OPPORTUNITIES AND CHALLENGES FOR STRUCTURAL ENGINEERING OF DIGITALLY FABRICATED CONCRETE

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Abstract

Digital Fabrication technologies utilizing Concrete (DFC) have recently enabled form freedom for the production of a variety of concrete-made objects having mainly architectural and aesthetic functions. Structural elements or civil/building structures made by DFC are demonstrating a high engineering potential, mainly for the opportunity of tailoring the final shape while optimizing the structural/functional performance, material use, overall costs and architectural effectiveness. However, DFC projects aimed to deploy structurally efficient DFC constructions or components have to often tackle the lack of a clear common approach to the structural engineering as well as the adaptation of current design knowledge to the specific DFC production particularities.

This paper provides a systematic overview of a number of DFC structural projects that have been developed so far. A comprehensive discussion about structural engineering details is provided, addressing the related fundamental structural issues and envisioning opportunities and challenges towards achieving the full potential offered by DFC.

Keywords

Digital Fabrication with Concrete; Structural Engineering; Construction Projects; Design with DFC.

1. INTRODUCTION

In recent years, advances in computational design tools and industrial automation have allowed architects and engineers to carry out construction projects characterized by an increasing overall complexity and a high level of digitalization [1–5]. The growing number of irregular-shape buildings or structures in the construction sector represents the evidence of such a relevant technological progress in which conventional construction materials, design and manufacturing methods are marginally applied owing to practical constraints, disjointed production systems, cost limitations and low degree of customization in advance. In this context, digital fabrication is becoming a valuable approach to overcome these fundamental problems, since it is able to transform digital design into physical products [6]. Generally, digital fabrication approaches are based on computational design methods combined with various technologies adopting one or more materials (polymers, steel, wood, clay etc.) and manufacturing processes (e.g., robotic assembly, extrusion, lamination, additive manufacturing etc.).

Different advantages are potentially offered in the specific construction project wherein digital fabrication is applied [7–9]. Besides a higher degree of customization, the positive performance of a digitally fabricated system can be evaluated by monitoring four main factors: time, cost, quality, and flexibility [10]. These aspects have been addressed in a number of studies up to now, whereas additional elements, commonly associated to the fulfillment of sustainability goals such as resource and energy efficiency, should be considered as a key decision-making factor in this field [6,11]. Indeed, potential environmental benefits expected by the implementation of digital fabrication firstly consist in the reduction of CO_2 emissions associated to construction and facilities management as well as to the modularization and prefabrication of components [2][12]. A further positive contribution in this direction is provided by the achievement of material and shape efficiency resulting from the use of appropriate structural design tools (including, e.g. graphic statics [13] and topology optimization [14,15]), leading to optimized structures which are, in practice, feasible without prohibitive costs for custom formwork. The potential for added sustainability-oriented functionality also represents a worthy rationale for the introduction of digital fabrication into the construction sector. This aspect has been addressed by different authors, in which, for instance, a complex internal wall geometry was shown to have a significantly increased thermal performance compared to a standard concrete wall [16,17].

Even though the construction industry is characterized by a slow innovation uptake, estimates for investments in infrastructures [18] have stimulated this sector and current trends demonstrate that digital technologies are actually transforming the way through which numerous engineering and construction firms operate [19]. This has yielded an increasing proliferation of digital fabrication projects around the globe. Due to the importance of the construction industry, these revolutionary changes are also being assessed in terms of potential impacts on future stability, national employment, and economic solidity [20]. A recent review by Austern et al. [21] classified the appearance of digitally fabricated projects in available literature by considering approximately fifteen different fabrication processes adopting more than ten different materials. Robotic fabrication (i.e. milling, hot wire cutting, layer deposition devices mounted on industrial robotic arms) steadily raised over the last decade up to 2016, in which it surpassed all other fabrication processes in terms of available projects. Among them, 3-axis milling, and additive manufacturing were found to be the most popular fabrication processes, especially in papers describing academic projects rather than from the building industry. All these fabrication techniques inevitably introduce feasibility and affordability issues in the process of making a complex design, which commonly force engineers and architects to adjust the design itself according to the constraints of a given technique. These constraints can be grouped into four main categories:

- fabrication constraints (e.g. limitation associated to available machine capabilities, size compared to that in the manufacturing industry etc.);
- material constraints (e.g. process-dependent physical and mechanical properties, durability etc.);
- construction constraints (e.g. easy of assembly, transportation etc.); and
- design constraints (e.g. code compliance, geometry etc.).

Currently, wood, steel, polymer and concrete are the materials mostly adopted in digital fabrication applied to construction projects [21]. Among these, polymers have the lowest prevalence and their use to produce building components is limited due to high manufacturing cost and low stiffness and strength [22]. On the contrary, robotic systems represent a mature technology for the fabrication of non-standard timber structures, being able to obtain automatic joinery [23] as well as large-scale assembly by adopting proper construction/fabrication criteria and new computational approaches [24]. A real case is represented by the "The Sequential Roof" project developed at ETH Zurich [25] and manufactured by implementing a custom six-axis overhead gantry robot (see Figure 1a); to guarantee compliance with building regulations, real scale specimens were subjected to mechanical load testing. On the other side, steel based structures are commonly digitally fabricated from powder bed fusion and directed energy deposition processes [22]. Large-scale applications have been implemented, for instance, in MX3D project [26], aimed to 3D print an 8 meter stainless steel bridge (a footbridge across the Oudezijds Achterburgwal canal) with a gas metal arc welding-based 6-axis industrial robot (see Figure 1b); the basic elements are stainless steel rods of 5 to 7 mm in diameter. Also in this case, experimental tests were needed to characterize the structural behavior for ensuring the compliance with building regulations [27].

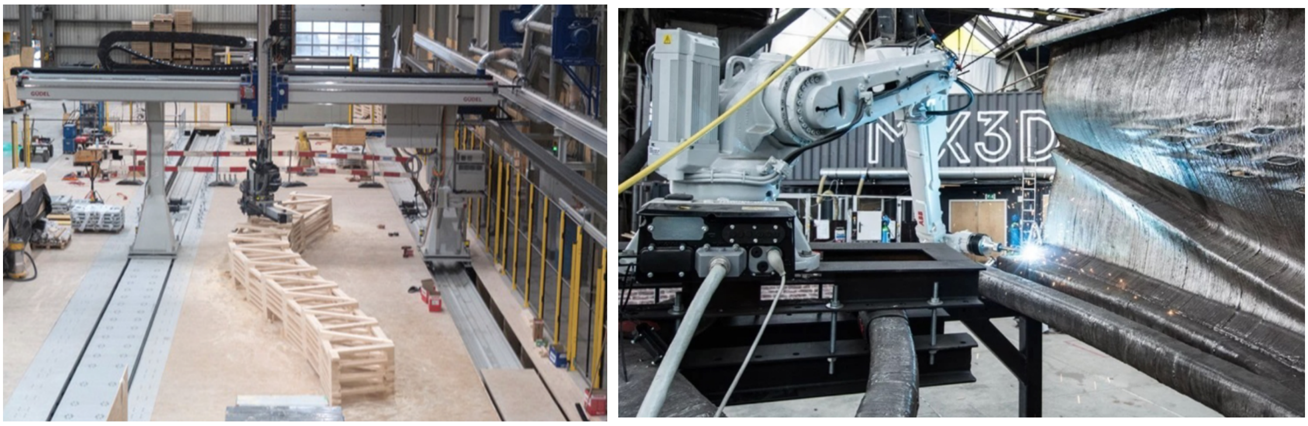


Figure 1: (a) "The Sequential Roof" project developed at ETH Zurich [25] and (b) MX3D project [26].

The interest in using concrete and cement-based materials in digital fabrication techniques has significantly increased in the last 5-10 years. In a recent study by Tay et al. [12] reporting the analysis of variants of concrete printing processes published worldwide over last twenty years, it was found that topic-related research works almost doubled in the years 2013-2016 compared to the previous sixteen years. Related activities have mainly focused so far on the development/control of automated printing machineries and on the requirements of printable cementitious materials [28] to obtain desired mechanical and quality performances (i.e. commonly addressed as pumpability, extrudability, buildability, finishing and others [29]). In general, the resulting automated manufacturing techniques are collectively identified as Digital Fabrication with Concrete (DFC), allowing the construction of both structural and non-structural products (to greater or lesser extent) without the use of traditional formwork. The implementation of the different DFC methods is currently capable of producing architectural items, load bearing and non-load bearing building/infrastructure components and also full-scale houses/structures; an explicit mapping of resulting digitally fabricated systems characteristics is provided in [30] whereas the variety of available methods can be generally grouped based on [12,31,32]:

- <u>*Process*</u>: *(i)* **extrusion process** in which concrete is automatically placed layer-by-layer through a moving nozzle which follows a predefined digital path reproduced by Cartesian gantry, robotic, crane or cable robot systems [29,33–35]; *(ii)* **formwork printing** through which concrete or other materials than concrete may be used to fill a digitally fabricated formwork [36]; *(iii)* **temporary supports** consisting in the design of a supporting structure, in terms of shape and load bearing capacity, which is then subsequently concreted [37]; *(iv)* **slipforming** consisting in a vertically moving formwork in which concrete is placed in the fluid state and let hardened in a controlled way to fabricate variable cross-sectional area structures (e.g. the Smart Dynamic Casting system developed by Lloret et al. [38,39]); *(v)* **particle bed fusion** which is based on the selective and automated deposition of a binder onto a layer of particles (e.g. see [40]); **hybrid techniques** which aim to introduce hybrid construction concepts using available fabrication processes or reinforcement (e.g. sparse concrete reinforcement in meshworks which combines robot-based 3D concrete printing and textile reinforcement meshes [41] or shotcrete 3D printing which is based on an automated shotcreteing process with the ability to integrate structural reinforcement [42]).
- <u>*Fabrication site*</u>: *(i)* **on-site construction** which is devoted to the production of full houses/structures in an open environment by means of machineries larger than the structure being fabricated (e.g. gantry printer in DCP [43]); *(ii)* **prefabrication** consisting in a more robust fabrication process enclosed in a controlled environment which produces components/subassemblies at the structural scales (but not entire structures) with a higher quality level [44,45].

The recent successful implementation of such DFC methods demonstrates their potential in achieving architectural and engineering projects characterized by a high degree of freedom, mainly consisting in concrete structures of complex geometry [46], such as thin and stable shells, arches, lightweight forms with complex topologies, advanced modular structures, custom concrete stairs [47], and even promising solutions for construction of human settlements on other planets such as the Moon and Mars [48].

