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ABSTRACT

Additive manufacturing is gaining ground in the construction industry. The potential to improve on current construction methods is significant. One of such methods being explored currently, both in academia and in construction practice, is the additive manufacturing of concrete (AMoC). Albeit a steadily growing number of researchers and private enterprises active in this field, AMoC is still in its infancy. Different variants in this family of manufacturing methods are being developed and improved continuously. Fundamental scientific understanding of the relations between design, material, process, and product is being explored. The collective body of work in that area is still very limited. After sketching the potential of AMoC for construction, this paper introduces the variants of AMoC under development around the globe and goes on to describe one of these in detail, the 3D Concrete Printing (3DCP) facility of the Eindhoven University of Technology. It is compared to other AMoC methods as well as to 3D printing in general. Subsequently, the paper will address the characteristics of 3DCP product geometry and structure, and discuss issues on parameter relations and experimental research. Finally, it will present the primary obstacles that stand between the potential of 3DCP and large-scale application in practice, and discuss the expected evolution of AMoC in general.

1. The potential of additive manufacturing of concrete (AMoC)

Concrete is the most used building material worldwide. Raw materials to produce concrete are cheap and readily available in most places on the globe. It is strong (in compression), durable, fire resistant, and, due to its fluid state before setting, can be applied in practically any shape. The term actually designates a large range of composite compositions, with the common characteristic that they consist of a filler of sand, gravel, or other granulate materials, bound by a matrix that is formed by an exothermal hydration reaction between cementitious materials (cement or cement-replacers such as fly-ash) and water. Additional or alternative additives, admixtures, aggregates, and cementitious materials are being applied to achieve specific properties such as self-compaction, high strength, low CO_2-footprint, ductility, etc. A considerable range of such compositions is known and accepted in practice; a plethora of other variants is explored outside practice.

Today, structural reinforced or prestressed concrete is manufactured in a limited number of fashions. Generally, it is cast in a preconstructed mould in which steel reinforcement has been positioned prior to the casting. This method is applied both on and off-site. The latter allows higher concrete qualities and quality control. Either way, it requires considerable labour both for the mould and the positioning of the reinforcement. The mould material may often be re-used, but not always. Another manufacturing method that is applied to some specific structural elements is extrusion, for example, for hollow-core floor slabs. Opposite to castable concrete, extrusion concrete requires fast-setting and low slump, as the material is unsupported after leaving the extrusion mould.

Notwithstanding the advantages of concrete as a structural material, it also faces several challenges that are gaining recognition. The production of cement is very energy intensive due to the burning of slag in a kiln. As a consequence, concrete production accounts for a significant per cent of the global CO_2 output (estimates and calculation methods vary, but the cement industry itself estimated that cement production is responsible for 5% of the global CO_2 output; World Business Council on Sustainable Development [WBCSD], 2002). The introduction of cement-replacers such as fly-ash (a blast furnace by product) has reduced the average concrete-related CO_2 output, but it is still significant. The fact that concrete raw materials are cheap, does not stimulate economical use and thus makes CO_2 reduction difficult.

Another main challenge is related to the physical labour involved, particularly for *in situ* cast concrete. Both the erection of moulds and the placement of reinforcement still require physically demanding labour, particularly when bespoke geometries are required. This results in personal health issues of construction workers that should be avoided as much as possible, particularly with an ageing work force as in many developed countries. The Occupational Health and Safety Administration of the US Department of Labor lists as potential hazards for workers in the concrete industry: eye, skin and respiratory tract irritation from exposure to cement dust; inadequate safety guards on equipment; inadequate lockout/tagout systems on machinery; overexertion and awkward postures; slips, trip and falls; and chemical burns from wet concrete (Occupation Health and Safety Administration; US Department of Labor [OSHA], 2004). A third challenge the concrete construction industry is facing is the use of material. Besides the moulds themselves, the necessity to make them and the low cost of raw materials discourage intricate structurally optimised geometries, but rather favour geometrical simplicity over optimal material use.

New Additive Manufacturing methods such as three-dimensional (3D) printing have been explored for the construction of concrete since the mid-1990s. In this paper these methods are generically indicated as AMoC, while specific methods developed by different enterprises and research groups are designated with the names the operators themselves generally indicate them with.

AMoC has the potential to address the challenges facing concrete construction described above. More than that, it could allow for a whole new design approach. Since the print head gradually builds up the complete structure, it is feasible that the composition and quantity of the printed material can be parametrically varied from one location to another, according to specific local requirements. A conceptual result of such an approach is given in Figure 1.

Albeit a steadily growing number of researchers and private enterprises active in this field, AMoC is still in its infancy. Different variants in this family of manufacturing methods are being developed and improved continuously. Fundamental scientific understanding of the relations between design, material, process, and product is being explored. The collective body of work in that area is still very limited. After sketching the potential of AMoC for construction, this paper introduces the variants of AMoC under development around the globe and goes on to describe one of these in detail, the 3D Concrete Printing (3DCP) facility of the Eindhoven University of Technology. It is compared to other AMoC methods as well as to 3D printing in general. Subsequently, the paper will address the characteristics of 3DCP product geometry and structure, and discuss issues on parameter relations and experimental research. Finally, it will present the primary obstacles that stand between the potential of 3DCP and large-scale application in practice, and discuss the expected evolution of AMoC in general.

2. Current AMoC technologies

2.1. History

Since the mid-1990s, technologies have been developed to manufacture solid objects through robotised deposition in stone-like materials without moulds, on a scale
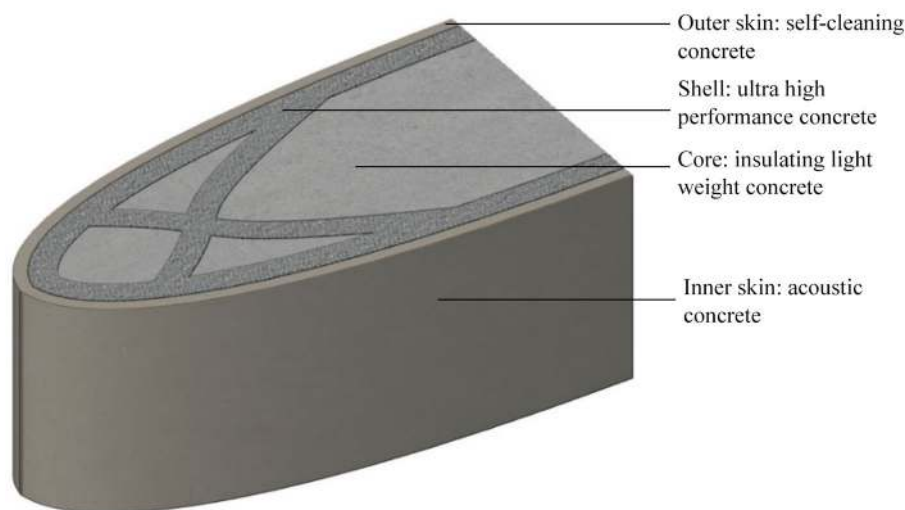

