Digital Fabrication in Concrete Construction

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Digital Fabrication in Concrete Construction

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Timothy Wangler, has been a postdoctoral researcher and senior research assistant in the physical chemistry of building materials since 2012. His research interests centre primarily on the intersection of three fields: chemical engineering, material science, and civil engineering. His education was primarily in chemical engineering, with a bachelor's degree from the New Mexico Institute of Mining and Technology. After working for some years in semiconductor manufacturing at the Intel Corporation in Rio Rancho, New Mexico, he joined the PhD programme at Princeton University's Department of Chemical Engineering, ultimately earning his PhD in 2009, under the guidance of Professor George Scherer, on the topic of understanding and inhibiting damage to heritage sandstones by swelling clays. He then joined the Laboratory of Building Science and Technology at the Swiss Federal Laboratories for Materials Science and Technology, Empa, in Dübendorf, Switzerland as a postdoctoral researcher, where he researched the topic of leaching of biocides from building façades into surface waters. He then joined the group of Professor Robert J Flatt, where he has since expanded the scope of his research.

ABSTRACT: The construction industry is primed for a revolution in productivity, driven by digital technology. Additive manufacturing technologies in construction, including digital fabrication with concrete, are expected to be a major component of this revolution. In this paper, the reasons for the development of these technologies is examined, followed by a brief review of the various technologies that have been developed to date. The current state of the field is discussed, with technological challenges and barriers to industrial acceptance at the forefront of the discussion. The prospects for sustainability in this expected revolution are highlighted, and key points for the continued technological development are noted.

KEYWORDS: DIGITAL FABRICATION WITH CONCRETE, RHEOLOGY, 3D PRINTING, SET CONTROL, ADDITIVE MANUFACTURING

Introduction

Digital fabrication with concrete has shown very rapid development, especially within the past 5 years. Research on the topic has exploded, culminating most recently in large high profile academic events [1], and the appearance of multiple large scale demonstration projects. Most recently, two 3D printed bridges were erected in China [2,3], and a two story building has been 3D printed by a startup in Dubai [4]. Dubai, in fact, has come under a mandate to have 25% of its new buildings 3D printed before 2030 [5], and concrete printing has been used to generate a number of demonstrations by various startups [6–8].

The accelerating trend towards industrialization of construction is leading to greater adoption of technologies such as prefabrication and overall digitalization in the construction industry [9]. Larger industrial players have been working towards, or are now joining, the world of digital fabrication with concrete as well, especially in Europe. For example, the Royal BAM Group in Holland recently opened a 3D printing construction facility in Eindhoven, after leading with TU Eindhoven the construction and installation of the first structural bridge made by extrusion printing of concrete [10,11]. Until now, however, the question has remained whether all this attention is merely hype, or representative of a tectonic shift in the way that construction will be performed in the future. In the following paper, the rationale for this technology's use in construction is discussed, followed by a review of the current technological capabilities, with an emphasis on the material technology. Finally, the current challenges and the outlook for this technology are explored.

Rationale for digital fabrication with concrete

Until now, many arguments have been brought forward for the implementation of digital fabrication technologies in the construction industry: reducing formwork costs, increasing design-to-construction efficiency, current and expected impacts of skilled labour shortages, increased worker safety, and enhanced shape freedom. However, they can generally be grouped into one of two main arguments: 1) increased productivity, and 2) increased sustainability; both of these are discussed below.

Increased productivity

It is a well known fact that the architecture, engineering, and construction (AEC) industry has been lagging behind other economic sectors in terms of productivity. Non-farm business labour productivity in the US, for example, saw an improvement of 153% since the 1960s, while construction labour productivity during that time has seen a 19% fall [12]. This is rather a serious issue for AEC, which accounts for 6% of global GDP and is the number one consumer of raw materials, accounting for more than 3 billion tonnes annually [12], and expected to increase in the coming decades with the continuing development of China and the expected rapid developments of India and Africa. This increasing activity calls for more efficient construction practices to cope with the expected burden on the natural resources of the earth. From the standpoint of the industrialized economies, an ageing workforce means skilled labour is already, or will be, in short supply [13]. Construction jobs are perceived by younger generations as dangerous, difficult and dirty, and remain unfilled as older generations retire or can no longer perform them.