This revolutionary shift in the approach to construction with concrete has introduced new possibilities and constrains for the design, dimensioning, detailing, and production of structures. The exploration of new possibilities offered by DFC, besides the extensively explored potential of geometric flexibility, is fundamental to exploit the full potential offered by DFC also in geometrically simple structures [49]. On the other hand, it is also necessary to focus on a systematic approach to address the new technological constraints that have turned into interlinked engineering challenges acting on multiple levels of implementation. At the material level, depending on the specific DFC method adopted, new requirements have been introduced for the fresh concrete state due to deep changes compared to standard formative processes. The rheological and mechanical properties of the growing object interplay with the structural buildup during the DFC process (especially in the setting regime), determining the need for reliable solutions regarding mix design and admixture selection, as well as issues such as layer interfaces, pumpability, buildability, printability, extrudability, fluid infiltration capability into the particle-bed [40,50–52]. New mix-design solutions along with the particularities of the various DFC processes have introduced new performances in the hardened state of printed concrete objects, making them remarkably different compared to those obtained from the well-established casting process. In particular, the additive nature of many DFC techniques yields layered object structures with a significant anisotropy with regard to strength (occurring both in vertical and horizontal direction) rather than stiffness. The resulting interfaces between adjacent layers are generally characterized by reduced bond strengths (both in shear and normal direction) and are commonly referred to as cold joints [42,53]. A range of factors related to the combination of the specific DFC process and material composition (e.g. print head speed, print nozzle height, resting time, moisture content among the others) has been shown to have quantitative effects on interface properties, leading in some cases up to 50% or higher reduction as compared to bulk specimens [54]. Similar considerations can be drawn also for other DFC processes, such as particle bed fusion, in which the compressive strength of printed cylinders has been shown to depend on the penetration ratio of the binder [40]. Moving to full scale construction projects with DFC, it's clear that all those mechanical aspects may represent an evident obstacle for DFC to reach maturity. In addition, unless compressed structures are considered, a key point is that the implementation of digitally fabricated concrete structures is made possible only in combination with reinforcement resisting tensile forces, which overcomes the lack of sufficient tensile capacity and ductility of cementitious materials. Reinforcement concepts and principles are currently adapting to the different DFC processes with the final aim of fully exploiting the benefits of digital design and fabrication. This progressive change will affect reinforcement technology (e.g. the various implementation techniques of fibers, rebar, rods, filaments etc. in DFC processes), dimensioning and detailing in contrast to conventional concrete constructions. A range of reinforcement approaches has been recently discussed by Asprone et al. [55], organizing all available solutions by structural principle, or place in the manufacturing process.

The growing number and ambition of the DFC construction projects to be delivered in the near future, the aforementioned situation points out the urgent need for new, unified and effective design-to-fabrication approaches [56][31], including testing methods and regulations. Indeed, at the current stage of development, DFC is not able to sufficiently guarantee product quality and design code compliance in many practical cases. Understanding the structural engineering peculiarities of digitally fabricated load-bearing concrete structures is rapidly becoming a priority challenge for their safe use. However, when evaluating the potential of structural engineering in DFC, a highly interlinked scenario must be taken into account, as depicted in Figure 2. For a given project, determining the relations between material performance, DFC process adopted, predefined function, reinforcement typology and design aspects represents the major challenge up to now. This paper aims to provide a useful contribution in this direction, reporting the structural engineering details of several DFC structural projects that have been developed so far in order to facilitate the development of a common understanding of such an interdisciplinary scenario.

The following sections will firstly review the available documented DFC construction projects; then a discussion about structural engineering principle/typology details is provided addressing the fundamental structural issues and envisioning opportunities and challenges towards achieving the full potential offered by DFC technologies. Finally, the current stage of development of DFC is discussed in reference to existing building regulations and full-scale validation testing.

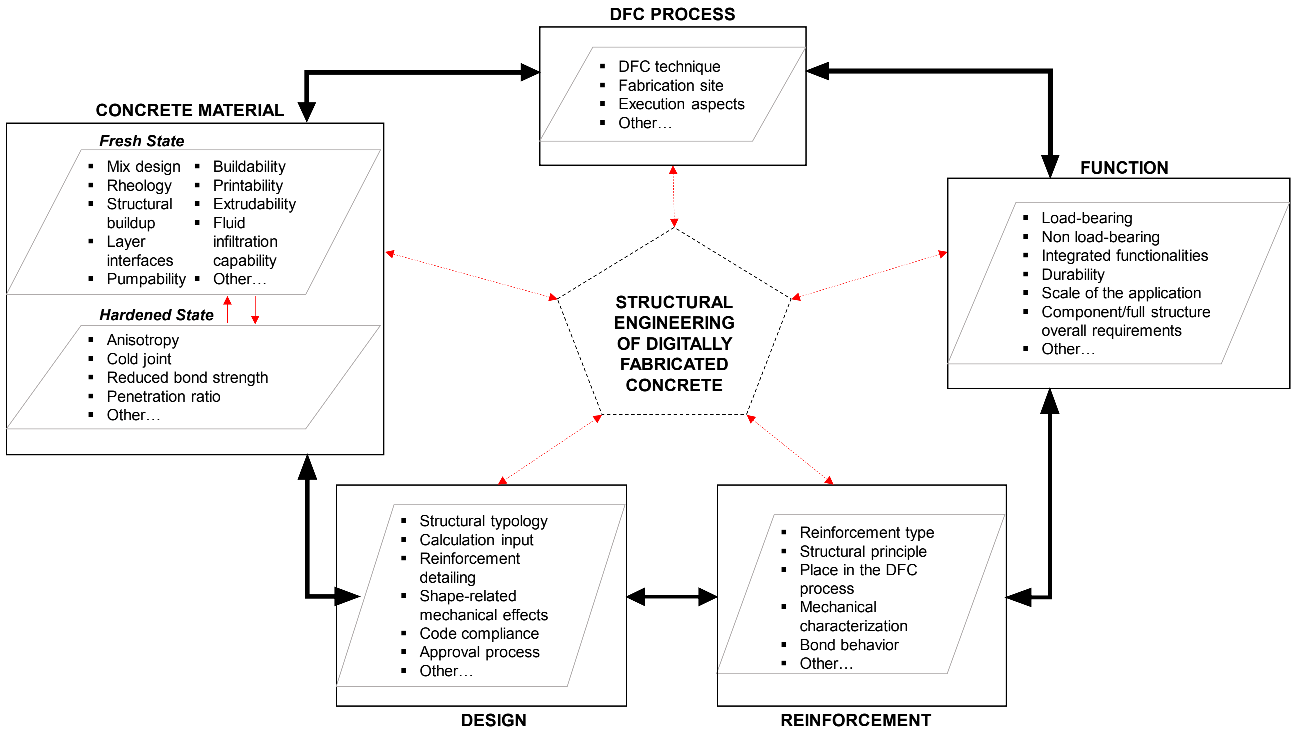


Figure 2: Interlinked aspects for the structural engineering of DFC structures.

2. AVAILABLE (DOCUMENTED) STRUCTURAL APPLICATIONS OF DFC

After an initial phase of realization of showcase projects (e.g. [57–59]), DFC is now being introduced into general use structures such as short-span bridges, single layer buildings, and stand-alone structures, see Table 1 and references therein. While the catalogue of examples held only a handful of projects two to three years ago, it is now expanding rapidly and will continue to do so judging from the number of announced projects [60–62]. Unfortunately, publicly available documentation on the structural engineering has been extremely scarce until now.

Asprone et al., 2020 [63], note that the application of DFC in the production and construction of structures, affects each of the pillars of its quality control methodology: materials, processes, and structural design. In the domain of structural design, they furthermore identify a number of challenges, related to unknown material properties, calculation input, and design issues such as reinforcement, joints, and inner pattern design. Besides challenges, DFC also brings about new design, dimensioning and detailing possibilities, which have great potential to improve the sustainability of concrete structures, as will be discussed in *Section 3*. In the following subsections, the structural design and engineering of a number of DFC projects is presented and discussed. Subsequently, the experiences from engineers in consulting practice will be discussed briefly.

Table 1: Realized structural DFC projects.

Project name or description	Location, year	DFC fabricator, country	DFC technology	DFC product	Ref.
3D concrete printed castle	USA, 2014	TotalKustom	Extrusion	Building/house	[64]
Leward Grand Hotel, Hotel Suite	Angeles City Pampanga, Philippines, 2015	Total Kustom, USA	Extrusion	Building/house	[65]

Office Building	Dubai, May 2016	Winsun, China	Extrusion	Building/office	[66,67]
Krypton post	Aix-en-Provence, France, 2016	XtreeE, France	Extrusion	Structural element	[68]
USH sinusoidal wall	Paris, France, 2016	XtreeE, France	Extrusion	Building component	[69]
R&Drone Laboratory	Dubai, 2017	CyBe, Netherlands	Extrusion	Building/house	[70]
Pedestrian bridge	Madrid, Spain, 2017	Acciona Spain with D-Shape, Italy	Particle bed fusion	Bridge structure	[71]
Bicycle bridge	Gemert, Netherlands, 2017	TU/e, Netherlands	Extrusion	Bridge structure	[72,73]
Apis Cor printed house, Russia	Moscow, Russia, 2017	Apis Cor, Boston, USA	Extrusion	Building/house	[66]
Maison Concept YRYS	Alençon, France, 2017	XtreeE, France	Extrusion	Building/house	[74]
Stormwater Collector	Lille, France, 2017	XtreeE, France	Extrusion	Infrastructure component	[75]
3D Housing 05	Milan, Italy, 2018	Italcementi with CyBe	Extrusion	Building/house	[76]
The BOD	Denmark, 2018	COBOD, Denmark	Extrusion	Building/house	[77]
KnitCandela	Mexico City, Mexico, 2018	NCCR Digital Fabrication, Switzerland	Hybrid techniques	Structural element	[78]
3D-Printed Concrete Pedestrian Bridge	Shanghai, China, 2019	Tsinghua University (School of Architecture)	Extrusion	Bridge structure	[79]
DFAB House	Dübendorf, Switzerland, 2019	NCCR Digital Fabrication, Switzerland	Slipforming, formwork printing, temporary supports, particle bed fusion	Building components	[55,80]
Future Tree	Esslingen, Switzerland, 2019	NCCR Digital Fabrication, Switzerland	Hybrid Technique	Structural element	[81]
‘*De vergaderfabriek*’, meeting room	Teuge, Netherlands, 2019	Cybe, Netherlands	Extrusion	Building/office	[82]
Cohesion Pavilion	Innsbruck, Austria, 2019	Incremental3D, Austria	Extrusion	Architectural structure	[83]
Building Apis Cor, Dubai	Dubai, UAE, 2019	Apis Cor, Boston, USA	Extrusion	Building/office	[84]
3D printed community	Tabasco, Mexico, 2019	ICON, USA	Extrusion	Building/house	[85]
3D-printed post-tensioned concrete girder designed by topology optimization	Ghent, Belgium, 2019	Ghent University (Concre3DLab), Belgium With Vertico, Nederlands	Formwork printing	Bridge structure	[36]