Figure 1. Conceptual result of material customisation by location (dubbed the 'colour' printer, metaphorically, because of its capability to print different materials at different places).
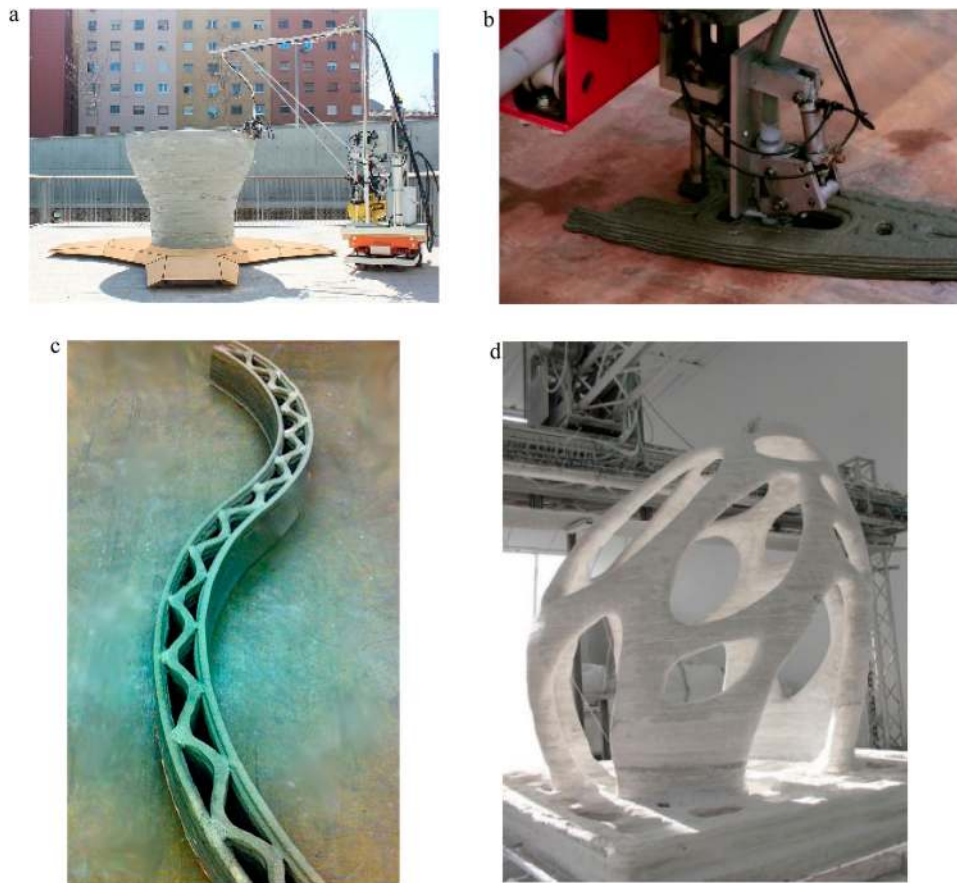
Figure 2. Images of AMoC by various institutes: (a) Minibuilders (Institute of Advanced Architecture of Catalonia), (b) Concrete Printing (University of Loughborough), (c) Contour Crafting (University of Southern California), and (d) D-shape.

relevant to buildings (10^{-1}–10^1 m). A variety of deposition strategies, robots, printer heads, and materials have been used.

A graphical impression of the development of 3D printing in the construction industry has been given by Langenberg (2015). Developments started in the mid-1990s in California, USA, when Khoshnevis introduced a technique termed Counter Crafting, see Figure 2(a) (Khoshnevis 1998, 2004, Khoshnevis et al. 2001, 2006). This involves the deposition of layers of continuous concrete-like filament on top of each other. With a few notable exceptions, most AMoC facilities around the globe operate on the basis of this Fused Deposition Modelling (FDM) principle. Until approximately 2012, developments have been steady. Besides Khoshnevis, pioneering work was done by the University of Loughborough (Le et al. 2011a, 2011b, Lim et al. 2011, 2012; Figure 2(b)), Shanghai-based contractor Winsun, and the company Total Kustom in Minnesota, USA. An alternative to working with single, large robots was introduced by the Institute of Advanced Architecture of Catalonia in 2014 (IAAC 2014; Figure 2(c)). While applying a similar extrusion technique, the deposition instrument is not a single large robot operating in a predefined space, but rather a group of small robots using sensoring technology to know their relative position and swarm technology to work together.

An altogether different approach, similar to Stereo-Lithograhy, was adopted by Enrico Dini, named DShape (Colla and Dini 2013, Cesaretti et al. 2014, Dhape.com 2016). He filed his first patent in 2006 and has been developing a range of objects since. Currently, Universe Architecture and contractor BAM are using the DShape technique to develop the Landscape House in Amsterdam, the Netherlands (3dprint.com 2016a).

In 2012, a turning point occurs. The number of entities exploring 3D printing for construction explodes, turning the previously more or less linear development into a quasi-exponential one. Currently, developments are going so fast that any overview of existing techniques and examples is out-of-date almost as soon as it is published. Nevertheless, Lim et al. (2012), Wolfs (2015), and Wu et al. (2016) give a sound impression of the development of the state of affairs.

New projects are presented on a regular basis. Some noteworthy examples include (Figure 3):

Figure 3. Noteworthy examples of projects using AMoC: (a) Two-storey house in China by HuaShang Tengda, (b) Office building in Dubai by Winsun, (c) five-storey building in Suzhou, China, by Winsun, (d) Hotel suite interior in the Philippines, by Total Kustom, (e) Villa in Suzhou by Winsun, (f) Castle in Minnesota, USA, by Total Kustom, and (g) series of 10 houses in Suzhou, by Winsun.

- Two-storey house in China, measuring 400 m^2, built by Beijing-based HuaShang Tengda in 2016 (3dprint.com 2016b).
- Office building in Dubai, UAE, measuring 250 m^2, 2016, by Chinese construction company Winsun. The building was printed using a $120 \times 40 \times 20$ feet 3D printer (approximately $36.6 \times 12.2 \times 6.1$ m), featuring an automated robotic arm (Cnet.com 2016a, Mediaoffice.ae 2016).
- Interior of a hotel Suite measuring $12.5 \times 10.5 \times 4$ m, in the Philippines, completed 20 September 2015, by Total Kustom (Totalkustom.com 2016a).
- Five-storey apartment building in Suzhou, China, completed in January 2015 by Winsun (Cnet.com 2016b).
- Also in Suzhou, China, a 1100 m^2 villa, by Winsun, completed early 2015.
- Children's Castle, Minnesota, USA, completed August 2014, by Total Kustom (Totalkustom.com 2016b).
- Series of 10 houses, in Suzhou, China, by Winsun, 2014. Printed with a massive $150 \times 10 \times 6.6$ m printer (Wu *et al*. 2016).

2.2. 3D concrete printing

The current 3DCP facility at the Eindhoven University of Technology (TU/e) adopts the Contour Crafting approach (NOS 2015, Wolfs and Salet 2015, Wolfs *et al*. 2015, Salet and Wolfs 2016). (see Figure 4). Concrete is mixed with water and pumped into a hose by a mixer-pump located on the side of the set-up. The hose is connected to the printer head situated at the end of the vertical arm of a motion-controlled 4 degree-of-freedom (DOF)

gantry robot serving a print area of $9 \times 4.5 \times 2.8$ m. The motion parameters maximum speed v_{max} and maximum acceleration a_{max} are listed in Table 1. The facility is in operation since September 2015.

Under the pressure of the pump, the concrete is forced towards the printer head (Figure 5), an element consisting of several parts allowing the concrete to be printed at the desired location, at the desired speed, and under the desired angle. The end part of the printer head is the nozzle, a hollow steel element with a designated section from which the concrete filament leaves the printer (Figure 6) and is deposited on the print surface.

Several nozzle openings have been tried. Initially, a round Ø 25 mm (491 mm^2) opening was used. The resultant round filament, however, was difficult to stack. Then a square 25×25 mm (625 mm^2) section was used. This increases buildability, but also requires the printer head movement to be programmed such that the orientation of the nozzle always remains tangent to the tool path (Figure 7). Otherwise, twisting of the filament will occur (Figure 8) – although this can also be accepted as a natural property of printed concrete. Currently, a 40×10 mm (400 mm^2) opening is used.