Digital technologies are expected to be necessary to address these challenges. The level of digitization in the construction industry remains embarrassingly low [14]. Implementation of digitization, from the standpoint of digital fabrication technologies with concrete, takes aim primarily at formwork. Formwork accounts for 50% or more of all construction costs in a reinforced concrete structure [15]; it requires skilled labourers to properly construct, place reinforcement, place concrete, and deconstruct; all time consuming, labour-intensive, and more physically risk-laden processes. It is no surprise that productivity in construction is low when one considers these factors. Digital fabrication promises increased productivity by essentially changing the way reinforced concrete construction can be performed.

Increased sustainability

Sustainability in construction is sometimes a nebulous concept, varying from country to country. For developed countries, it can be captured in the US Environmental Protection Agency's definition as "the practice of creating structures and using processes that are environmentally responsible and resource efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction". Taken from the standpoint of embedded CO_2 emissions, one can define the environmental impact with the following ratio:

$$Environmental\ Impact = \frac{\frac{embedded\ CO_2}{unit\ material} \times total\ material\ used}{service\ life}$$

Until now, the general argument for using digital fabrication to create more sustainable structures has focused on the ability to create more materially efficient structures, thus focusing on the second part of the numerator in the above equation. More materially efficient structures are generally more complex structures, and as Figure 1 shows, more costly to produce.

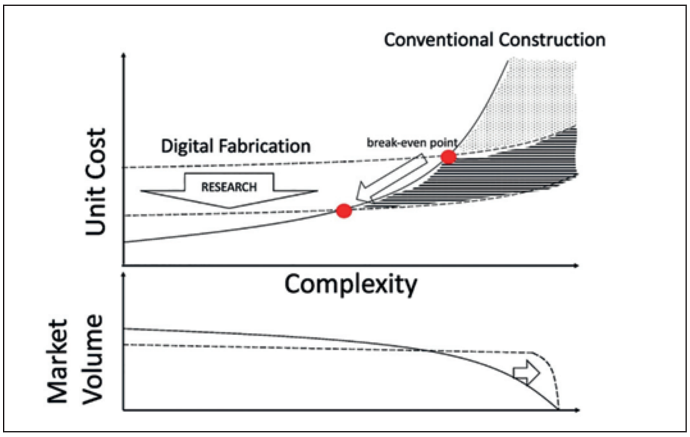

Figure 1: Cost v complexity curve for digital fabrication v conventional construction[16]

Structures are more efficiently produced by easy to construct, reusable formworks, and complex shapes usually requiring bespoke formwork production, both costly and wasteful. The use of digital fabrication technologies, on the other hand, creates what is known as "complexity for free", essentially making the cost of producing a simple part the same as a complex part. As seen in Figure 1, there is a point where conventional construction and digital fabrication become competitive. With continuing research and development, digital fabrication is expected to become more competitive at even simpler geometries. Additionally, one would expect that as the cost of more complex construction becomes cheaper, the demand for it will increase. This expected impact on design is currently difficult to predict, but remains the greatest chance for digital fabrication to make an impact in terms of sustainability.

Research and development drive the break-even point to the left, making less complex components competitive against conventional construction. Lowered cost for more complexity could also be expected to drive higher demand for more complex components.

Already, studies examining digital fabrication in the context of sustainability and productivity have been performed. A robotically fabricated structural wall was examined from both of these perspectives and found that increasing complexity drove the incentive towards digital fabrication technologies [17,18], which means that until now, this technology has not been competitive for standard construction.

Another output of that study also indicated that, from a material perspective, digital fabrication is not competitive in terms of material usage per unit volume. Digital fabrication concretes are highly paste-rich due to processing requirements, and often require high cementitious material contents within the paste to achieve the necessary activation. Whilst this can be improved, it can be assumed that the processing demands on the concrete will still require high paste contents, and thus making a digitally fabricated concrete that is equal to a normal concrete in terms of performance for sustainability is very difficult, if not impossible.

A final point on possibilities to increase sustainability; following the above argument on increasing cost with complexity, multifunctional components could also be created with digital fabrication . This has been deemed a "concrete colour printer" by the team at TU Eindhoven [19], with the idea being the ability to print different materials, thus paving the way for functionally graded materials and multifunctional (for example, both thermal and structural) components. The sustainability analysis of multifunctional materials was also carried out[20], and again a tradeoff was shown, this time between the benefits of multifunctionality against the drawbacks to recyclability at end of life.