2.1 Built examples

2.1.1. DFAB HOUSE

DFAB HOUSE is a collaborative demonstrator of the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication on the NEST building of Empa at Dübendorf, Switzerland. The project consisted in designing, planning and building a three-story house using predominantly digital processes developed within the NCCR Digital Fabrication [86]. DFAB HOUSE, designed for a lifetime of five years, opened in 2019 and it is used as a residence for long-term research guests. The NCCR Digital Fabrication conducted the architectural design and project management, while Dr. Schwartz Consulting performed the structural design with inputs from the researchers of the NCCR Digital Fabrication. Six innovative technologies were used in the fabrication, including Spatial Timber Assemblies [87] and lightweight translucent façades [88], besides the technologies used for the production of concrete structures (see Figure 3) that are presented in the following. The design loads and the structural design followed SIA 260:2013 [89], SIA 261:2014 [90] and SIA 262:2013 [91] codes. No tests of prototypes were conducted for the DFAB HOUSE since the structural engineer merely requested material and small-scale structural tests proving that the behavior was according to conventional structural concrete principles; note that the Swiss structural design codes allow exceptions, provided they are well founded theoretically or experimentally (SIA

260:2013 [89]). All structural elements were monitored and inspected periodically, showing no particular issues after one year of use. The only remarkable observation were shrinkage cracks in the Smart Dynamic Casting mullions. These cracks were reported already before their installation [39], but they do not compromise the structural performance due to the presence of reinforcement, as will be shown in the following.

Figure 3. Concrete innovations in the first floor of the DFAB HOUSE: left, mullions produced with the Smart Dynamic Casting technology; right, Mesh Mould double curved wall; up, Smart Slab (photo: Roman Keller).

Bespoke concrete mullions (Smart Dynamic Casting)

Smart Dynamic Casting (SDC) [39,92] is an extension of slipforming for producing bespoke concrete structures, which was used in the DFAB HOUSE to fabricate 15 slender reinforced concrete façade mullions (Figure 3, left). The architectural design concept required a variable spacing between the mullions (700 to 1400 mm), leading to different structural requirements for each mullion. Thanks to the bespoke fabrication capabilities of SDC, the cross section of each mullion could be reduced to its strict actual needs.

The connections of the mullions to the top and bottom slabs were designed to avoid the transmission of vertical loads. Therefore, the mullions behave as simply supported elements resisting only the wind loads acting on the glass façade. In SDC, concrete manufacturing is continuous and longitudinal reinforcement can easily be added before the production (Figure 4.a). Hence, conventional structural design provisions were used to verify the integrity of the mullions and to limit their deflections to 1/400 (due to the requirements of the glass façade). 2xØ12 longitudinal reinforcing steel bars were added to resist the bending actions. While shear capacity based on experiments was sufficient without transverse reinforcement[39], Ø6 transversal welded steel bars were finally introduced to ensure building code compliance (see final reinforcement in Figure 4.a). Because of fabrication constraints, the minimum cross section was set in all cases to 100x70 mm. The widest cross-section of the 15 mullions was varied from a minimum of 70x120 mm up to 70x180 mm to fulfill strictly in each mullion the deflection requirement.

Figure 4. Details of production of concrete structures for the DFAB HOUSE: (a) reinforcement of the mullions installed prior concrete production [92]; (b) onsite robotic fabrication of double curved reinforcing mesh [93]; (c) 3D-printed formwork for a 7.1 m segment of the Smart Slab [94]; (d) installation of the prefabricated Smart Slab [94].

Mesh Mould double curved wall

Mesh Mould [93,95] unifies concrete formwork and structural reinforcement to avoid using conventional formworks. This system was used in the first floor of the DFAB HOUSE to produce a 12 m long and 120 mm thick double curved wall (Figure 3, right) that supports the loads of the structural elements above (i.e. Smart Slab and Spatial Timber Assemblies). The initial design concept consisted of a curved S-shaped wall but, based on preliminary analysis assuming linear elastic behavior [93], local folding was introduced below the ribs of the upper Smart Slab to improve the behavior of the wall.

The design value of the vertical loads acting on the Mesh Mould wall was 860 kN, a moderate value for a structural concrete wall. Hence, the system was designed in order to produce a reinforcement mesh compliant with provisions of minimum reinforcement content (Ø6 vertical continuous bars and Ø4.5 horizontal welded segments, in both cases at an average spacing of 40 mm). The behavior of the welded segments was studied in both material tests and structural bending tests in elements of 400 mm span [93]. The bending tests exhibited a ductile behavior prior the failure of the welding. The observed ductility was caused by shear deformations induced in the perpendicular continuous reinforcement. While this deviates significantly from conventional structural concrete, the experimentally proven high deformation capacity allowed conducting a plasticity-based design. The double-sided welded steel reinforcement mesh was produced on site by the "in-situ fabricator" robot [96] (Figure 4.b) in about nineteen working days. In the Mesh Mould technology, the dense robotically fabricated mesh is filled with a special concrete mix that achieves sufficient compaction without flowing out the mesh, eliminating the necessity of using formwork. Despite specific concrete mixes were developed for this purpose, the DFAB HOUSE wall was finally filled using a ready-mix concrete (Sika Monotop 412N) due to logistic reasons of the contractor [93]. The concrete cover was sprayed using a ready-mix mortar (Sika Monotop 352N) ready mortar mix. The potential formation of weak joints between the core and the cover of the wall was studied for different concrete mixes and casting procedures by means of partially loaded area tests, which generated tensile forces between the layers.

Smart Slab

The idea behind Smart Slab is achieving free-form shapes and high-resolution geometric features in concrete structures by using 3D-printed formworks that can be filled and/or sprayed using conventional concrete. In the DFAB HOUSE, the 78 m^2 Smart Slab is supported by the Mesh Mould wall (see Figure 3 and Figure 4.d) and acts as a double cantilever, carrying the two-story Spatial Timber Units above it. The design concept for Smart Slab was to develop a highly optimized structural component embedding all the details for the façade and technical installations such as sprinklers and lighting, while at the same time proposing radically new aesthetics (e.g. microstructures and deep undercuts) that were computationally designed to visualize the force flow [94]. The Smart Slab was conceived as a post-tensioned structure, with ribs parallel and perpendicular to the supporting Mesh Mould wall. The slab consists of eleven prefabricated concrete segments, which were mounted on site using scaffolding until the post-tensioning was activated (Figure 4.d). The ribs transversal to the Mesh Mould wall carry the main loads, with a maximum cantilever of 4.5 m that required depths between 300 and 600 mm. The secondary ribs (parallel to the support) have a constant depth of 300 mm and carry posttensioning strands used to compress the joints between the prefabricated segments, guaranteeing the composite action of the whole Smart Slab. By using binder jetting sand printed formworks (Figure 4.c), the thickness of the concrete soffits between the ribs was reduced to only 20 mm in thickness. This allowed reducing the total weight of the slab to around 15 tons (average concrete thickness of 80 mm), corresponding to roughly 35% of a conventional post-tensioned flat slab [94] working over the same spans for the same service loads. However, this comes together with a high formwork waste unless the 3D-printed formwork can be reused. The Smart Slab is an example of what can be considered a conventional concrete structure built with a digitally fabricated formwork. Therefore, conventional structural design provisions were used to dimension it. Besides the post-tensioning tendons carrying the main forces, the ribs also included conventional shear reinforcement.

Future Tree

The Future Tree [97] is a permanent outdoor pavilion (Figure 5.a) built in 2019 in a courtyard of the offices of the structural engineering company Basler & Hofmann in Esslingen, Switzerland. The idea of the Future Tree was to develop a project to explore the potential of parametric design and to create an iconic architectural element attracting the attention from inside the building located next to it. The final design included two digital fabrication processes: the Eggshell technology was used to build a structural 2.1 m tall concrete column, which supports a permeable timber roof of around 100 m^2. The geometry of the concrete column reflects the timber roof morphology with eight outer ribs serving as a support for the timbre profiles (Figure 5).

In the Eggshell method, an ultra-thin 3D-printed formwork (Figure 5.b, left) is digitally filled with set-on-demand concrete at a speed that is controlled to limit the build-up of hydrostatic pressure to values that the formwork can support [92,98]. The concrete technology is similar to the one in the Smart Dynamic Casting process, but the use of an ultra-thin formwork allows for more complex geometries, as well as for local textures of the concrete surface. In the Future Tree, the formwork was just 1.5 mm thick and made from a polymer that could be recycled after the column was built. Researchers of the NCCR Digital Fabrication carried out the architectural design and digital fabrication of the column, while Basler & Hofmann was in charge of the structural analysis. Eggshell allows the digital fabrication of complex column structures in a continuous casting process with similar mechanical performances as conventionally built structures. Hence, in those cases where a reinforcing bar cage can be fit to the formwork geometry (as for the Future Tree column, see Figure 5.a, center), the structural design can be addressed by essentially conventional procedures. In this particular application, the design loads and the structural design followed SIA 261:2014 and SIA 262:2013 codes [90,91]. The core of the column was dimensioned to resist the global loads of the timber roof, which required 8Ø14 longitudinal bars and Ø10 stirrups at a spacing of 150 mm. Minimum reinforcement for crack width control and to avoid brittle failures at cracking was disposed as well in each of the column's eight ribs, which had a maximum cross section of about 200 x 70 mm. This reinforcement consisted of Ø14 longitudinal bars at the edge of the ribs and transversal Ø10 bars at a spacing of 80 mm. The structural engineer did not require tests of prototypes since the dimensioning was possible following essentially conventional methods, and the loads are low.