Like the nozzle opening, determining a workable default print head speed and pump frequency (and resultant pump pressure) setting was the result of a parameter sensitivity test programme. Obviously, these three parameters are closely interrelated, and highly dependent on the concrete viscosity as well (which is, in turn, a function of the concrete mix composition and water/cement ratio). At the moment, a default linear print speed of 100 mm/s (0.1 m/s) is maintained and a pump pressure of 1–3 MPa (10–30 bar). In corners the
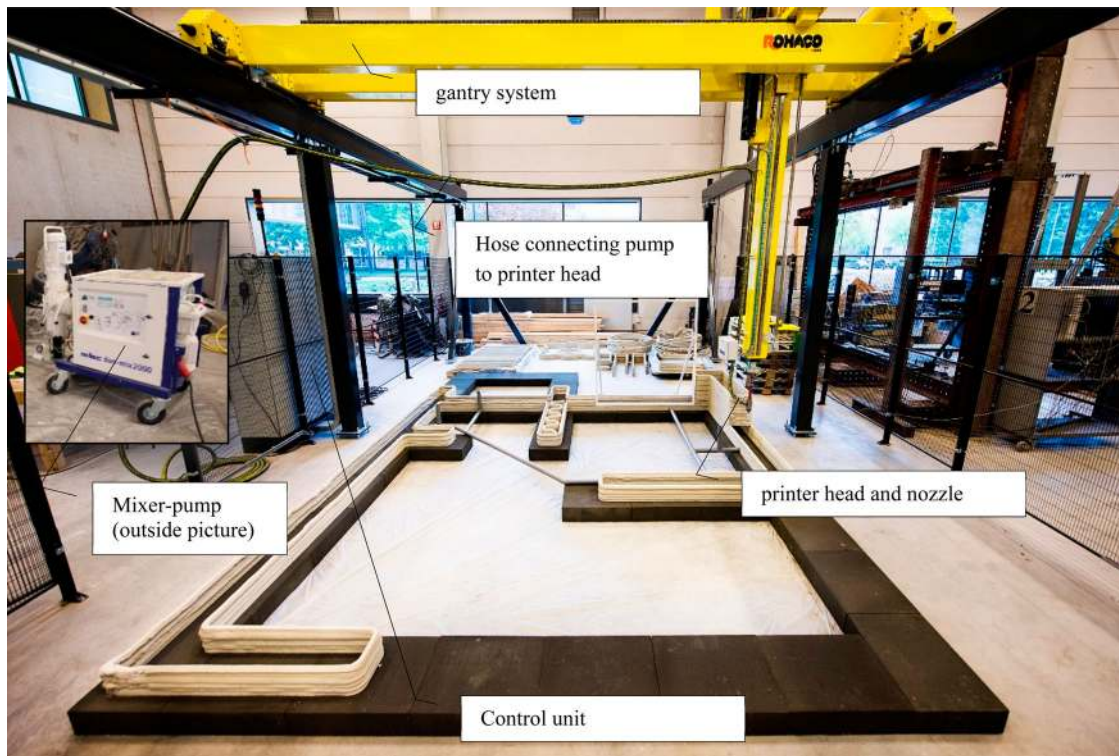
Figure 4. 3DCP facility at the TU Eindhoven, with some examples of printed objects.

Table 1. Gantry robot motion parameters.

DOF	v_{max}	a_{max}
Translate x-axis	1.8 m/s	1.0 m/s^2
Translate y-axis	1.8 m/s	1.0 m/s^2
Translate z-axis	1.8 m/s	2.0 m/s^2
Rotate z-axis	3.0 rad/s	6.0 rad/s^2

speed and frequency are reduced, depending on curve radius.

The height of the print head above the print surface has considerable influence on the geometry and properties of the printed product. Again, a default setting has been found by running a parameter sensitivity test programme. The height $h_{printhead}$ of the flat underside of the print head is equal to the nozzle opening width $b_{opening}$. This results in a relatively predictable printed filament of which the section is practically equal to the nozzle opening. The printed result can be influenced by pressing the print head into the printed product, that is, $h_{printhead} < b_{opening}$ (Section 3.2.5).

For the research, a custom concrete mix was developed by SG Weber Beamix. The mortar is comprised of:

- Portland cement (CEM I 52,5 R),
- siliceous aggregate with an optimised particle size distribution and a maximum particle size of 1 mm,

Figure 5. Printer head and nozzle.

Figure 6. 3D concrete printer in operation. No-slump concrete leaves the nozzle as a relatively stiff continuous filament.
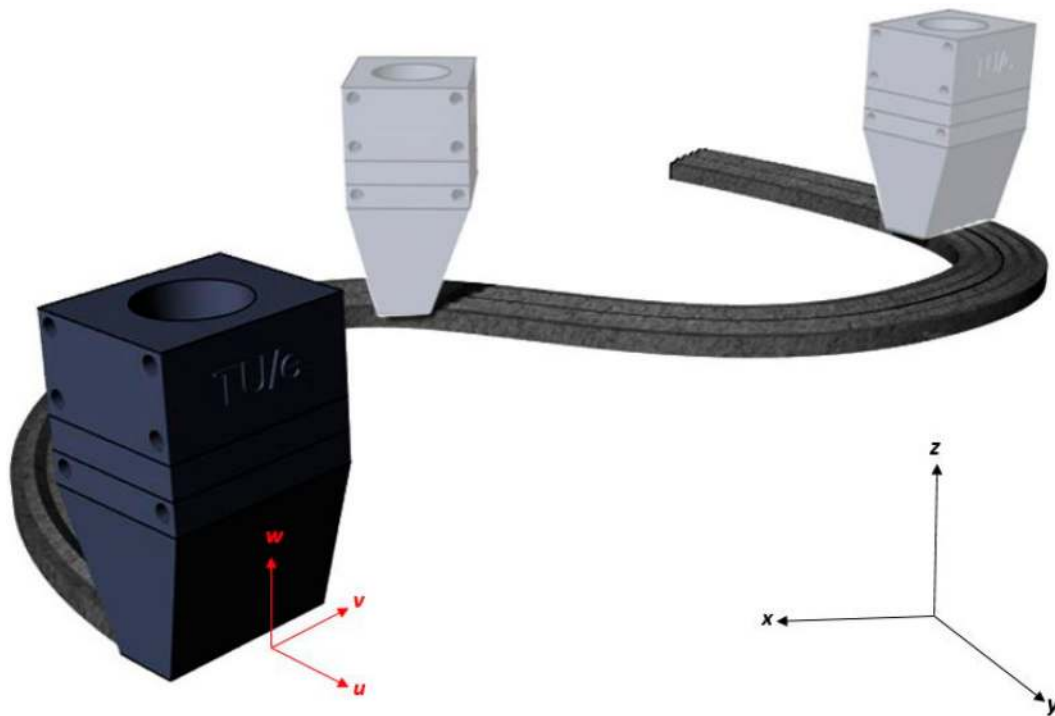
Figure 7. To avoid twisting of the filament, the nozzle should remain tangent to the tool path.

- limestone filler and specific additives for ease of pumping,
- rheology modifiers for obtaining thixotropic behaviour of the fresh mortar, and
- a small amount of polypropylene fibres for reducing crack formation due to early drying.

Performance of the mortar with regard to strength development and speed of strength development can be easily adjusted by adding accelerators and/or by changing the ratio Portland cement/limestone filler. The currently applied mortar attains a 28-day compressive strength of in the order of magnitude of 30 N/mm^2, and 28-day flexural tensile strength of around 5 N/mm^2.

Figure 8. Twisting of filament.

There were several reasons for selecting these properties. The no-slump character allows an easily understandable relation between print path, nozzle opening, and printed geometry. Hence, it also allows geometrical precision and building of layers on top of one another. The long setting time keeps the surface chemically active to form interfaces between layers of which behaviour is close to the bulk material, without great dependency of the time interval between subsequent layers. Furthermore, it is forgiving to the system as it does not clog up elements when disruptions occur for whatever reason.

In the TU/e 3DCP research, it has been a key assumption that there is a strong interdependency between design, material, print process, and product. Furthermore, it was suggested (Wolfs 2015), in order to properly control the 3DCP as a manufacturing method, that parametric associative modelling is required to quantify these dependencies and to adjust, for example, print process parameters to the printing of specific designs to obtain consistent quality and properties of the printed product. The selected concrete mix is particularly suitable to test this assumption (see further discussion in Section 4).