Digital fabrication methods

In the following section, the methods of digital fabrication with concrete are briefly summarized. Some examples are shown in Figure 2.

Extrusion

Concrete extrusion, the most widely known and investigated method of digital fabrication, was pioneered by Berokh Khoshnevis as Contour Crafting [21], further developed at Loughborough University [22], and practiced by many since. Fresh material is delivered to a nozzle by a pump, and the nozzle is controlled digitally to place the material. Nozzle positioning can be performed by either a large gantry or delta printer system, requiring a printer larger than the component being printed, or with a robotic arm that can be stationary or mobile.

Shape freedom is greatly enhanced, but numerous challenges remain, particularly that of reinforcement of the structure, and ensuring dimensional stability and tolerance. Until now, the reinforcement question has been resolved either by post-tensioning, or by placing passive reinforcement in voids and infilling with more concrete – which makes the print into what amounts to a lost formwork.

Formwork printing

Following the above, a recent report [23] has stated that printing formwork is most likely the greatest potential for digital fabrication with concrete at the moment, with market potential now. Until now, in fact, most commercial applications of extrusion 3D printing of concrete have been essentially printing concrete masonry walls with voids for infilled structural columns [24]. It need not be necessary to print the formwork out of concrete, however – polymer fused deposition modeling (FDM) printing has been used in a process called "Eggshell" at ETH Zurich, in which the printing and infill occur simultaneously [25]. What also appears promising is the use of other materials to add functionality to the formwork being printed. For example, the research team at ETH Zurich recently, with the Mesh Mold technology (seen in Figure 2), printed a formwork out of steel reinforcement – a formwork that served not only to provide the shape, but also the reinforcement after the concrete was applied [26].

Shape forming supports

Another method to produce digitally designed structures involves the production of a shape in space with the use of flexible formwork. This can be done in either a prefabrication scenario, as demonstrated by researchers at TU Delft [27], or on-site, as was recently done by ETH Zurich researchers with the process known as Knitcrete [28]. In the former case, a flexible support is shaped and concrete is cast onto the mould, and in the latter case, a knitted textile is tensioned in space to form a shape which is later concreted by successive stiffening with layers. The KnitCandela, an on-site demonstrator, is depicted in Figure 2. The use of flexible formwork has many advantages in concrete construction, and a recent review describes these advantages and the challenges to be researched [29].

Figure 2: Four processes

Figure 2 above shows, the Mesh Mold process (top left) in which a steel reinforcement cage is produced on site by a robot that bends, cuts, and welds steel *(photo: Norman Hack)*. The Smart Dynamic Casting process (top right) a slipforming process where concrete is shaped by a vertically moving formwork *(photo: Ena Lloret)*. The KnitCandela (bottom left) by Zaha Hadid Architects and the Block Research Group at ETH Zurich, produced using Knitcrete, a process in which a form is tensioned in space and successive layers of concrete are added *(photo: designboom.com, by Juan Pablo Allegre)*, Digital Grotesque (bottom right) created by architects Benjamin Dillenburger and Michael Hansmeyer, printed using particle bed fusion in a sand bed with an organic binder *(photo: Benjamin Dillenburger)*.

Particle bed fusion

Particle bed fusion is a technique in which a layer of particles is evenly spread out, and then a printhead selectively deposits a binder to bind particles together where desired. The next layer of particles is then spread out and the process continues until a three dimensional object is completed within the print bed. Unbound particles are later removed and can be recycled after the completed object is taken out of the particle bed. This process has been used to cast metal parts, and the process was pioneered at the construction level by Enrico Dini. It has been recently reviewed in depth by Lowke et al.[30]. At the construction level, it has been used to print formwork [31], using sand and an organic binder. It has also been used to directly print objects with cementitious and geopolymer binders [32,33]. Advantages of the process include high resolution (theoretically as low as the maximum aggregate size of the bed) and a support structure for cantilevers provided by the unbound particles. However, the extended post-processing and low recyclability of inorganic binding systems are limiting this type of fabrication process to niche prefabrication components. An example of a sand print is seen in Figure 2.