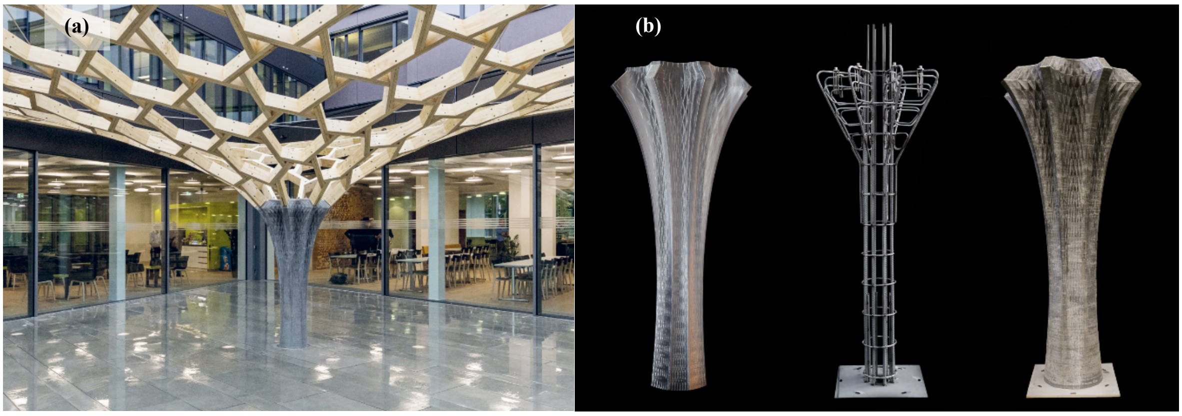


Figure 5. Future Tree pavilion in Esslingen, Zurich: (a) completed pavilion (Image: Basler & Hofmann AG, Stefan Kubli); (b) Eggshell column, from left to right, printed ultrathin formwork, reinforcement cage and finished concrete element (Image: Gramazio Kohler Research, Joris Burger).

KnitCandela

KnitCandela (Figure 6) is a thin, undulating, 50 m^2 concrete shell built in 2018 at the *Museo Universitario Arte Contemporáneo* (MUAC) in Mexico City as part of an exhibition of Zaha Hadid Architects. The shell was designed in collaboration between Zaha Hadid Architects and researchers of the NCCR Digital Fabrication as a homage to the Spanish-Mexican shell builder Félix Candela. The concept for this shell was to explore how the range of buildable concrete shell geometries, usually restricted to hyperbolic paraboloids in Candela's designs due to constructive reasons, can be expanded thanks to the use of novel computational design methods and a KnitCrete formwork. The KnitCrete formwork system uses a custom knitted textile as a lightweight stay-in-place formwork, which integrates channels to insert reinforcing or tensioning systems [37]. The formwork is coated with a thin layer of fast-setting cement paste [99] that serves as a first stiffening layer for the textile, minimizing formwork deformations during the application of further concrete layers. The inner layer of the formwork was left uncoated and used for aesthetical purposes (Figure 6).

The structural engineering in KnitCandela was in charge of researchers from the NCCR Digital Fabrication, namely of the Block Research Group. KnitCandela was a temporary element located inside a museum and carrying only the self-weight; hence, it was classified as an artwork and the structural design did not have to fulfill any building code or other structural design regulations. The structural designed consisted in verifying maximum and minimum concrete stresses as well as maximum deflections, both calculated based on a linear elastic analysis [99]. Since the shell was considered as unreinforced (the contribution of the textile was neglected), the design relies on the capacity of concrete in tension. A small amount of glass fibers was added to the concrete mix provided by Holcim Mexico, in order to control crack distribution and to allow for a safe application of the followed admissible stress approach. Instead of a constant thickness shell, a ribbed structure (Figure 7) was designed to minimize material use. The ribs were simply created by inserting inflatables in some pockets integrated in the knitted textile. The shell thickness was 30 mm, which increased to 70 mm in the ribs. This final configuration led to a peak tensile stress of concrete below 60% of the design material tensile strength, which was considered as admissible. It should be noted that the design and construction was carried out over a period of only 3.5 months.

Figure 6. Finished KnitCandela concrete shell showing the soft textile interior and the smooth concrete exterior [99].

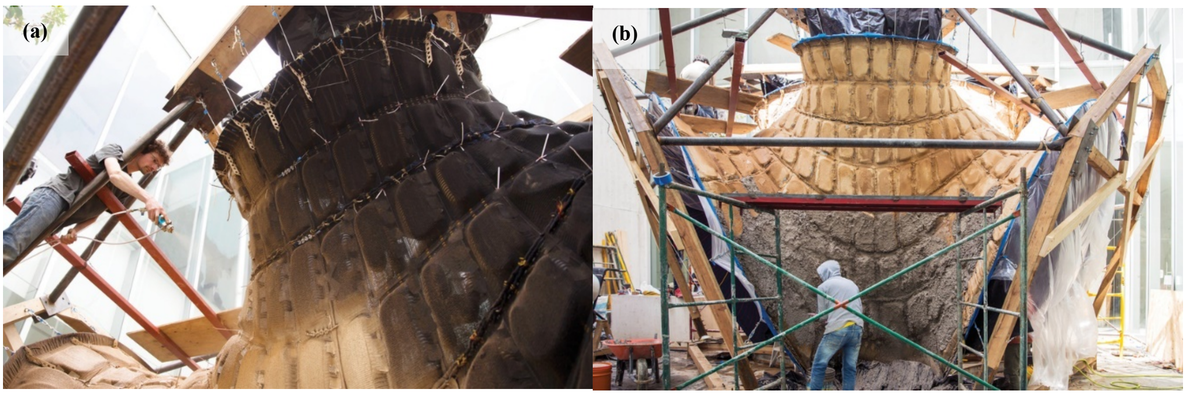


Figure 7. Concreting steps in KnitCandela: (a) thin cement-paste coating; (b) application of concrete layer on top of the coated textile (Images: Block Research Group, Mariana Popescu).

2.1.2. Bicycle bridge Gemert

In 2017, at the initiative of contractor BAM, a bicycle bridge mainly consisting out of 6 extrusion-based 3D concrete printed parts was realized in Gemert, the Netherlands, as part of a larger infrastructure project (Figure 8). The project took approximately 6 months and is extensively described by Salet et al. [44,100]. Structural engineering was performed by Witteveen+Bos consulting engineers, in close collaboration with Eindhoven University of Technology (TU/e), which also provided all experimental testing. The parts were printed at the TU/e 3DCP facility and moved to site, where they were joined into the bridge element, which was subsequently hoisted into place.

Figure 8: 3DCP bicycle bridge in Gemert, at the opening event in October 2017 (photo: Kuppens Fotografie)

As the bridge would be the first of its kind, a conservative fail-safe concept was adopted. It featured parts that would be rotated 90° after printing and stacked together by full prestressing (i.e. at the ultimate limit state, there is no tensile stress in the span direction, which due to the orientation of the layers would be the most uncertain in terms of flexural tension resistance).

The design of the single segments was purposefully kept relatively simple, keeping the characteristics of the 3DCP facility in mind. The segments contain no cantilevers and have two straight sides, acting as top and bottom of the bridge. In between, a 'bottle-shaped' pattern of the filament was designed to transfer shear forces (Figure 9). The density of the infill pattern and the outer dimensions (to some extent) were at the discretion of the structural engineer as a function of structural requirements. Contrary to the default 4 cm width of the facility, a 6 cm filament width was applied to increase robustness. For this, a custom nozzle was developed. The print head speed and pump pressure were adjusted accordingly.

Figure 9: Printing of one of the parts of the bicycle bridge at the 3DCP facility of the TU/e

To avoid any unforeseen structural behavior, a full 3D non-linear Finite Element Model (FEM) was developed for the structural calculations. The design loads were taken from EN 1991 [101,102], while the input material properties and checking criteria were obtained from experimental testing at the TU/e, from which design values were derived according to EN 1990, Annex D [103]. This provided directionally dependent compressive and tensile strength data, as well as data on stiffness, shrinkage and creep. However, despite a rather extensive experimental campaign, it should be noted that, due to the high number of parameters to be tested, the average sample size is still limited and not all process variables could be taken into account. Also, the applied experimental methodologies were in early stages of development and are still evolving.

In the direction of the main span, the prestressing action was applied by post-tensioned rods, anchored in cast concrete head blocks and fed through openings in the segment structure, which serve as active reinforcement. This concept is convenient as it does not disrupt the printing process. In the perpendicular direction, an innovative concept of entrained high strength steel cable reinforcement was applied over a part of the height [104,105]. These cables were intended as torsion reinforcement in case of misalignment in the abutments.

The building permit was obtained from local authorities based on the 'Design by Testing' approach provided by Annex D of the EN 1990. In addition to the material tests, two large scale tests were performed. First, a destructive 4-point bending test on a 1:2 scale mock-up of the bridge was done to verify the failure resistance and failure behavior. Subsequently, an on-site loading test to the serviceability limit state was performed on the actual bridge. Considering the design concept in relation to the results of the experimental results on different scales, the bridge was considered safe for use.

Important lessons were learned from this first bridge. According to the design, the anchor blocks should have been supported continuously on two foundation beams supported by piles. However, these beams and the bridge were not fully aligned, resulting in a torsion moment in the post tensioned but unreinforced printed segments. It is suspected this is the cause of some cracks that have appeared. Besides, the impact of shrinkage differences caused by both drying shrinkage and temperature gradients has induced longitudinal cracks in the printed segments over time. Neither crack is critical, but they are a consequence of the slender dimensions of the printed filaments compared to massive traditional structures, which is a serious issue to consider.

2.1.3. Cohesion pavilion Innsbruck

The Cohesion pavilion was designed, fabricated and constructed on a publicly accessible square in Innsbruck, Austria, in 2019 over a period of just 11 weeks (Figure 10). It celebrates the 350th anniversary of the University of Innsbruck. The architectural and structural design was developed by a small team of students and staff of the University of Innsbruck in collaboration with Eindhoven University of Technology. The complex free form pavilion, characterized by a multitude of developing and merging double curved surfaces, consists of 47 radially positioned, unique parts. In each part, the individual layer height increases from one side to the other to achieve the required radial curvature. The outer surface of each part was dictated by the architectural design, while the infill was to be designed according to structural needs. The parts were produced by Incremental3D by extrusion-based 3D concrete printing, with the two-stage material supplied by Baumit. On-site construction was performed by contractor PORR. A detailed description of the project is provided by Grasser et al., 2020 [83].

Figure 10: Cohesion pavilion, celebrating the 350th anniversary of the University of Innsbruck (Photo: Rupert Asanger).

Considering the short time span available, a robust and efficient approach was opted for. First, the structural principles were determined. Each part was designed to be self-supporting. To avoid extensive reinforcement, the parts were dimensioned not to exceed the concrete tensile strength, with the exception of the heavily cantilevering ‘table’. Reinforcement was only applied to ensure structural safety – not to act in tension in the in-service conditions. Due to the orientation of the print filament, the tensile stresses act in the plane and dependency on the uncertain tensile strength of print layers interfaces is avoided.

To determine the loads, the pavilion was considered as a CC1 (Consequence Class 1), RC1 (Reliability Class 1) type structure as defined by the EN 1990-1, with a 5-year reference lifetime. Determining the location and magnitude of loads that should be considered to act on the structure is difficult due to the irregular geometry. Conservative assumptions had to be made. The distributed and concentrated vertical loads were considered feasible on any part of the structure with a slope of 45° or less with the horizontal. However, the concentrated horizontal line loads were governing in the more critical parts.