However, during the experiments a number of drawbacks to the currently used mix were also encountered. An important consequence of the selected concrete properties is that the concrete is in its pre-setting state (often referred to as 'green' or 'dormant') for the duration of a print session. As a result, the buildability of layers is

limited, as it depends on the relatively low stiffness and (to a lesser extent) strength of the printed 'green' filament. Another observation that has been made is that the filament consistency during a print session can change. The filament then temporarily suffers from cavities. This is possibly partly caused by the interstitial zone between the hose internal surface and plug flow occurring in the middle, as described, for example, by Öcel and Yücel (2013), were shear stresses induce segregation and other irregular effects. Material from this zone may enter the flow irregularly. Irregular consistencies occurring already in the mix reservoir (before the pump) may also be a cause. The no-slump character of the mix does not allow such cavities to be filled again by the flowing concrete. It is noted from video footage available from other AMoC projects, often a fast-setting mix with higher slump is used (although such data are not generally published). This results in better buildability due to higher stiffness of previously deposited layers, more consistent quality due to self-filling of cavities, and possibly better interface quality due to better filling of contact surfaces. The 1:1 relation between nozzle section and printed geometry on the one hand, and process forgiveness, on the other hand, are lost. Nevertheless, a reconsideration of the appropriate material mix is planned for.

2.3. Comparison of AMoC operators

A full analysis of the print processes adopted around the globe is not possible, as generally, due to competition considerations, crucial details are not publicly shared. For many of the showcase projects mentioned in the previous section it is, for example, not known exactly what parts have been printed, what material compositions have been used, how the equipment operates, and how structural safety and the main load bearing have been arranged. Nevertheless, some global comparisons can be made on a number of distinctive parameters.

With the exception of D-shape, all AMoC operators adopt the contour crafting approach of stacking layers of filament. Geometry and structure characteristics of the 3DCP method, which belongs to this family, are discussed in Section 3.

Gantry robots with 3 or 4 DOF, and articulated robots with 6 or more DOF are most commonly used. The former particularly for large projects, the latter generally for somewhat smaller objects. The group of minirobots operated by the IAAC is quite unique. The D-shape method requires a gantry-style setup but a different type of printer head depositing layers of powder material and subsequently binder of the full width of the set-up, rather than filament on a singular location.

Little is known in detail about the materials being applied by the various operators. The FDM methods likely all operate with high cement ratio, fine aggregate mixes – quite different from traditional concrete. The printing requires early form stability. This can be achieved through a combination of low slump and fast setting, where one complements the other: the faster the setting, the more slump can be allowed, or vice versa. In Section 2.2, some consequences of the setting time/slump proportion have been discussed.

Lim et al. (2012) and Le et al. (2011) provided details on the material mix used by the Concrete Printing research group of Loughborough University. It consisted of 54% sand, 36% reactive cementitious compounds, and 10% water by mass (Lim et al. 2012). Le et al. (2011) mention that the binder material is a mix of CEM I cement, fly-ash, and undensified silica fume. A retarder is added, and an accelerator has been experimented with. The mix contains '12/0.18 mm length/diameter polypropylene micro fibres to reduce shrinkage and deformation in the plastic state'.

For the 2014 housed 3D printed by Winsun, reportedly high-grade cement and glass fibre were used (Wu et al. 2016). Pictures of the project, however, seem to suggest glass fibre is not used as additive to the mix, but rather as a separate mesh in between printed layers. Liang and Liang (2014) suggest to use a high percentage of waste and recycled materials in future prints, to obtain cheap but decent housing, for which there is an enormous need in China and fast construction is thus also important. It is, however, questionable how that target relates to the use of high-grade cement.

It is claimed (3dprint.com 2016b) HuaShang Tengda has used ordinary C30 class concrete to print its two-storey house. However, considering slump behaviour and particle size in relation to printer geometry, this is improbable. It would, however, make the technology credible as low-cost construction alternative.

Although often not reported explicitly, images suggest that most concrete printers apply nozzle section sizes of 1 to several centimetres for length and width. Total Kustom operates with a default nozzle opening of 30×10 mm (Totalkustom 2016b). This is similar to the 40×10 mm nozzle applied by the TU/e. The Concrete Printer of Loughborough University uses smaller, circular nozzles of Ø 6–20 mm, resulting in a layer thickness of 6–25 mm (Lim et al. 2012), whereas the Contour Crafting reports a layer thickness of 13 mm resulting from a Ø 15 mm nozzle (Hwang and Khoshnevis 2004).

Most AMoC facilities seem to operate in the scale of up to 10 m lengths, and around 3 m height. The $150 \times 10 \times 6.6$ m polymer printer erected for printing a series

of houses in Suzhou, China, by Winsun in 2014, suggests that larger parts have been printed, but no data have been published on that aspect. Facilities operating smaller nozzles generally also print smaller objects.

2.4. Comparison to other 3D print processes

The solidification of the print material in 3DCP occurs as a (relatively) slow chemical process, namely the exothermal hydration reaction between cementitious materials and water. The setting reaction starts from the moment the concrete mix and water are mixed in the mixer-pump at the side of the print facility. It is dependent on a number of parameters further discussed in Section 4. Other 3D print techniques often use physical or fast-acting chemical processes that require completely different conditions to control. A fundamental difference resulting from this solidification mechanism is the status of the layers beneath the current layer that is being printed. While in most non-concrete 3D print methods they are solidified (sometimes in need of reactivation of surface), in 3DCP and other concrete-based methods, they are in an in-between state, depending on the time since deposition and material setting time (Figure 9). This requires extensive characterisation of the development of several material parameters such as strength and stiffness over time, as a function of several print process parameters in the system.

Apart from that, the print material, concrete, has a range of specific characteristics different from other materials, such as shrinkage, creep, age-dependent strength, etc. Although extensively investigated for common concrete applications, these properties also have been explored only very limitedly in relation to 3D printing.

The most striking difference of 3DCP with other industrial and consumer 3D print methods is of course its sheer size – although a $12 \times 12 \times 12$ m 3D polymer printer based on FDM was presented by Qindao Unique Technology (Liang and Liang 2014). In relation to previously mentioned aspects of slow curing and other material characteristics, print size is very relevant to the way the print process should be conducted and the quality of the end result. Particularly, the stability of the printed object during printing should be considered as loading increases on non-cured layers. This is strongly related to print time, setting time, and layer interval time.

More than other 3D print techniques (except for D-shape), AMoC geometries are dominated by the linear deposition of filament. Filament has a direction, which introduces a direction dependency – if not in the properties of the set product, then at least in the print strategy. This has a major influence, for example, on angles in a geometry, which will often be curves (with a minimum
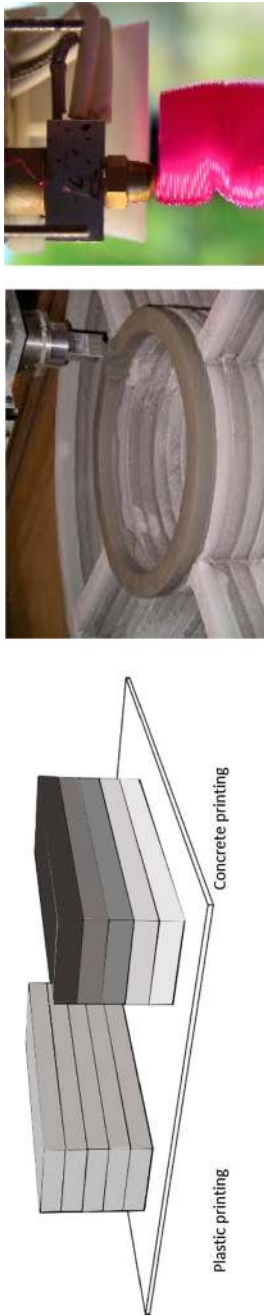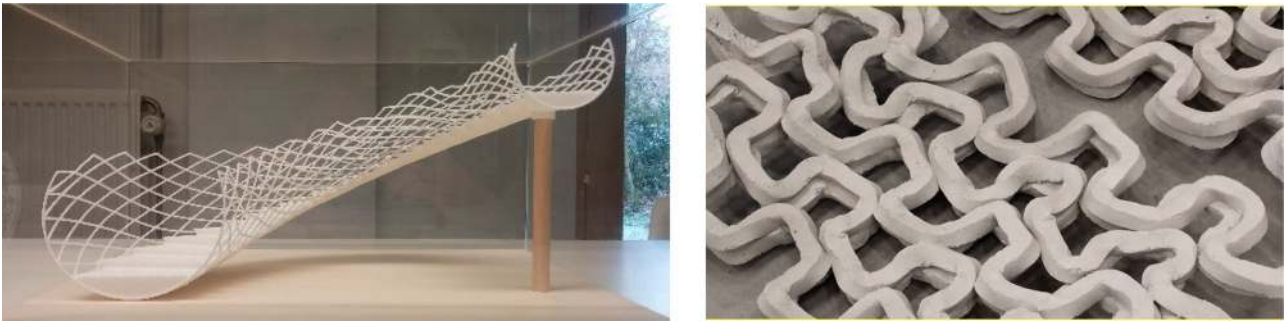

Figure 9. In non-concrete 3D printing, the layers beneath the layer being printed are in an equal set condition. In concrete-based methods such as 3DCP, those layers are all in a different state of curing.