Slipforming

Slipforming, a process that is already used to produce massive vertical structures such as silos, has been scaled down to a digitally controlled process known as Smart Dynamic Casting, seen in Figure 2 [34]. Scaling down to this level requires hydration control of the concrete to precisely control when the concrete builds strength as it comes out of the formwork. Challenges in this form of processing include balancing between having not enough strength (to avoid collapse) to having too much strength (which leads to high friction, and tear-off within the formwork) [35]. This process is somewhat limited in its geometries, restricted primarily to columnar elements, but the surface quality that is produced is far superior to that of other processes such as extrusion. It has recently been used to produce in-service structural components in a demonstration house in Dübendorf, Switzerland [36].

Current challenges in digital fabrication

Rheology

Until now, the focus in digital fabrication with concrete has focused on the concrete itself, particularly the rheological behaviour. Like all concrete construction, the concrete must be mixed, transported, and formed before it sets so that it can later bear a structural load. The common rheological steps that place the strictest requirements on digital fabrication processes with concrete are generally the following three:

1) the concrete must be transported to the point of placement by pumping, so it must have *pumpability,*
2) the concrete must be placed, either by extrusion (*extrudable*) or casting, with minimal vibration (*castable*), so it must have *placeability*,
3) the concrete must build strength to support itself as further layers are added, so it must have *buildability*. These steps are illustrated in Figure 3 for various processes. It is the final step, buildability, that is unique to digital fabrication compared to other concrete processes, as this step until now was taken by the formwork. This has created a great interest in the understanding of early age strength of cementitious systems, and how best to control it [37].

All processes require pumping to the point of placement, where generally an activator is added so that the concrete can build strength in absence of traditional formwork (depicted by gray scale). [38]

As seen in Figure 3, the buildability requirement can require the addition of an activator to best control when the concrete builds its strength. This is a requirement for fast production times, depending on how quickly the concrete builds strength through thixotropy (sometimes called "green strength") and the maximum height desired, which is limited to heights not much higher than half a metre through thixotropy alone [39]. Controlling this strength can be accomplished either by the addition of highly stiffening viscosity modifying admixtures [40], the addition of an admixture that initiates the primary hydration peak (silicate peak) [34,41], or the addition of an admixture that precipitates a secondary phase that can lead to "buildability strength", which is enough strength to be self-supporting during the production [42]. The use of chemical admixtures in digital fabrication has been recently reviewed [43].

While solutions exist for material control of concrete for digital fabrication, it is important to note that this places very strict requirements on the material, and may ultimately make it difficult for the concrete to meet the other demands. For example, the precipitation of a secondary phase for material control is typically achieved by the rapid precipitation of ettringite by calcium aluminate cement substitutions, calcium sulfoaluminate cement substitutions, or aluminum sulfate-based solutions. This can lead to sulfate depletion, with a negative effect on the ultimate strength of the system [44].

Another study showed that the process required such high quantities of calcium nitrate-based accelerator to work, that it was more susceptible to carbonation corrosion, as well as crystallization pressure from precipitated salts [36]. Thus, one should avoid sacrificing certain elements of performance (such as durability or dimensional stability) for the sake of the process. It is important at least to consider the trade-offs.

Shrinkage

One of the more recent material challenges to arise has to do with shrinkage. Until now, the formwork has served as a skin for traditionally cast concrete. However, the removal of traditional formwork now tends to expose nearly all surfaces of digitally fabricated concrete to the ambient environment, and control of the curing conditions gains a higher importance due to the potential for plastic shrinkage. Additionally, digitally fabricated concretes are naturally more susceptible to all forms of shrinkage, including drying shrinkage, due to the inherently high paste contents. High paste contents are due to the processing requirements, and these same requirements usually limit the maximum aggregate size. Finally, in the literature many digitally fabricated concretes are also high performance, with low w/c, and therefore are susceptible to autogenous shrinkage.