Each part was individually designed and analyzed. A simple linear elastic 2D FEM approach in one or more radial planes of the part was adopted. Although this ignores beneficial effects of the tangential curvature, this method was chosen due to its modelling and analysis efficiency. For the larger parts initially a model with linear geometries was used to gain insight in the order of magnitude of stresses and develop a principle design of the infill pattern, which was followed by a surface geometry-based analysis to check and verify. The maximum principal tensile stress was taken as the checking criterion.

The material supplier provided data on the bending and compressive strength of the material, as well as the Young's modulus and an estimate of shrinkage. However, due to a lack of standardized testing methods, these had to be treated as global indicators because details such as sample size, testing direction, printing conditions, and so forth, were unreported. Globally, a material safety factor $\gamma_M = 2.0$ was applied to account for the limited experimental data available. Additional safety was to be provided by the reinforcement.

The structural geometry design was based on the assumption that any geometrical width should be a multitude of the print filament width of 3 cm. The internal structures were mostly designed in an orthogonal manner (vertical and horizontal) as it was expected this would be the easiest to control in printing and would result in parts that are less susceptible to shrinkage stresses than parts with diagonal infills. Care was taken that the structural dimensioning matched the requirements of a continuous print path in each layer as well as a consistent print path topology over the print element height. Figure 11Figure 10 shows the pavilion during construction, with some insides of the parts on display.

Figure 11: Cohesion pavilion, celebrating the 350th anniversary of the University of Innsbruck (Photo: Freek Bos)

Woven carbon fiber reinforced polymer (CFRP) strands were applied as reinforcement. All CFRP elements form continuous (semi-rectangular) geometries so that their reinforcing performance would not depend on the bond with the concrete, as this should be expected to be limited due to the strand smoothness. Due to time constraints, this innovation was only applied to a selection of the higher parts in the outer ring, while manually embedded d = 6 mm conventional reinforcement bars were applied to reinforce critical sections of the other parts. As advanced bar bending equipment was unavailable at the manufacturer, only straight bars or bars with one 90° angle were used. In several cases, the infill pattern was particularly designed to allow the embedment of such bars.

Generally, reinforcement (either CFRP or steel) is applied twice in each part, between layers at approximately 1/5th and 3/5th of the part height, and calculated to be sufficient to carry the ultimate limit state tensile loads in the respective section. Due to the size and location of the pavilion on university grounds, no separate approval for the structural design was required by authorities.

During construction, one part was severely damaged by collision from a fork-lift truck, to which they are more sensitive than conventional concrete parts due to their filigree nature. In the months after construction, several shrinkage cracks have been reported in the parts. A comprehensive evaluation of the state of the structure is planned for a later date. Printing mortars generally exhibit a high level of shrinkage, but in this project the speedy fabrication process, which in some cases saw parts being implemented on-site in a week after printing, may have been aggravated by the lack of controlled curing conditions.

2.1.4. 3D-printed concrete girder designed by topology optimization

The lab-scale footbridge project showed in Figure 12 and Figure 13, thoroughly discussed in [36], is a post-tensioned DFC girder (4 m span) that was constructed at Ghent University in 2019. The 2D shape of this girder was optimized using topology optimization techniques developed at Technion - Israel Institute of Technology. Using advanced algorithms, not only the concrete distribution was optimized using general topology optimization, but also the optimal shape and curvature of the post-tension cable was determined. The objective was to minimize the displacements at the top surface of the beam, due to the combined action of the external loads and the post-tensioning tendon [106]. Ongoing work is focused on a more practical formulation that includes the tendon force as a design variable; curvature constraints on the tendon; and stress and overhang constraints for the concrete. As the implementation of the optimization procedure was so far developed in 2D, some design post-processing was necessary, and a 3D finite element analysis was performed to find the design values and limits. Similar to the bridge project in Gemert, the final structure was made from multiple segments, that were printed independently, and afterwards compressed together with tendons. However, in this case study, the internal cavity was grouted to create a solid shape (cfr. the topology optimization result). As such, and in contrast to the other projects, the digitally fabricated system can be classified as a formwork printing process. With regard to the 3D finite element analysis, it should be noted that the FE model of the girder did not include the complex interaction between the 3D-printed formwork and the solid infill. Instead, a homogenized Young's modulus and associated concrete grade (C30/37) were used in the simulation. The production of the 3D-printed segments was realized in collaboration with Vertico and the printing setup was made of: (i) a 6-axis ABB robot arm, (ii) a mortar (screw) pump with a delivery rate between 2 and 29 L/min, and (iii) an open source concrete printing mixture. The assembly, integration of reinforcements, and grouting process was performed at Magnel Laboratory for concrete research. There, the produced segments were positioned with their large side flat on the floor, rebars (Ø12 mm) were inserted, and the segments slightly prestressed up to 5 kN. Next, the joints were sealed with a foam gun to close the remaining gaps and four 30 mm holes were drilled to fill the internal cavity with grout. The same pumping system, as for the 3D concrete printing, was used to pour the grout. This grout material was a high-quality shrinkage-compensating high-strength seal mortar with a compressive strength of ~60 MPa and a tensile strength of ~12 MPa. After a hardening period of 14 days, the girder was lifted from the ground and the full post-tension force of 50 kN was applied to the lower tendon (type: 3/8″; presented in 'cyan' in Figure 12). Finally, the girder structural performance was experimentally verified using digital image correlation and its deflection was compared to the numerical results. The upper chord showed an excellent fit between the experimental and numerical results. No destructive testing is yet performed on this case study. In the referenced paper, a comparison is also made to a T-section girder with the same total deflection, presenting material savings of roughly 20%. In the end, this project showcases that a combined approach of structural optimization and digital fabrication is key to unlocking material optimization and reducing CO_2 emissions for DFC structures.

Figure 12: Results of the topology optimization procedure for a single-span beam subjected to a uniform load. Black represents concrete; white represents void; cyan represents the tendon [36].

(a) *(b)*

Figure 13: Completed optimized girder - Source: Vertico 3D concrete printing (a); and the individual DFC elements before assembly (b) [36].

2.2 Structural engineer's perspective

The issues associated with structural engineering of DFC projects are further confirmed by structural engineers operating in practice. The authors spoke to Hans Laagland of Witteveen+Bos consulting engineers. At the time of writing, he had been closely involved in 3 completed projects and was working on at least 3 further projects in preparation in Dubai and the Netherlands, all of which were bridges or small buildings with extrusion-based 3D concrete printed (3DCP) structural elements and with building permits for general use. This subsection discusses his experiences.

In conventional structural concrete projects, seasoned engineers have developed an extensive grasp and confidence from personal experience, codes and guidelines. For a variety of reasons, this is entirely lacking in 3DCP. This results in questions like: 'what is the variation in material quality?', 'what dimensional variations occur?', 'how well are layers stacked on top of each other?', 'how well founded are given properties from a statistical point of view?', and so forth.

To deal with this, an approach is needed that significantly deviates from the conventional way of working. First of all, it requires the structural engineer to be explicitly involved in many aspects of the project – most of which are normally regulated by codes and therefore do not need further explicit involvement. This includes material production, determination of structurally relevant properties, print production process control, logistics, and on-site construction. Furthermore, it requires careful consideration in structural modelling, with customized material properties. For instance, the density may have to be increased artificially to account for possible increases of filament width, without simultaneously influencing sectional stiffness as the filament width may also be nominal or less instead of more. In addition, a risk inventory ('what if…') is an appropriate instrument to reduce the failure probability.

In conventional concrete construction, the dimensioning and checking rules based on mechanical static analyses are supplemented by detailing rules based on experience to account for unexpected deviations from the actual structure to the modelled one, as well as for effects that are not explicitly covered in those analyses. Since such experience-based rules are unavailable for 3DCP, much more explicit consideration and testing of possible failure mechanisms, as well as quality control is required.

Another important effect of the introduction of 3DCP is that the nature of concrete structural elements in terms of mechanical response strays from that of conventional concrete. Local stability and strength effects like local and plate buckling, become highly relevant and possibly governing. In this sense, the structural engineering of DFC begins to show similarities with structural steel analyses. Due to the filigree nature of 3DCP structures, the thermal storage capacity is also much less, which may result in cracking due to thermal expansion. This, too, is generally not of concern to conventional cast concrete structures. To identify all these possible failure mechanisms, Witteveen+Bos performs extensive 3D non-linear Finite Element Analyses (FEA) on their 3DCP projects, both on mechanical and thermal loads.

Structural engineering with DFC is further complicated by the fact that there are no material classification standards. The few commercially available printable mortars vary widely in composition, properties, and price. Often, element manufacturers only work with one material supplier. Structural property data are often not easily shared by material suppliers due to the competition in material development. This makes an economical, fit-for-purpose selection of material and structural design very difficult. The lack of certified ancillary products, such as anchors, is furthermore a practical but significant obstacle in the general structural use of DFC. Nevertheless, the experiences of Witteveen+Bos is acquiring building permits for DFC structures is fairly positive. In Europe, the Annex D of the EN 1990 provides a global basis to approve structures that fall outside the scope of other parts of the Eurocode. It has turned out to be workable in practice. When given the proper attention, e.g. by showing production facilities, authorities both in Dubai and the Netherlands have shown willingness to give this new technology and required a reasonable amount of testing to prove structural safety. The testing sequence, generally, consists of four steps. Material tests are initially needed to determine the properties required for structural analysis. Subsequently, a (destructive) mock-up test is required to examine the validity of the design, and no unexpected failure mechanisms occur. When this has been confirmed, the design can be constructed and tested in-situ to ensure the actual construction has been produced according to the design. Finally, a checking or control procedure during the life span of the structure should be enacted to identify possible unknown long-term effects.

Currently, in DFC projects based on structural concepts similar to those developed earlier, Witteveen+Bos is moving from full scale testing of overall structures to more detailed testing of local effects. As experience is gradually growing, this allows a step-by-step reduction of excessive safety measures towards more optimized topologies. Finally, it should be recognized that the application of such innovations requires openness that can only be achieved in combination with real teamwork.

3. OPPORTUNITIES

3.1. Specialized computational methods

Terms like 'design complexity' and 'freeform architecture' are often cited as the primary advantage of digital fabrication of concrete. Nevertheless, its true implications for creating optimal, sustainable and weight-efficient constructions are largely underexploited. More often, design complexity is enforced by designers and architects for aesthetic reasons only, while the structural design opportunities envisioned by digital fabrication are somewhat being neglected, likely also because appropriate tools to fully exploit them, also in terms of a commonly agreed "tailored" design and code-regulation framework, may not be yet fully available.