Figure 10. One of the submitted designs (a staircase, by BiermanHenket Architects, (a) 3D printed scale model) for a 2015 design challenge for architects on the 3D printing of concrete, and the (b) printed part of the railing. The railing pattern had to be adjusted, and a bespoke curved print surface had to be produced to obtain the design intent.

radius) in the tool path. A pixelised approach based on a x,y,z space divided in equal in all directions is inappropriate. When additives, such as fibres, are introduced, the directional dependency increases even further.

Finally, it may be observed that for many 3D print techniques, the movements and rotations in x,y-plane are made by the printer head, while movements in z-direction are made by the print surface. In comparison to the other mentioned differences, however, this seems only a minor one.

3. Geometry and structure characteristics of 3DCP

Although 3D printing seems to imply that any Computer Aided Design (CAD) geometry can be produced independent of process planning, this is far from true for FDM-based AMoC, such as 3DCP. The method is limited by rather specific geometrical possibilities. Furthermore, the printed product properties both in green and set state depend highly on process parameters. This latter issue is discussed in Section 4. This section deals with the geometrical and structure characteristics of 3DCP. The purpose of explicitly dealing with this issue is to open the road to the creation of print job files that can be automatically generated from CAD geometries, without the interference of a production and product specialist, that is, much as a print file is currently generated from a text-processing application to print an ordinary document on paper. In the current state of affairs, this is not yet possible. Projects in which AMoC has been applied have been designed with the particularities of the production method as a guiding principle. In 2015, a design workshop for architects presented at the Bouwbeurs 2016 Trade Fair, in Rotterdam, the Netherlands, yielded results of which parts could only be printed after considerable redesign efforts by the TU/e 3DCP production team (Figure 10(a) and (b)).

3.1. Tool path

The guiding principle in the generation of 3DCP geometries is the tool path the printer head follows during printing. Generally, modern gantry and articulated robots can follow practically any thinkable tool path through 3D space, whether they are defined by Euclidean geometrical shapes or more complex definitions such as splines.

Hence, this also allows printing on any non-planar surface. This approach, that opens new avenues in the geometrical possibilities of contour crafting, has been explored by the TU/e for the previously mentioned design workshop and is currently subject of further research (4tu.nl 2016). However, for clarity, the rest of this section assumes printing on a flat plane. Most considerations will apply to printing on non-planar surfaces as well, although their implementation may be more complex. In literature on AMoC, no standard has been set on the designation of the coordinate system. Le *et al*. (2011) introduce directions I, II, and III, where I is parallel to the printer head direction, II is parallel to the perpendicular of the top printed surface (since this is a horizontal plane, this amounts to being parallel to the vertical), and III is parallel to perpendicular on the printed side surface. Here, however, it is suggested to use a slightly different designation which we consider better in line with 3D drawing conventions, namely u, v, and w (see Figure 7). It is proposed to appropriate u for the direction of the tool path (positive in the direction of movement; u is thus similar to direction I), v for the direction perpendicular to u in the print plane, making the u,v-plane the plane in which is printed (v is than similar to direction III), and w for the direction perpendicular to the print plane (similar to direction II). The designations x, y, and z should be reserved for global coordinates.

Currently under development at the TU/e is an adaptation to the printer head allowing interruption of the

flow of filament, so that printing can stop at one place, and continue at another after movement of the printer head. Several AMoC facilities around the world are already capable of this.

3.2. Geometry

3.2.1. Tool path and single filament

The movement of the printer head and continuous flow of concrete result in the deposition of a linear filament. The section dimensions of this single filament depend on a number of parameters, such as speed of concrete flow and printer head speed, nozzle section, slump and setting characteristics of the concrete, and inclination of the print surface. In the default settings at the TU/e, the single filament section is almost equal to the nozzle section.

The single filament section, with in principle endless length and which can be adjusted as a function of the mentioned parameters as well as a number of print strategies discussed below, is the basic building block for 3DCP geometries. Obviously, the smaller the filament section, the more detailed a printed object can become, generally at the price of the overall print speed.

3.2.2. Cornering in the u,v-plane (print surface)

When deviating from printing a straight line, that is, introducing corners, a difference in deposition rate arises between the inside of the filament (near the corner centre) and the outside, resulting in a difference in material deposition. If this difference becomes too big, this may result in tearing of the outer edge of the filament and skewing of the section due to the deposition difference. Hence, a minimum radius of curvature

should be maintained, the value of which, however, is highly dependent on the individual 3DCP parameters, including the filament section itself (a broad filament results in a larger deposition difference than a narrow one).

3.2.3. Vertical stacking of filament

The basic method of creating 3D objects through contour crafting is the vertical stacking of layers of filament. To describe the extent to which layers can be stacked, Lim *et al*. (2012) introduced the term 'buildability'. A simple straight stacking is nevertheless complicated by the slump, setting time, and flow behaviour of the concrete. As explained in Section 2.4 (Figure 9), a number of layers beneath a current printed layer *n* has not yet solidified. Each of these layers has a different stiffness $E(t)$ and strength $f(t)$, both functions of their age *t*. In combination with imperfections that may occur due to printer head accuracy, filament inconsistencies, or the dynamic deposition of filament, this may lead to premature collapse of the structure through instability during printing. In other words, the stacking is predominantly governed by the effective stiffness of the combined layers, rather than by their strength. The lower limit of buildability is determined by considering the phenomenon in 2D in the *v,w*-plane. However, actual stability is determined by the material properties as well as the actual 3D geometry, which can hugely improve over the 2D situation, for example, when a corrugated geometry is applied.

Fully set layers, on the other hand, may be considered to be sufficiently stiff and strong to allow stacking well beyond practical size boundaries of the printers. Several AMoC operators, such as CyBe in the
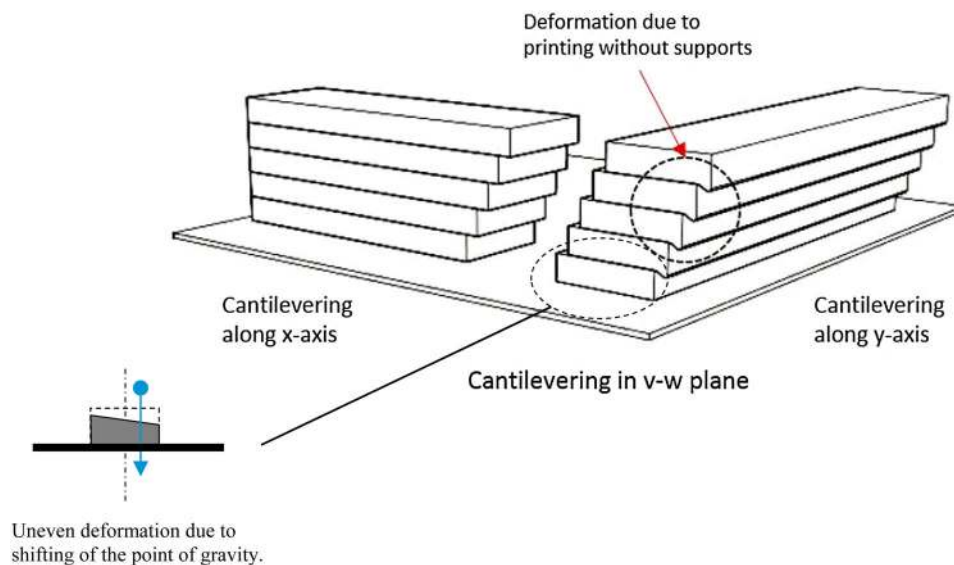

Figure 11. Cantilevering layers of filament in the *v,w*- and *u,w*-plane.