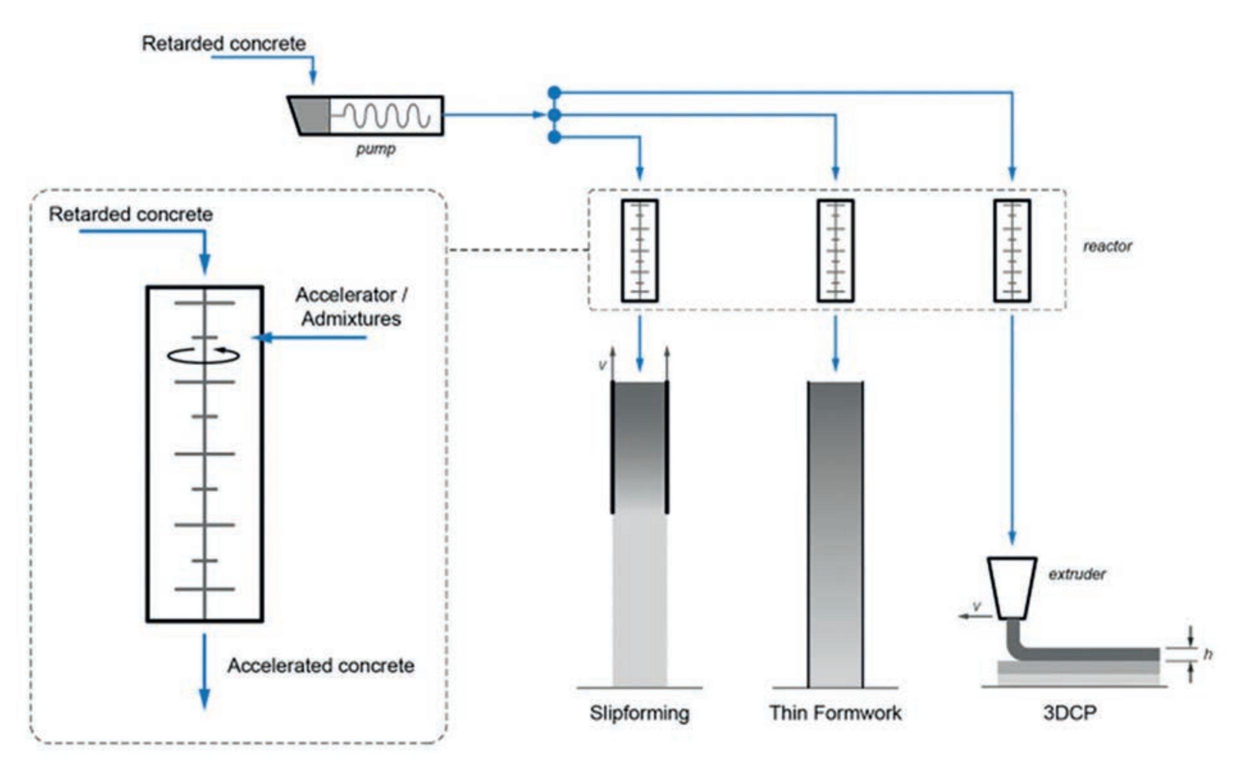

Figure 3: Schematic of three different concrete digital fabrication processes.

Until now, the problem has only been indirectly addressed in the literature, with the consideration that traditional approaches for shrinkage should be adopted in digitally fabricated concrete, and few studies with actual shrinkage measurement on 3D printed concrete mixes exist, although one very recent study has directly addressed this topic [45]. Proper curing procedures, such as spraying the surface with water, using an external curing membrane cover or foil, or shielding from wind and sun, generally can help to solve some of these issues, but being able to adapt these curing procedures to in-situ construction might be difficult, making prefabrication more attractive for these technologies.

Proper mix design is another way to reduce shrinkage of all types, but mix design constraints due to processing (i.e. small max aggregate size, high paste content for processing) limit options there. Many 3D printed concretes contain flexible fibres, which help mitigate shrinkage while also giving additional yield stress in the fresh state. Other methods that could address the issue from a mix design standpoint include the use of shrinkage reducing admixtures (SRAs) and materials that carry internal curing water, such as saturated lightweight aggregates or superabsorbent polymers. These also carry risks as the use of an admixture to solve one problem may produce issues for another part of the process. The general problem of admixture interactions is an issue not just for digitally fabricated concretes, but also for many speciality concretes.