Many recent projects mention structural optimization theories, often referring to topology optimization and generative design, in an attempt to optimize the structural efficiency. Topology optimization (TO) is a mathematical method that is generally used to optimize the material layout within a design space for a specific set of loads and design constraints. Using this technique, engineers can impose limits so that a design uses the resources optimally while remaining physically viable. As the results from such an optimization are often very complex in shape, their coupling with DFC (or additive manufacturing, in general) is natural. The most common TO approach is the minimum compliance design problem, which minimizes the strain energy of a structure (equivalent to maximizing its stiffness), as depicted in Figure 14. Currently, engineers mostly use this method in their structural designs because the mathematical implementation is straightforward and computationally very efficient. For each iteration in the optimization process, only one finite element analysis needs to be performed to gather all the necessary sensitivity information. However, when linking TO to the design of concrete structures, the use of a conventional compliance-based method is rather limited because it fails to incorporate the non-linear behavior of the material (i.e., concrete having different strengths in traction and compression). In response, several extensions to the original formulation have been proposed so far [107–110] and also for simultaneous optimization of concrete and rebars [111–113]. However, only few of these algorithms have found their way into mainstream use; the common methodology consists in using minimum compliance designs in the conceptual design stage, thereafter several more design iterations are performed using traditional finite element modelling for studying e.g., buckling behavior of local members, fatigue constraints, vibrations, fire safety, robustness, etc.

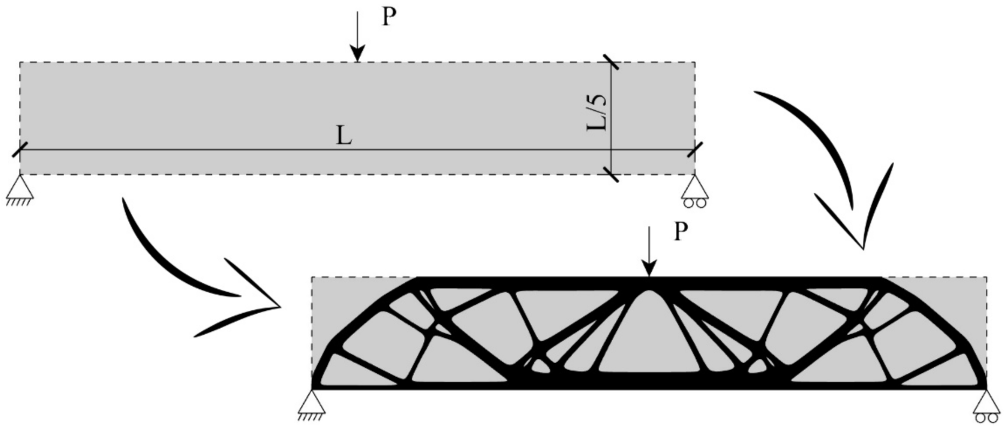
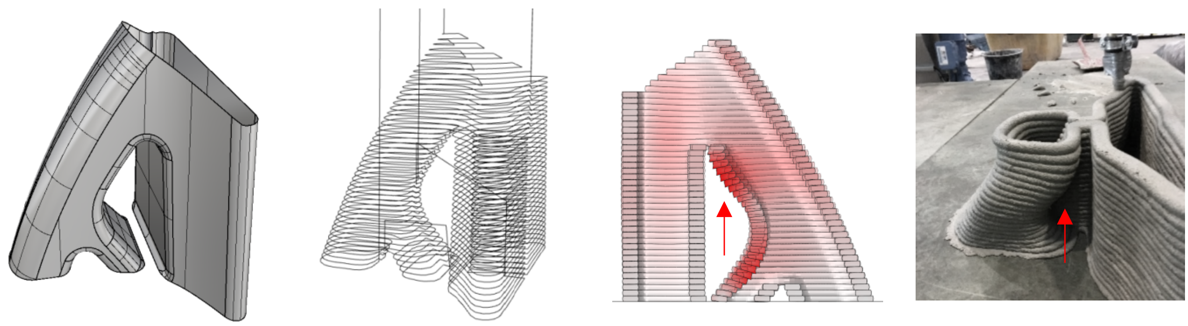


Figure 14: Result of a topology optimization study of a rectangular design domain subjected to a concentrated load [16].

Additionally, in order to not restrict the practical cases to formulations specifically made for the design of concrete structures, recent approaches have been also developed for linking TO to additive manufacturing in general, e.g. overhang limitation for TO [114,115], minimization of support structures [116], and optimization with anisotropic materials and infills [110,117,118]. Besides, several multi-disciplinary aspects could be included in the optimization process as well, e.g., the optimization of the thermal resistance of wall structures, or fire safety and acoustics are all very important and often make use of multi-material optimization techniques where the positioning of the materials is crucial; in this latter case, a link can be also made to multi-material 3D printing [119,120].

Finally, because of the novelty of 3D concrete printing techniques, the process-specific limitations and constraints imposed by the manufacturing process are still mainly unclear. Therefore, designs that are optimized according to specific TO algorithms (in their current implementation) may behave unexpectedly or even suffer damage due to unforeseen consequences of the digital fabrication process. The application of TO algorithms that incorporate the anisotropic material properties of digitally fabricated concrete will be required, but currently awaits fundamental investigation about time, location and fabrication path dependent material characteristics. Also, advanced properties such as layer cohesion, layer interaction, release of hydration energy, thermal strains and relaxation shrinkage will be important as well. With the final aim of providing better input for the TO algorithms, a first structural design opportunity therefore lies in the investigation of these advanced mechanical characteristics.

A second opportunity is not focused on optimizing the design in a hardened material state, but rather optimizing (or maybe just simulating) the finalized design for the manufacturing phase. The reason for this is that many optimized designs are just ‘not ready’ to be digitally fabricated with the current technology capabilities. As such, the development of sophisticated simulation models could bring aid. By this, we mean models (analytical and numerical) that could determine and predict how a DFC element behaves while the concrete is still fresh. Firstly, such models could offer direct improvements in reducing costs and labor-intensive printing experiments, and limit failed printing attempts. Secondly, these models could offer the potential to further tune existing structural optimization strategies and help to solve key challenges for the future. Several elementary models already exist that are developed specific for concrete-printed applications (mainly layered extrusion DFC processes). For example, Suiker [121] proposed a mechanistic model to analyze and optimize the mechanical performance of straight unreinforced wall structures in 3D printing processes. The model investigates the influence of printing speed, curing of the material and geometrical features on failure mechanisms like elastic buckling and plastic collapse. Roussel [51] on the other hand presented a set of analytical equations studying the rheological requirements for printable concrete structures needed to control the final geometrical dimensions of a structure. Among others, layer interface strength, strength-based stability of the first layer, and overall buckling stability of the total structure are discussed. Both methods demonstrate good agreement with the experimental results. However, they can only be used in the case of simple rectangular structures or structures with straight cross-sections, as the application of these equations is not valid for all (freeform) shapes. In response, Wolfs et al. [54,122,123] first proposed a numerical model using 3D finite element analysis to investigate fresh early-age mechanical behavior of 3D-printed structures. The model uses the implicit solver within Abaqus to simulate the continuous extrusion of concrete layers on top of each other, until failure. While requiring a significantly higher computation time, the model provides interesting new insights into the print process, paving the way for simulate complex geometries. A different approach is taken by Kruger [124] and Reinold [125] where the rheological material properties form the basis for the prediction analysis. Reinold [125] developed a numerical model based on particle finite element method that could assist the understanding of the complex interaction between the printing process and the evolution of structural parameters throughout the manufacturing process. The potential for all these simulation techniques is to provide quick preliminary data and enable improved production processes for DFC. Basic implementations could help construct design rules, and link digital design information with the physical production processes (e.g. as in the process of Figure 15). Secondly, a coupling between existing topology optimization algorithms could be made and open unexplored design opportunities.



(a) *(b)* *(c)* *(d)*

Figure 15: Complete digital design-to-manufacture process of a segment from of the optimized design presented in [36]: (a) 3D polysurface (b) slicing and toolpath generation, (c) process simulation, (d) actual fabrication.

In conclusion, it should be noted that the simulation techniques described above are focusing primarily on the printing process, which rather than being the goal of DFC, is merely an indispensable tool for the fabrication. Much less work has been carried out to date related to the structural design of the final product of the fabrication process. Here, these methods should combine the intrinsic properties of 3D printed concrete with structural integrity requirements and related mechanical models for conventional reinforced concrete structures. Thereby, it is possible to find new structural design concepts, such as weak interface design which will be discussed in the next paragraph.

3.2 Structural design concepts

The digital fabrication research community has developed over the past year diverse digital fabrication technologies with strong focus on material and geometrical aspects. In these developments, structural engineering aspects were typically regarded only as challenges. For example, the difficulty to integrate reinforcement during the manufacturing process or the negative impact of weak interfaces on the mechanical behavior have been extensively discussed, but not solved. It should be noted that digital fabrication also offers many new opportunities to the conceptual design, dimensioning, detailing, and production of concrete structures. Some opportunities related to structural design aspects are discussed in this section. The potential of geometric flexibility is the only one that is being extensively explored already. With digital fabrication, concrete can be placed selectively where needed and complex geometries may be produced without additional effort. This is certainly a major advantage, which opens the way for using structurally optimized shapes (reducing material consumption). However, this advantage is limited in many cases, particularly in buildings, due to the existence of requirements for geometric simplicity that are independent of the construction technology [126]. Despite geometric flexibility is already being explored, most promising processes are currently competitive only for special applications. Therefore, further opportunities for more efficient structural design should be explored in order to be able to exploit the full potential offered by DFC also in geometrically simple structures and solve current issues of high costs and lacking compliance with structural integrity requirements. One possibility to comply with requirements of geometric simplicity while taking advantage of the geometric freedom and the possibilities of multi material printing consists on using complex cross sections, in which the material/s are selectively placed to optimally fulfill several functions (e.g. insulation).