Netherlands, have succeeded in achieving properties between slump, setting time, and flow behaviour that eliminate the number of maximum layers to be stacked as a constraint.

To increase geometrical diversity, layers can be stacked non-centrally above another, creating a cantilever in the v,w-plane. In current techniques, the possibilities to apply this principle of this are fairly limited. They are restricted both by local behaviour of the filament partially deposited without support (the cantilevering part) and global stability issues (Figure 11). In a 2D consideration, an upper limit of cantilevering is determined by the shifting of the point of gravity outside the supports (which have no tensile capacity), but the actual limit is significantly lower as shifting of the point of gravity outside the mid-point of the support introduces uneven compressive stresses, causing uneven deformations, which result in premature failure. Here, again, the 3D geometrical constraints may be smartly exploited to nullify such stability issues and nevertheless create sections cantilevering in the v,w-plane.

Assuming an interruption mechanism is in place, similar considerations could be made for cantilevering in the u,w-plane. In this case, the mass available in the plane of cantilevering positively influences the maximum angle of cantilevering (Figure 11). The accuracy of the interruption mechanism will also determine what is practically possible.

A particular point in the stacked layer geometry is the transition from one layer to the next. Several strategies are possible, as illustrated in Figure 12. In strategy 1, the print head gradually moves upwards from the print surface, with the upwards movement evenly distributed over a major portion of the deposition plane of the filament. The consequence is that the drop height of the filament is non-optimal (namely $h > b$) over a large length of filament. The second strategy also includes a gradual shifting of the print head over the w-axis, but distributed over a much smaller length, of one to three times the layer thickness. The TU/e currently employs this strategy, which results in relatively small areas of discontinuity, and a smooth printing process. A third strategy involves local shifting along the w-axis, without movement in the u-direction. This obviously results in additional material deposition in that area. Finally, a sophisticated interruption mechanism could allow printing of a single layer, temporary stop, and movement of the print head along the w-axis before continuing the next layer. Theoretically, this would produce the smoothest results.

3.2.4. Horizontal arrangement of filament
Geometries of more than one filament thickness in the v-direction can be created by printing filaments next to
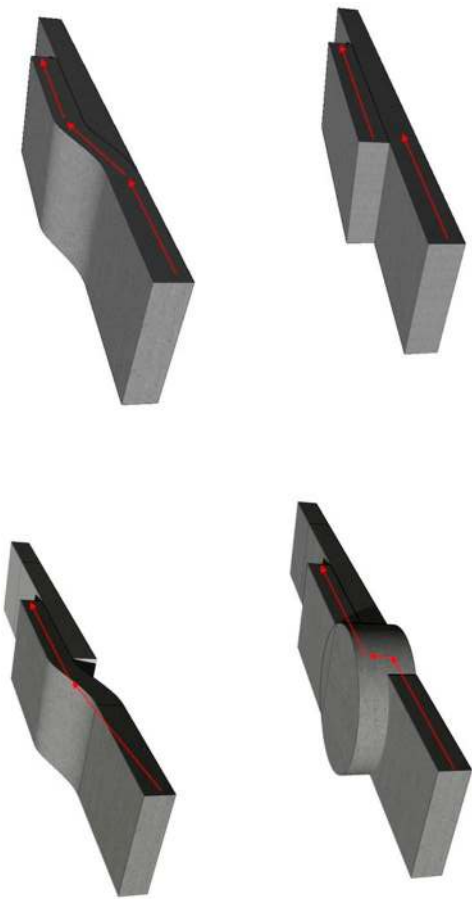

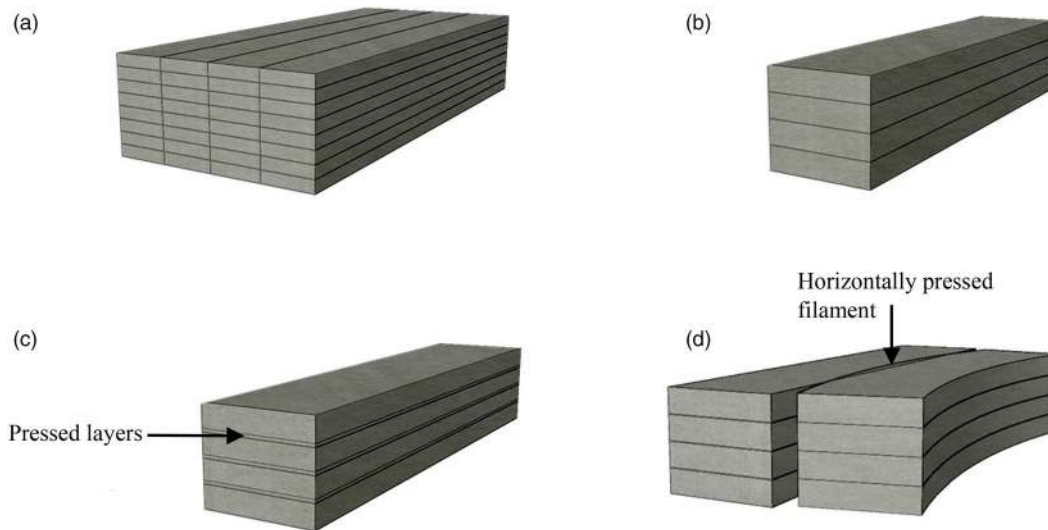**Figure 12.** Tool path strategies to go from one layer to the next.

Figure 13. Interfaces and stacking: (a) interfaces in the *u,v*- and *u,w*-plane, common in high-resolution AMoC, (b) interfaces in the *u,v*-plane, common in other AMoC, (c) interfaces in the *u,v*-plane, with layers pressed together to obtain higher compaction and improved interface adhesion, and (d) interface in the *u,w*-plane, with filament pressed together.

each other. When square or rectangular filament is used, or filament with sufficient flow capacity, this can result in solid sections. However, as, reported by Le *et al*. (2011), circular filament with insufficient flow can cause air cavities in between filaments next to each other.

3.2.5. Pressing layers

At the TU/e, a default approach is maintained that the height of the print head above the print surface is equal to the nozzle section width. This results in a smooth deposition of the print filament, and avoids (pressure) interaction between the filament and the print head. For researching the dependencies between printed product and process and material parameters, eliminating this additional, difficulty quantifiable parameter.

However, pressing the printer head slightly into the filament (i.e. $h_{printer\ head} < b_{nozzle\ section}$) can have several effects that positively influence the (structural) properties of the printed product (see Figure 13(c)). The pressure generated in the green printed product under the printer head should improve compaction as well as interface adhesion.

Horizontally layers can also be pressed into each other (Figure 13(d)). This should generate similar favourable effects on compaction and interface adhesion.

3.3. Interfaces and bulk material

A characteristic of contour crafted concrete is that it is built up from filaments of bulk material joined by interface surfaces. These interfaces may theoretically occur

in three orientations: in the *u,v*-plane (generally horizontal, in the *u,w*-plane (vertical), and in the *v,w*-plane (Figure 13). However, due to the linear toolpath in *u*-direction, interfaces in the *v,w*-plane are rare to nonexistent in a typical 3DCP structure. *U,w*-plane interface surfaces are also uncommon in most examples, as the larger printed projects generally make use of vertical stacking of a single column of filament.

