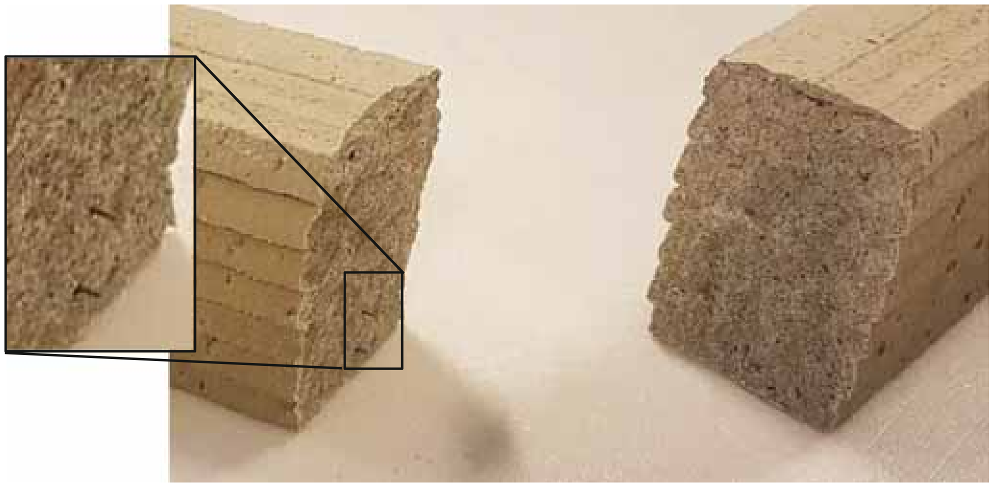

Fig. 15. Printed beam after testing.

this strategy does not address the core of the problem and squanders some of the potential advantages of 3DCP. It may nevertheless prove to be a necessary step towards structural applications of 3DCP.

More advanced concepts include the application of in-process applied cable reinforcement. The TU/e has developed an entrainment device capable of embedding various types of cables. First test results show significant post-crack failure strength and deformations can be obtained (Bos et al. 2017b, Figs. 14 and 15). Subsequent studies will focus on anchorage strength and transfer length as well as the stress-strain behaviour of different cables to develop calculation models to determine reinforcement requirements for printed concrete.

Another generic solution is to print a fiber reinforced concrete. (Hambach and Volkmer 2017) have presented initial results on small 3D concrete printed, fiber reinforced specimens (outer size maximum several centimeters) printed with a 2 mm diameter print nozzle. Because the fibers that were used in that study were longer than the diameter of the nozzle (3–6 mm), this resulted in a strong fiber orientation that was deemed favourable. As a result, the tensile strength of the specimens strongly depended on the filament orientation in relation to the orientation of the bending load. Although scale effects may be expected when implementing fibers into the TU/e 3DCP system, these results nevertheless indicate that favourable effects on the tensile strength and ductility are likely. However, it should be noted that applying fibers are likely to cause some engineering problems that will have to be solved before they can be properly mixed and applied.

More fundamentally though, both reinforcement cables and fibers will probably not improve the interface tensile properties significantly. Thus, brittle failure behaviour in one direction may still remain. Further research and development is planned to investigate and, if necessary, address this potential problem.

Beyond the crucial question of ductility lie structural optimization potentials. More advanced forked print nozzles allow the printing of sandwich elements (Fig. 16). At a larger scale, topology optimized structures can be printed (Figs. 17a, b and 18), provided a material concept is chosen that allows significant cantilevering.

Fig. 16. Printed sandwich beam in 4-point bending.

Fig. 17. (a, b) Optimized column designed and manufactured by CNC milling

Fig. 18. A similar biomimical type of column printed by XtreeE (Gosselin et al. 2016)

Fig. 19. Prestressed printed concrete street furnature

Finally, it should be noted that designs can be optimized to other criteria than structural ones as well, e.g. to aesthetical or ergonomic criteria (Fig. 19; this elements that form this bench have been connected by external prestressing).

Conclusion

Additive manufacturing of concrete is being explored in many places around the world. Showcase projects show the potential, that some say is strong enough to be disruptive to concrete construction as we know it. However, before this occurs a much better understanding of the technology and its resulting products needs to be developed.

Current 3DCP research at the TU/e evolves around 3 core areas: exploration of possibilities; process modelling & printing strategies; and structural printed concrete. The first is required to obtain a first intuitive understanding of the technology. It has shown that realizing the potential of 3DCP coincides with an increasing level of process control. This instigated in-depth research into the process relations between material (printable concrete), 3D printer (including its environment), and the printing geometry. Four levels of system parameter control have been identified: (1) Prescribed, (2) Informed, (3) Analysed and (4) Optimized. These levels indicate the extent of repeatability and predictability of the print process and its result (the printed product). The TU/e system parameter control can be categorized as level 2/3. Efforts are directed at developing a method to model the printing process, given a certain material and print path, including the time-dependent structural behaviour (in terms of strength, deformations and stability) of the printing geometry. Future research will aims at higher levels of control in which printing strategies will be developed that, together with the structural models, will allow for print strategy optimization.

On the other hand, structural applications are investigated, both on the material and the structure scale. A key quest is to obtain sufficient tensile strength and ductility. Several strategies, including in-print embedded reinforcement and fiber reinforcement are being explored, but are still in early stages.

The research not only requires extensive experimental and numerical research, but also a significant development effort. The 3DCP system is regularly being updated with improvements, but also the test methods both on the fresh and hardened concrete are being developed, as existing and accepted test methods are unsuitable and/or inappropriate for printed concrete. This is mostly unchartered territory, but one in which major progress may be expected in the coming years.

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References

Bos, F.P., Wolfs, R.J.M., Ahmed, Z.Y., Salet, T.A.M.: Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual Phys. Prototyp. (2016). doi:10.1080/17452759.2016.1209867

Bos, F.P., Wolfs, R.J.M., Salet, T.A.M.: Directional dependency of 3D printed concrete strength (2017a, in preparation)

Bos, F.P., Ahmed, Z.Y., Wolfs, R.J.M., Salet, T.A.M.: 3D Printing Concrete with Reinforcement, *fib* Symposium, Maastricht, the Netherlands (2017, this conference)

Denlinger, M.: Effect of stress relaxation on distortion in additive manufacturing process modeling. Addit. Manuf. **12**, 51–59 (2016)

Dunbar, et al.: Experimental validation of finite element modeling for laser powder bed fusion deformation. Addit. Manuf. **12**, 108–120 (2016)

Gosselin, C., Duballet, R., Roux, Ph., Gaudillière, N., Dirrenberger, J., Morel, Ph.: Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. Mater. Design **100**, 102–109 (2016)

Hambach, M., Volkmer, D.: Properties of 3D-printed fiber-reinforced portland cement paste. Cement Concrete Composites (2017). doi:10.1016/j.cenconcomp/2017.02.001

Wolfs, R.J.M., Bos, F.P., Emiel, C.F., van Strien, E.C.F., van Salet, T.A.M.: A real-time height measurement and feedback system for 3D concrete printing. In: *fib* Symposium, Maastricht, the Netherlands (2017a, this conference)

Wolfs, R., Bos, F., Salet, T.A.M.: Early age mechanical behaviour of 3D printed concrete (2017b, in preparation)