It is of particular note that until now these 3D printed components are typically unrestrained after printing , therefore do not tend to build high stresses during curing. The introduction of restraints (such as reinforcement) creates stresses that easily lead to cracking, as was shown in the façade mullions made for the DFAB House (Figure 4), which were created by digitally controlled slipforming, and showed consistent shrinkage cracks along its length [46]. These cracks appeared during curing and are related to drying shrinkage, and were the first such cracks observed in digitally slipformed components, as they were the first to have reinforcement directly incorporated.

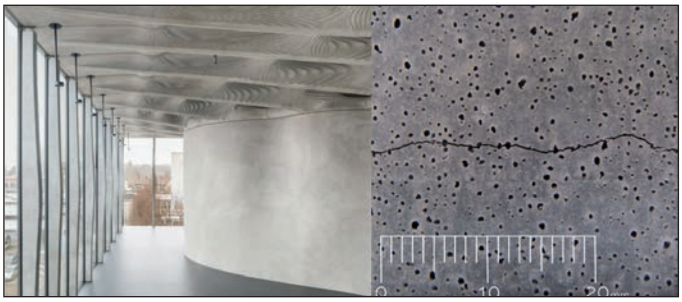

Figure 4: Finished concrete components of the DFAB House in Dübendorf, Switzerland. Left: Façade mullions fabricated by Smart Dynamic Casting seen on the left side (photo: *dfabhouse.com***). Right: Shrinkage crack observed within days of fabrication of one of the façade mullions (photo:** *Thibault Demoulin***)**

Reinforcement

The reinforcement is currently probably the greatest challenge in digital fabrication with concrete. The digitally controlled placement of concrete has been very well studied and has developed rapidly in recent years, but reinforcement has been largely treated as a secondary problem, in spite of the criticality of its existence in a reinforced concrete structure. Reinforcement strategies for digitally fabricated concrete have been recently reviewed [47], and as would be expected, the method of reinforcing is usually directly impacted by the digital fabrication process.

The 'traditional' method of placing steel reinforcement and then infilling a structural concrete has usually been the method used until now for concrete 3D printing, where the printed concrete serves as a lost formwork that may or may not be functional. This method, of course, is still typically done manually, although robotic placement of reinforcement had been considered as far back as the 80s by the Japanese [48]. The automatic placement of vertical reinforcement in 3D concrete printing is obviously hindered by the movement of the printhead, but transverse reinforcement solutions have been developed, most notably the inlay of a cable in the extrusion filament, first developed at TU Eindhoven and used to provide transverse reinforcement for a 3D printed bicycle bridge. Post tensioning cables were used in the bicycle bridge for the primary longitudinal reinforcement, and this method has also been used recently in a topologically optimized girder fabricated at Ghent University [49]. Fibre reinforcement seems an obvious choice and has also been developed, but cross-layer reinforcement remains an issue due to flow-induced fibre alignment. A printable ultra-high performance fibre-reinforced concrete (UHPFRC) has been developed [50], and the potential for engineered cementitious composites (ECCs) and strain hardening cementitious composites (SHCCs) has been recently reviewed [51]. Another method for 3D printed segments is a strut-and-tie external reinforcement developed at the University of Federico II in Naples [52] but, of course, this method exposes the steel to potential corrosion issues.

Other fabrication methods have been able to reinforce directly as part of the primary fabrication process. For example, slipforming allows for the use of traditional steel reinforcement, as it is a vertically moving process and the formwork can simply slip around the reinforcement [36]. The use of thin formworks also allows the use of traditional steel reinforcement, similar to 3D printed concrete lost formworks [53]. The Mesh Mould process, discussed earlier, attacked the reinforcement problem directly essentially by printing the steel reinforcement as formwork. The use of textiles, for processes such as those that produced the KnitCandela, is very interesting as textiles generally allow lighter structures by eliminating the need for a concrete cover. A final possibility comes from the minimization or elimination of reinforcement altogether through compression only structures, although this avenue has not really been explored due to fabrication limitations.

From the standpoint of productivity, the digitally controlled production and placement of reinforcement, and its incorporation in a full manufacturing process, is a challenge that the field should focus on, and will require collaboration with robotics experts.

Durability

Until now, durability remains largely ignored in digital fabrication with concrete, as researchers seek to first develop processes that work. It is, however, an essential performance component that must be investigated. Earlier in this paper, environmental impact was defined as inversely proportional to service life, and while it is possible to lower environmental impact by either lowering the embedded CO_2 per unit of material or lowering the total amount of material in a component, this should not come at the expense of a component's service life.