Anisotropy may occur both in the bulk material and as a consequence of interface properties of the different interfaces. It is likely the structural properties of the interfaces will govern the overall structural performance, with the bulk material properties the upper limit of what performance could theoretically be achieved. Due to the high number of interfaces, it seems appropriate to
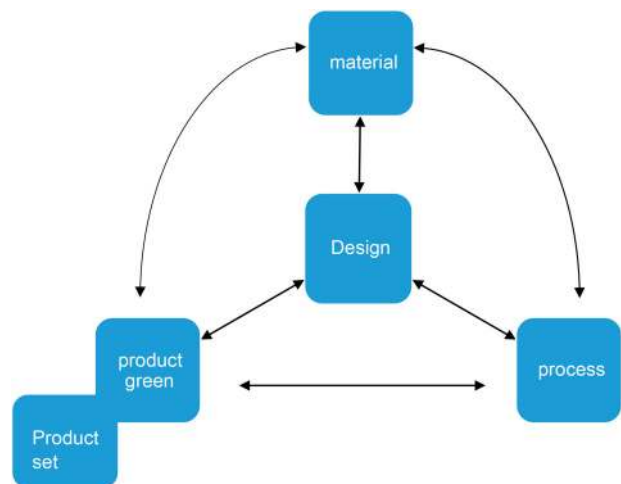

Figure 14. Interdependency of design, material, process, and product.

Table 2. Reaction conditions and print process parameters.

Condition	Process parameters
Concrete age (time between mixing and printing)	- The mixing process is not a continuous steady process, but rather a step-wise process in which the mixer fills a reservoir above the pump and mixes additional material once the reservoir level has fallen under a certain threshold. Thus the age of the concrete in the system varies - Pressure in the system (varies, see below) - Non-continuous printing. Currently, the printer lays continuous filament. However, in order to achieve reasonable versatility, it is imperative the filament stream can be stopped and restarted, so that a printed line can be terminated and continued at another location. Since this introduces a waiting time in the system, this will influence the age of the filament upon leaving the nozzle head - Stagnation: in ordinary concrete construction setting is delayed by continuous mixing. However, this not possible in the current 3DCP system
Mix temperature	- Environmental conditions and start temperature of the system - Friction in the system, which depends on a range of sub-parameters such as the pump pressure, section dimensions of subsequent parts, hose length, and curves and angles in the system. Using a low-slump concrete increases the sensitivity to this aspect - Heat conductivity of the system - Setting reaction itself (exothermal)
Mix internal pressure	- Parameters similar to friction: pump pressure, section dimensions of subsequent parts, hose length, and curves and angles in the system. The no-slump concrete requires a particularly high pump pressure to move through the system
Density of printed material	- Compaction - Pressure (see above) - Linear nozzle speed
Material mix	- Many variants possible
Water/cement ratio	- Machine setting in mixer-pump

analyse the interface properties to assess the structural performance of a printed product, and assume the bulk material properties will not be governing.

The extent of anisotropy both in the bulk material and in the interfaces is yet unknown. In the research presented by Le et al. (2011) a direction dependency was found, with failure strength differences in flexural bending of sample beams in the order of 10–15%. In that study, bulk material and interface were not treated separately, but the presence of interfaces was rather treated as a cause for anisotropy in the globally assessed

specimens. Thus, the directional difference found was not a directional dependency of either the bulk material or the interface, but rather a directional difference caused by the fact that in one direction the interface was loaded in flexural bending perpendicular to the interface surface, whereas in the other two directions the bulk material was loaded in flexural bending and the interfaces were loaded in shear or were actually not loaded. Ongoing research in this area at the TU/e has not yet produced conclusive results.

4. Experimental research on 3DCP

It is imperative to recognise that in 3D printing, design, material, process, and product are all strongly interdependent (Figure 14). In 3DCP, this interdependency is even more pronounced for two reasons. Firstly, the slow setting reaction in the printed concrete results strong interaction with the applied print parameters and strategy such as print speed, pump pressure, filament stacking, etc. Secondly, concrete of itself is not a single fixed material, but can actually have a wide range of compositions that may be more or less suitable in relation to the printing process and the required end product performance properties. Thus, a print strategy cannot be chosen independently from design, material, or (desired) end product considerations. The design of a product influences the green and end product properties, or the process and material parameters have to be adjusted to avoid this. Table 2 provides an exploration of some expected dependencies between setting reaction conditions and print process parameters (thus, still a limited part of all dependencies).

To complicate matters, the quality of green and set concrete not only depends on the chemical reaction, but also significantly on the physical compaction (densification). In ordinary concrete applications, compaction is achieved either through post-cast vibration, or by the use of (low viscous) self-compacting concrete. In 3DCP, neither is possible. No-slump and self-compaction are contradictory aims that can only partially be fulfilled simultaneously (Hoornahad 2014). A level of slump has to be accepted in order to obtain significant compaction, or (i) the concrete mix has to be redesigned to obviate the need for post-printing compaction, or (ii) the print system may be redesigned to compact the concrete under pressure before printing.

Of course, testing of the green and set properties of the printed concrete produced under different conditions forms the basis under the mapping of parameter relations. This is complicated by the fact that suitable and generally accepted test methods have to be developed as well. Particularly for concrete in the pre-set state,

this is a challenge. In the literature, two fundamentally different approaches to characterising the pre-set concrete behaviour can be found.

The contour crafting research group has applied uni-axial plate stacking tests, and subsequently, a more controlled method to apply uni-axial loads on fresh concrete cylinders was presented by Di Carlo *et al.* (2013). The recorded Poisson ratios and internal friction angles were used to develop a Drucker–Prager material model, thus assuming the pre-set concrete to be a solid material with plastic failure behaviour. It is, however, questionable whether this uni-axial test provides sufficient information on the failure behaviour in different 3D stress states, as it only results in a single Circle of Mohr. The Drucker-Prager model generated from these tests is probably only valid for one hydrostatical stress state. Preferably, a tri-axial test for fresh concrete is developed as well, to assess different 3D stress states. For existing methods used in soil engineering, however, it takes well over 10 minutes to prepare a specimen, whereas the time frame up to 10 minutes is the most relevant to 3D printed concrete. New or adjusted methods would need to be developed.

Alternatively, the Loughborough University research group considered the pre-set concrete as a Bingham fluid (plastic fluid) and performed shear vane tests as reported by Le *et al.* (2011) to obtain the relevant rheological parameters – although the study only mentions determination of the shear strength whereas also the plastic viscosity needs to be determined to obtain a complete Bingham fluid model. Approaching pre-set concrete as a plastic fluid is common in evaluating the workability of concrete compositions and was, for example, also maintained in an extensive study on concrete workability in general (not related to AMoC) by Özel and Yücel (2013), although the rheological parameters in that study were obtained by a Two Point Workability Test Apparatus.

Both the Drucker–Prager plastic solid approach and the Bingham plastic fluid approach are applied to the analysis of pre-set concrete. Which approach is most suitable depends on the specific purpose of the analysis: a plastic fluid approach may be more suitable to assess workability in the printer system, whereas the plastic solid model is more suitable to strength and stability analysis of the printed filament during printing. But it also depends on the specific concrete mix being analysed. A low viscous fast-setting printable concrete may correspond better with a Bingham fluid model, whereas a high-viscous slow setting printable concrete may correspond better with a Drucker–Prager model. Vice versa, the concrete mix for a significant part

determines which tests can be performed and thus which data can be retrieved to formulate a material model: the uni-axial compression tests are not possible on low viscous pre-set concrete, whereas applying the viscometer test to obtain rheological parameters does not work with high viscous pre-set concrete as it results in so-called 'plug'. The correlation between both approaches should be subject of research to determine the most appropriate approach. In any case, it should be considered that for buildability actually the stiffness of the printed filament is of paramount importance, even before failure and plasticity occurs (either as solid or as fluid). Thus, development of test methods should aim at obtaining accurate stress–strain relations for the pre-set concrete.