Mata-Falcón et al. [49] formulated additional opportunities related to the saving of structural reinforcing steel. For example, reinforcement quantities required for ultimate limit state can be significantly reduced by using robotic placement of reinforcement [96] which allows providing reinforcement in the optimum directions and strictly in the statically required amount. This might be particularly interesting for walls and slabs. Another promising opportunity is the reduction of minimum reinforcement, which often makes up for more than 50% of the total reinforcement content [49]. The minimum amount of reinforcement is always required in concrete structures to avoid brittle failures at cracking and increases proportionally to the cracking load of the structures. Therefore, measures aimed at reducing/controlling the cracking load might reduce minimum reinforcement very significantly. One possibility in this direction is tailoring the concrete grade locally to the actual needs (e.g. reducing the cement content where a low concrete strength is sufficient) [49]. While current DFC processes do not allow for this, it is likely that this will be possible in the future, given the great potential to decrease both the use of cement and reinforcement. Besides reducing the tensile strength of concrete everywhere, a further option to reduce the cracking load and to ensure a proper serviceability behavior is to produce weak sections in the structure. This corresponds to the concept of crack initiators that digital fabrication technologies could introduce by means of geometric or material discontinuities [49]. One example of intrinsic crack initiators caused by material discontinuities are the weak interfaces between concrete layers generated in many additive manufacturing processes (e.g. 3D concrete printing). A simple mechanical model [49] shows that a reduction in the tensile strength at the weak interfaces allows reducing proportionally the cracking load, crack spacing and crack widths for a given load (Figure 16). In this sense, in spite of being a source of concern for the mechanical behavior (mostly unjustified in elements properly reinforced), weak interfaces can be used to reduce the content of minimum reinforcement and/or improving the durability. Results of experimental tests on reinforced tension chords have proven the tendencies predicted by the mechanical model on weak interfaces [127]. In spite of these advances, most of the discussed opportunities for improving the efficiency of structural designs remain unexplored today. Moreover, there will be still plenty of unforeseen opportunities. One of these could be the development of more structurally efficient or more environmentally friendly reinforcing strategies, which could be only suitable thanks to digital fabrication processes. Therefore, it is likely that an effort in this field of DFC will contribute to finding the key for producing more sustainable and economic concrete structures.

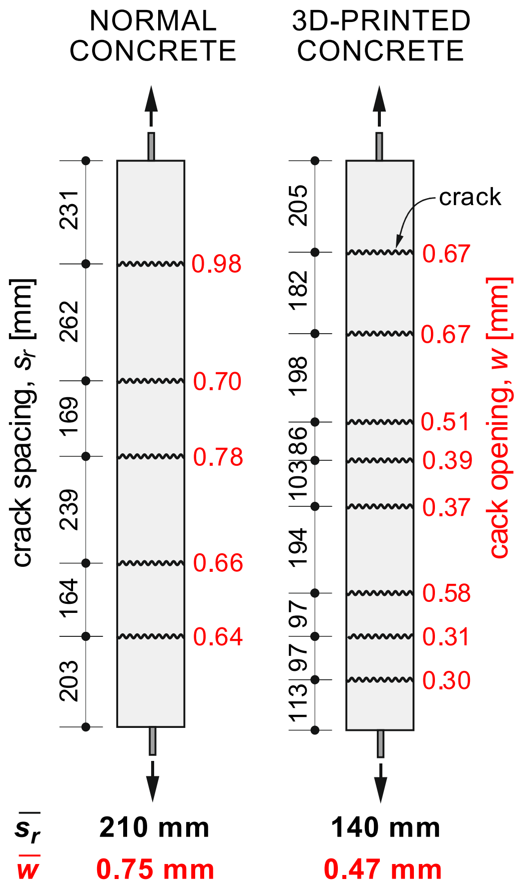
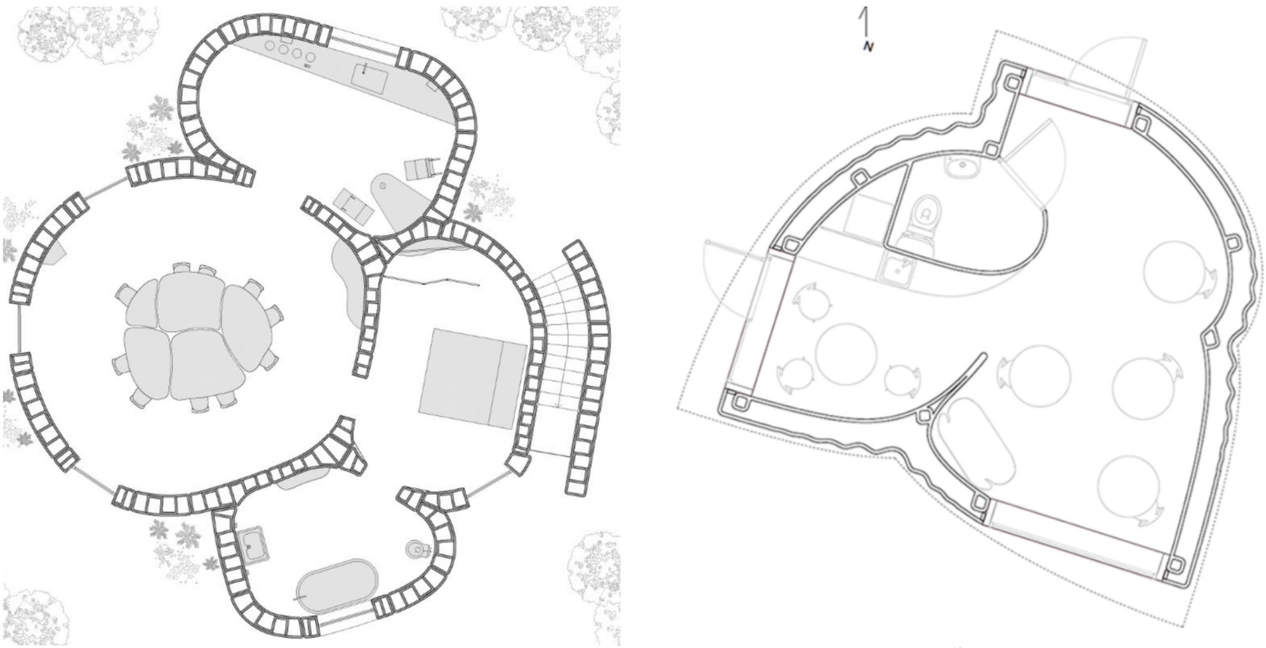


Figure 16. Potential of 3D printing weak interfaces as crack initiators: direct tension tests on tension chords fabricated with weak interfaces (70% of the concrete tensile strength) show a reduction of 30-40% in the mean crack spacing and crack width at the onset of yielding with respect to reference, conventionally cast specimens [127].

4. DISCUSSION

The information collected in Table 1 point out that the number of realized large-scale construction projects employing digital fabrication techniques has surprisingly increased in the last two years, without even considering those that are ongoing. DFC by means of extrusion process is by a large margin the technique most used so far for fabricating whole house systems as well as bridge structures or components; this circumstance can be explained by its practical flexibility and process reliability for either off-site or on-site production, as well as by the much larger research and development effort put into this technology with respect to other DFC processes. In terms of target products of DFC, the fabrication of building systems represents the most frequent solution, mostly driven by the possibility of rapidly implementing construction projects and achieving affordable housing with unusual aesthetic properties. In most of these cases, the walls of the houses are fabricated by a continuous printing process, large scale particle bed techniques or by assembling components consisting of concrete panels produced either off-site or on-site and then connected by means of conventional steel anchoring/connection systems (e.g. see Figure 17).



(a) (b)

Figure 17: Plan view of assembled DFC panels for housing: 3D Housing 05 [76] (a); and "the BOD" [77] (b).

From the structural point of view and for the design of these construction solutions, the realized houses resemble the behavior of (unreinforced) masonry structures, or of an assembly of load-bearing walls subjected to vertical loads. Indeed, for a limited number of situations (e.g. based on in-service conditions, type of applied load etc.), the requirement of tensile capacity and ductility can be over-ridden by designing structures loaded only in compression or with minimal levels of tension. This solution is reasonably feasible and easy to apply as it neither requires additional manufacturing steps to insert reinforcement while guaranteeing form freedom, but it should be also noted that unreinforced single curved walls (the standard case in the listed applications) could have been built cheaper using other conventional techniques. Moreover, the fully structural characterization of such type of structures is yet to be determined (e.g. in-plane/out-of-plane behavior etc.), especially focusing on the mechanical role of layer interfaces/bond in such possible design approaches. Design limitations and requirements should be carefully considered also in reference to the risk of shrinkage cracks and tensile stresses induced by imposed deformations, especially involving support settlements and displacements. In this regard, available standards, such as EN 1996-1-2 which deals with unreinforced masonry and reinforced masonry where the reinforcement is added to provide ductility, strength or improve serviceability or EN 1992-1-1 for load-bearing walls, could represent a possible inspiration for adapting current available design. However, being those types of structures dependent on new materials properties and DFC particularities, the principles and application rules given in the mentioned standards may be not entirely applicable, needing to be supplemented for instance by experimental validation.

As far as infrastructural objects are concerned, it comes out from available literature that the most common way to produce bridge structures consists in digitally fabricating concrete segments by extrusion process (with an almost freeform in the cross section), and then assemble them on-site by means of post-tensioning in the direction of the stacked layers of concrete. This is somehow similar to already available technology on precast segmental bridges [128] regulated by post-tensioning design principles. The evaluation of the structural integrity of those types of structures should be complemented by experimental validation (as described in the following subsection) in the case that provisions about minimum reinforcement are not fulfilled and/or problems of weak interfaces are expected. For other bridge examples obtained by a different DFC process (e.g. particle bed fusion fabricated by D-shape), there was not enough documentation to be discussed in this paper.

At the structural element scale, in addition to some research works and practical cases demonstrating the high potential for the structural implementation of beams, columns etc. (e.g. [47,97,129,130]), temporary projects have normally been classified as an artwork (e.g. KnitCandela) and, for this reason, did not require strict structural design regulations.

In general, given that the applied design methodologies are in early stages of development and are still evolving, some common features characterizing construction projects so far developed can be pointed out:

- The reference lifetime for structural design input is relatively short, probably due to a not sufficient knowledge about durability behavior of innovative DFC products (e.g. 5-year reference lifetime).
- The structural design is frequently reliant on inputs from the researchers from academia (especially for material properties input).
- It is exploited the fact that different available structural design codes allow exceptions in reference to innovative construction products/systems, provided they are well founded theoretically or experimentally. For instance, in the case of reinforced concrete structures, the design loads can be taken from EN 1991[91,92], while the input material properties and checking criteria could be derived from experimental testing; corresponding design values could be determined, for instance, according to EN 1990, Annex D. It should be noted that the safety factor commonly used to calculate the design concrete compressive strength has been increased in some DFC cases in order to account for the larger scatter in the mechanical properties of digitally fabricated concrete.
- In unreinforced DFC products, structural design provisions are mostly used to verify the structural integrity in terms of maximum and minimum concrete stresses as well as maximum allowable deflections. For those DFC structures containing reinforcement, all design provisions concerning the composite action of concrete and reinforcement were considered as well.