The durability of concrete components is generally tied to the protection of the reinforcing steel against corrosion, although direct attack on the cement paste or aggregate can also be important. Considering the variety of reinforcement possibilities in digital fabrication with concrete, the durability criteria may vary widely. However, if one considers the currently most feasible strategy of using digitally fabricated concrete as a lost formwork for traditional reinforcement, then one must consider the greatest durability threat to be ingress of chlorides or carbon dioxide leading to steel corrosion, and thus the transport properties of the digitally fabricated concrete are very important. This consideration has led to the first studies of durability of these concretes, where transport of water has already been examined [54] and even the first studies showing rapid transport of chlorides through printed interfaces have also been performed. The layer interfaces sometimes show increased porosity, especially when a so-called "cold joint" is formed due to excessive waiting time between layers [55]. The interfaces between successive layers of digitally fabricated concrete may prove to be more of a threat to structural health due to durability concerns rather than their weakening effect. The effect that these interfaces and their additional porosity may have on the freeze/thaw durability is also an open question, although recent results show poor freeze/thaw resistance of a 3D printed concrete [56] and there are currently researchers examining how to incorporate air entrainment to improve this [57]. The effect of material design, waiting time between layers, and processing conditions still must be fully characterized in a systematic way.

A final durability concern with digitally fabricated concrete has to do with the highly processed nature of the concrete. Following the general theme of processing limitations leading to restrictions in material design and, potentially, to performance, certain steps required for a functioning process might lead to deleterious effects. As an example, the previously discussed façade mullions of the DFAB House required very high quantities of a calcium nitrate based accelerator for successful processing [36]. This high amount of calcium nitrate leads to a higher risk of carbonation corrosion [58], and also the potential for salt precipitation in the pores to cause cracking. It remains to be seen how other aspects of digital concrete processing may lead to potentially negative effects related to durability, and how these can be overcome.

Sustainability vs. Productivity?

Earlier in this article, the arguments of improving sustainability and productivity with respect to these technologies were raised. There is generally an argument that sustainability is improved through customization and shape freedom – less material is used overall in a structural design. It can also be argued that the removal of traditional formwork contributes to a lower overall environmental impact due to material reduction. The potential productivity gains are also quite clear, as the time and labour required to erect formwork is now removed. However, sustainability in terms of embedded CO_2 is inherently worse with digitally fabricated concrete due to the higher clinker contents per unit of material.

Until now, the two main uses for digitally fabricated concrete have been: 1) on-site prints of buildings, and 2) prefabrication of building or infrastructure components. On-site building prints have generally been performed by printing the walls and structural members as simulated concrete masonry, as seen in Figure 5. While this is likely to be a very big benefit in terms of productivity, it remains to be seen if this is a benefit or even equivalent in terms of sustainability. Thus, an analysis of this type of problem should be carried out to ensure that productivity gains do not come at the expense of sustainability. This is a complex problem, as sustainability may have different meanings for different regions of the globe, and can also mean much more than simply the embedded CO_2 in the materials and the overall service life for a 3D printed concrete building. Life cycle analyses will be instrumental in evaluating overall performance of these new constructions to ensure that they are producing a net societal benefit.