Furthermore, it should be noted that the developed tests are not performed on actually printed pre-set concrete filaments. There is no obvious solution on how this could be done, but it should be considered that the experimental results are likely influenced by the test method and specimen preparation itself (e.g. casting in a cylinder for the uni-axial loading test, or cast in a container for the shear vane test), and thus may provide properties that differ from those of printed filament. The effect of this needs to be calibrated.

In addition, it needs to be assessed which method is most appropriate for parameter sensitivity studies. Both the shear vane and uni-axial loading test are relatively simple, a tri-axial test provides more universal data, but is much more difficult to execute. This also warrants calibration between the methods.

5. Towards practical applications and outlook

Notwithstanding the exciting experimental projects that are being presented around the world (shown in Section 2), general admission of AMoC in (main) load bearing building structures is still some distance away. Several issues will need to be solved.

Due to the many related parameters in 3DCP discussed in Section 4, obtaining sufficient consistency in quality for different designs, printed from different material badges under varying conditions, still needs to be proven. It is likely this will first require improvement of the existing 3DCP facilities and development of understanding of the parameters that influence the final quality. Also, data will need to be collected for 3D printed concrete on some common characteristics, such as shrinkage and creep, to compare the printed material to the concrete commonly applied. Furthermore, connection methods need to be developed to join printed elements together.

5.1. Structural safety

The key question is whether a generic strategy can be developed to obtain sufficient robustness and ductility for structural applications. In common structural concrete, reinforcement is applied before the concrete casting to obtain composite structural elements with ductility. This approach is not an obvious standard for AMoC. The projects discussed in Section 2 apply a variety of alternatives. The concrete bench presented in Lim *et al*. (2012) has hollow sections over the height of the object. Post-tensioning prestress bars are fed through them after printing. This strategy is also commonly applied in a variety of concrete structures and introduces stiffness and tensile capacity, but not necessarily ductility. In the high-rise project of Winsun, it is actually unclear to what extent 3D printed concrete has been applied structurally, and what strategies have been applied to achieve structural safety. In the 2014 houses, glass fibre mesh has been applied in between printed layers. However, it is unknown whether additional measures have been taken. Pictures of the 2015 villa show reinforcement bars in between printed contours, suggesting that the voids have been filled with cast concrete and that (locally) the printed concrete acts as a mould in itself, rather than as a structural component. HuaShang Tengda adopts a method of erecting a steel frame on-site and printing around it. The Total Kustom projects, for example the Castle, seem to rely mainly on compressive forces to overcome the necessity for application of ductile tensile materials (under compression, concrete fails in a semi-ductile fashion caused by crumbling of the concrete).

An approach more appropriate to AMoC could be to develop a fibre-reinforced printable concrete with sufficient ductility and tensile strength. An extensive review by Yoo and Yoon (2016) on Ultra-High Performance Fiber Reinforced Concrete (UHPFRC, reinforced with steel fibres) shows the favourable strength, strain hardening, stiffness, fracture energy, and crack opening behaviour of such materials under various loading conditions. Most studies combine UHPFRC with steel or other reinforcement bars to obtain the optimal structural performance, but the model stress–strain curves for UHPFRC (without additional reinforcement) under compression and tension provided in that study as reproduced from AFGC-SETRA (2002) provide sufficient indication that the bulk material could be applicable for a host of structural applications. Other fibres, such as glass, basalt, or carbon fibres, have also been mixed with concrete to obtain structurally favourable strain behaviour. For Glass Fibre Reinforced Concrete (GFRC) Tassew and Lubell (2014) and Kizilkanat *et al*. (2015)

report various strain softening curves, indicating that GFRC could have structural applications albeit perhaps not as part of the main load bearing structure.

Two main challenges are connected to the application of fibre reinforcement in 3DCP. First is the actual even application of 1–3 VOL% fibres into the concrete which could lead to clogging, segregation, and non-uniform distributions (both in quantity per volume and in direction). The second is ensuring effectiveness of fibres across interface boundaries. Obviously, improvement of the bulk material properties makes little sense if the governing interface properties are not equally improved.

5.1. Evolution of AMoC

Whereas it is quite clear AMoC provides enormous potential for the construction industry, it is not at all obvious in what way we will see it applied in practice. Quite possibly, different variants will evolve to suit different purposes. It seems two fundamental choices will govern the evolution of the different members of the family of AMoC, briefly formulated as:

(a) Optimise production versus optimise performance and
(b) Off-site versus on-site.

With regard to (a) Optimise production versus optimise performance, one direction aims at developing AMoC as a cheap, fast but nevertheless customised alternative for traditional construction. This choice would aim at using local, cheap materials and optimising the manufacturing method in terms of speed and cost. Manufacturing would occur locally as well (either on- or off-site). Limited demands would be set with regard to the performance characteristics (structurally, aesthetically, and/or with regard to building physics) of the products that are manufactured this way. Likely uses are (wall) filling and other secondary uses. Additional cladding could be applied to achieve sufficient performance. Given the fact that the application of scaffolding and moulds in modern construction account for 50% of the concrete construction cost, the potential of AMoC is clear − even though it should not be expected

Table 3. Strategic choices by different AMoC operators.

	Off-site	On-site
Optimise production	Winsun	HuaShang Tengda
	Contour Crafting	Contour Crafting
Optimise performance	Concrete Printing	Total Kustom
	Contour Crafting	IAAC Minibuilders
	D-Shape	Contour Crafting
	3DCP	

these costs can be reduced to 0. Against the background of the enormous need for improved housing in China, it is logical that Chinese construction companies like Winsun and HuaShang Tengda look like taking this direction.

Alternatively, a choice could be made for high-end performance of the printed product. This implies development of high-performance printable concretes, methods to print structurally optimised shapes, and the overall aiming at the highest possible quality. Full customisability both of shape and printed material per location (explained further below) should be developed. This requires complex features in the machinery as well as the software and modelling controlling them.

Related to this issue is the expected visibility of the printed concrete. A product optimised on performance would be expected in view, whereas for a construction optimised printed concrete, additional cladding could also be suitable. The Winsun projects generally make use of cladding, whereas the HuaShang Tengda house shows how it was made. The Contour Crafting research group developed elaborate automated trowelling devices on a printer to obtain a smooth, presentable surface finish directly from printing (Kwon 2002). Again, different approaches are likely to evolve.

The other choice, (b) Off-site versus on-site, is self-explanatory. The technique may be developed as an alternative to the concrete mixers and application apparatus we see on construction sites nowadays, or as a next step in the prefab industry where it can work together with other robots that can add other features to products, such as door and window frames. The Winsun projects have been printed in the factory. Total Kustom, on the other hand, printed the hotel suite interior on-site and seems intent on pursuing this strategy (Totalkustom.com 2016a). Likewise, the two-storey house presented by HuaShang Tengda was printed on-site.

When comparing the different methods of AMoC today, it is noted that all combinations of these fundamental choices are being pursued, see Table 3. Some operators, such as Contour Crafting, aim at multiple choices, with envisioned applications as widely ranging as low-income housing to space colonies.

The 3DCP research group of the TU/e focuses on Off-site and Optimising Performance. The goal is to develop what is dubbed the 'Colour' printer, and the knowledge and understanding required for that. In this case, 'colour' is not to be taken literally, but rather as a metaphor for a 3DCP technology that can adjust the material by location (Figure 1), depending on the properties needed at that location. Thus at one point, the printer would deposit structural concrete, insulating concrete at another, further on self-cleaning concrete, etc. The fact that the printer head passes by each location in the complete structure once makes this theoretically feasible. That would allow a radically new and exciting approach to the design of concrete to improve our buildings.

6. Conclusion

AMoC was introduced as a promising family of methods to address challenges facing concrete construction today, as well as to open up new avenues of design possibilities. Different variants have been analysed and compared, and the 3DCP method applied by the Eindhoven University has been extensively introduced. Geometrical and structural characteristics, caused by the composition from linear continuous filament, have been introduced. Issues regarding experimental research have been discussed. Finally, research and development areas have been identified to allow application in practice and an outlook has been given into possible evolutions of these technologies.

Disclosure statement

Funding

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