- Unreinforced digitally fabricated products are dimensioned in the way that they do not exceed the design concrete tensile strength. Therefore, they are restricted to applications with very low structural demands, such as vertical walls of single storey building.
- Classical approaches for the simulation of the behavior of structural elements are only suitable for simple 1D or 2D geometries. The simulation of all complex shapes enabled by DFC processes requires detailed numerical modelling using either linear or non-linear material models for the structural calculations.

In terms of envisioned opportunities to exploit the benefits of DFC, it appears that topology optimization procedures certainly represent the most promising approach due to the high compatibility with the free form fabrication approach. Indeed, through the preventive choice of a reference mechanical model and constraint conditions, the shape of a structural element can be tailored with reference to applied loads and/or allowable deformations. In some cases, DFC can be use also to control concrete cracking as well as to provide additional opportunities related to the saving of structural reinforcing steel. However, it is clear that the design conceived in this way is currently too demanding for topology optimization procedures since their level of development is still not sufficient to deal with particularities of DEFC techniques or reinforcing strategies.

4.1. Standards and guidelines for DFC structures: ongoing initiatives

In the highly stimulating and dynamic framework of increasing digitally fabricated applications with a large variety of cement based materials, clearly led by the industry, the research community has felt the need to flank and support such a challenging activity setting up adequate transnational initiatives aimed at highlighting, first of all, the material science and engineering fundamentals underlying the concept, design and production of “digitally manufacturable” and “digitally manufactured” cement based materials. Such a task is also instrumental to highlight research needs and foster the development and technology transfer in a coordinated manner, but also to pave the way towards the development of material and product standards and coordinated design approaches which can also be consistently and coherently harmonized with the ones currently governing the design of conventionally cast reinforced concrete structures.

As a matter of fact, RILEM launched, already in May 2016 at the 8th International RILEM Symposium on Self-Compacting Concrete held in Washington, D.C., USA, the first transnationally initiative on digitally fabricated concrete, through the namesake *Technical Committee 276-DFC Digital Fabrication with Cement Based Materials*. The Committee, having regularly convened at least thrice a year, has not only started to organize a successful series of International Conferences, now at its second edition, but is also on the way to release the first international state of the art report on the topic. The report, moving from the material science fundamentals governing the concept and explaining the processing properties and signature performance of digitally fabricated materials and structures, provides a framework to rationally tackle the conceptual and structural design of the engineering applications.

This challenging task, like a gauntlet thrown by the RILEM RC, has been undertaken by the recently constituted *fib Task Group 2.11 Structures made by digital fabrication*, which has held its kick-off meeting in Krakow in May 2019. The goal of the Task Group will be the development of specific testing and design guidelines in the growing area of digital fabrication with concrete, with the goal of defining preliminary structural code prescriptions, e.g. in the form of annexes to current codes, such as *fib* Model Code 2010, valid for conventionally cast reinforced concrete structures, as well as complying with recently reapproved ISO - ISO 22966:2009 - Execution of concrete structures[131].

In the same framework, and fruitfully exploiting its signature healthy contamination between academia and industry, as well as the synergy with existing technical committees dealing with related specialty topics, from material science to workability to fiber reinforced concrete, ACI has also recently formed *ACI Committee 564: 3D-printing with cementitious materials*. The Committee held its first meeting as such during the 2018 fall Convention and has undertaken the task of writing a State-of-the-Art Report in a form consistent with the ACI document library. Besides, it has been also regularly organizing dissemination and educational events on topics related with 3D printing, which are instrumental at marking the most recent global milestone developments as well as addressing cutting edge topics, such as the integration of reinforcement in 3D-printed/digitally manufactured concrete structures.

Multifold involvement in either of the aforementioned initiatives of scholars and industry leaders is a guarantee of synergic cultural cross-fertilization in fostering the development of a topic that is likely to stand as a breakthrough milestone in revolutionizing the innovation uptake of concrete construction industry.

4.2.1 An example of DFC structural design protocol

An example of the need of providing an internationally harmonized structural design and material acceptance framework for digitally fabricated structures, as well as by the pathway which has to be followed in implementing such a task, is represented by the case-study of 3DCP bicycle bridge in Gemert, the Netherlands. In detail, it is well-accepted that the current public system of regulations governing structural design and construction aims to guarantee essential performance requirements to protect the citizen. With focus on Europe, this means that the safety in the construction industry is organized at basis of three different segments: building preparation or design (EN-1992-1-1 [132]), building construction (EN 13670 [133]) and materials supply (EN 206 [134]). Unfortunately, the pre-stressed bridges at issue do not comply with any of these regulations. In terms of design a minimum amount of reinforcement is lacking, in particular in the cross-section. Besides, the flow of forces is much more constrained in the printed segments by the toolpath, leaving less room for redistribution of forces in combination with plastic deformations of reinforcing steel. Moreover, the materials properties of printed concrete are not known from the regulations and cannot be tested accordingly to it. This is since testing cannot be done using standard cylinders without applying intense vibration. Besides, the impact of the typical layered structures most likely needs to be tested as well, taking notice of the printer settings and ambient conditions. One could even question whether the mortars that are printed, without coarse aggregates, can be considered as concrete indeed. Finally, the construction is fundamentally different in terms of printing, but the construction of the segments into a bridge contrary is rather traditional and well regulated.

Fortunately, the regulations have anticipated on such a situation. Annex D of EN-1990 [103] describes a procedure to support the design by testing. A special protocol has been developed to embed the idea in the design and realization of the post-tension bridges, as schematically shown in Figure 18.

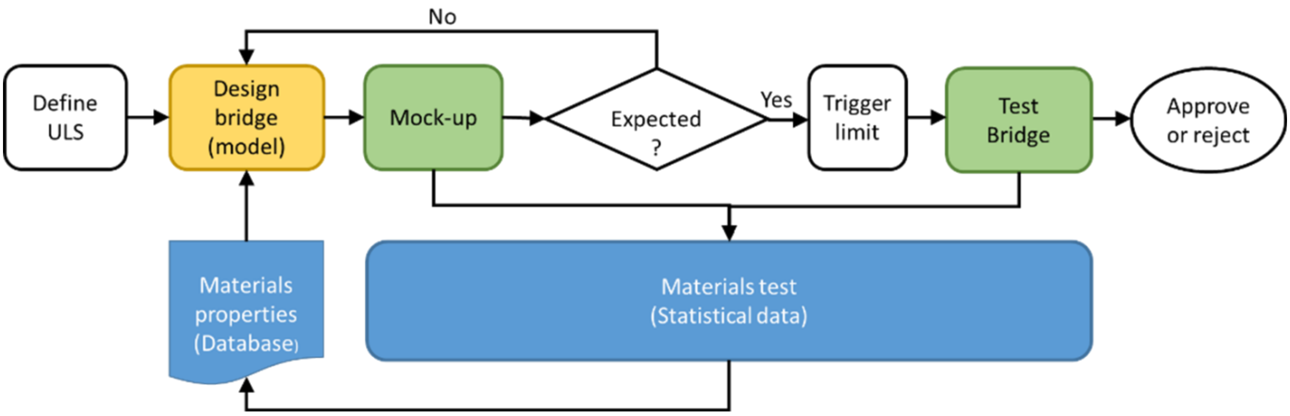


Figure 18: Protocol followed in the design of the post-tensioned bridges

The protocol starts by defining the ultimate limit state and design the bridges accordingly to this using the standard tools and available design code. Materials properties of printed concrete still have to be assumed in this stage, based on data collected from previous tests. Thereafter a mock-up is made and structurally tested up to failure and its structural behaviour compared to the design predictions (Figure 19). The predictions must be updated prior to the comparison with the materials properties tested on the actual mock-up. The additional materials tests provide the designer with the required stochastic data that are collected in line with the rules defined in attachment D of EN-1990. It is worth remarking that the responsible designer also needs to define the kind of structural behaviour that needs to be compared between design and tests upfront and thus the need for proper measuring devices.

Figure 19: Large scale testing, as part of the protocol at TU/e.

In case of an unexpected behaviour, a re-design might be needed. If the behaviour in the test matches with the design, the production can start. However, in the case study at issue, the bridge will be tested on-site again on its structural integrity before being used. The reason for the additional tests is the difference in the manufacturer and manufacturing circumstances between the mock-up and the full bridge and the simple fact that the real bridge is much larger than the part tested in the mock-up. This leaves higher changes on imperfections. Obviously, the on-site testing of the bridge is not conducted up to failure. Instead a kind of diagnostic test is performed, which can in case also be coupled with a continuous monitoring to check any deviation, if any, from the predictions along the time, because of different causes, including, e.g., material and structure aging, accidental events, change in loads and environmental actions etc. The test load should be high enough to measure any structural response, but not that high to avoid unnecessary damage. This trigger limit is defined from the mock-up. Finally, the materials properties of the bridge are again tested as a measure of quality control.

It is realised that the protocol it is rather robust, particularly if the bridge is loaded in the diagnostic test up to the ultimate design load again. However, the idea is to consider the bridge as a mass customised type of product that will be produced in series over time. The ones tested with a mock-up most likely are just the first out of a large series. Once the confidence has been gained that the structural behaviour can be well predicted with design tools, attention may then focus on single components of the bridge, like shear strength (including size-effect), embedded anchor blocks as previously discussed and anchors e.g. to mount a parapet to the printed concrete.

5. CONCLUSIONS

This paper has collected and discussed recent construction projects carried out by means of DFC technologies. The focus has been put on the aspects of structural design and engineering of DFC with major emphasis on extrusion-based concrete 3D printing, as it is one of the most widely used DFC technologies so far.

Depending on the specific DFC process adopted, the structural use of DFC products requires proper attention throughout the project, from the design, to the analysis, production, assembly, experimental validation, and in-service use. Progress has been made in this sense, in particular for the general approval of construction projects as well as for code compliance of DFC products; this has been possible mainly considering that different available structural design codes allow exceptions on the condition that proper experimental testing is used for validation. Different international working committees are also active on these topics and practical standards/guidelines are expected to be released in the coming years to foster the widespread use of these technologies. However, it is clear that much research needs to be done in order to consider DFC as a standard construction method. One of the priorities is represented by the definition of appropriate parameters for extensive concrete material characterization to be used as input in the structural design. The development of suitable numerical modeling approaches is also desired in order to achieve further improvements on topology/functional/structural optimization capabilities of DFC. The application of reinforcement is still scarcely compatible with DFC processes because of geometrical complexities, uncertainties regarding the reinforcement-to-matrix bond, and the integration of the application of reinforcement bars in the printing process. This circumstance has limited the structural design as well, thus requiring much research efforts on this topic.

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