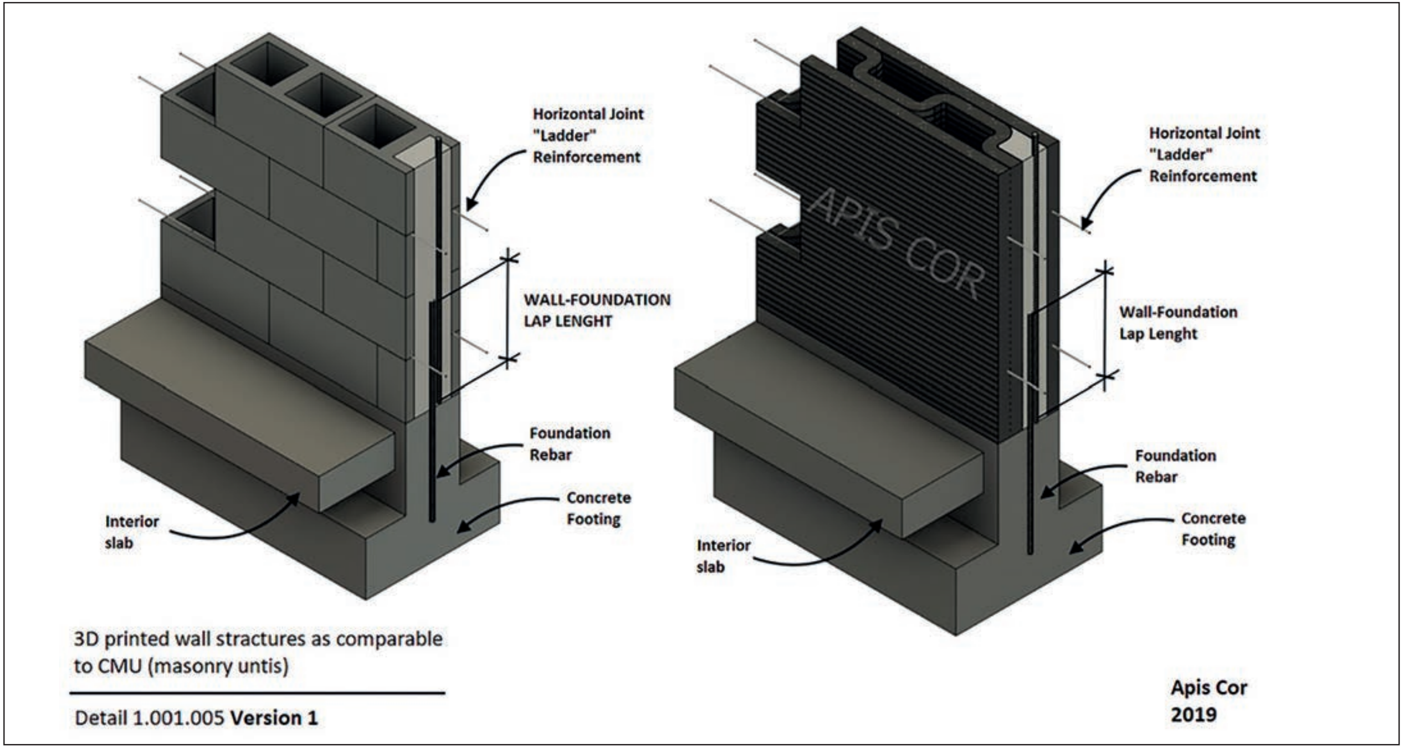

Figure 5: Apis Cor 3D printed concrete wall structure equivalent to a concrete masonry unit. (taken from the Apis Cor web site [24])

Conclusions

"Construction 4.0" is AEC's portion of Industry 4.0, which encompasses the current revolution in digitalization and automation. Additive manufacturing technologies, including 3D printing with concrete, are seen as a crucial piece of this transformation. Construction-scale demonstrations of these technologies have become so commonplace now that the proof-of-concept stage in the development of these technologies is largely over. This article has been a short overview of the current landscape of these technologies, and the following points should be considered in the progress towards industry acceptance:

- In terms of technology development, reinforcement is now the crucial point that must be addressed. While automatic placement of the cementitious material has been developed and proven again and again at varying speeds and material formulations, the automatic incorporation of both transverse and longitudinal reinforcement is being performed manually (at least partially), which does not bring any productivity benefit, and is a major hurdle to be addressed or avoided by the use of less traditional reinforcement methods;
- Durability has been largely ignored until now, but ensuring that digitally fabricated concrete matches or exceeds standard concrete construction in terms of service life is essential;
- More prefabrication of concrete will require more robust concrete processing systems, thus rheology remains an important aspect;
- There is potentially a conflict between sustainability and productivity as these technologies develop, and it is imperative to manage this in the coming years. Life cycle analyses will be critical to this management;
- Exploration of multifunctionality that digital fabrication can bring is a new and potentially impactful research area;
- The examples of use of these new technologies vary widely, especially considering on-site vs. prefabrication scenarios, and how these impact the construction landscape is an interesting and open development;
- Digitalization is much more than just admixture manufacturing, but the visibility and impact that admixture manufacturing technologies bring might be enough to start the proliferation of the many other digitalization innovations that have already increased the productivity in the manufacturing sector.

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